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(54) METHOD OF DESIGNING THICKNESS OF COATING FILM AND SEMICONDUCTOR PHOTONIC DEVICE

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(30) **Foreign Application Priority Data**

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Publication Classification

(51) **Int. Cl.**
G02B 6/10 (2006.01)
H01S 3/091 (2006.01)

(52) **U.S. Cl.** **385/131**; 372/79

(57) **ABSTRACT**

A coating film is provided on an end surface of a semiconductor photonic element including an active layer through which light propagates. The coating film has a two-layer structure including a first layer film and a second layer film arranged in a stacked relation. The thicknesses of the first and second layer films are determined so that the value of the amplitude reflectivity of the coating film is equal to an imaginary number.

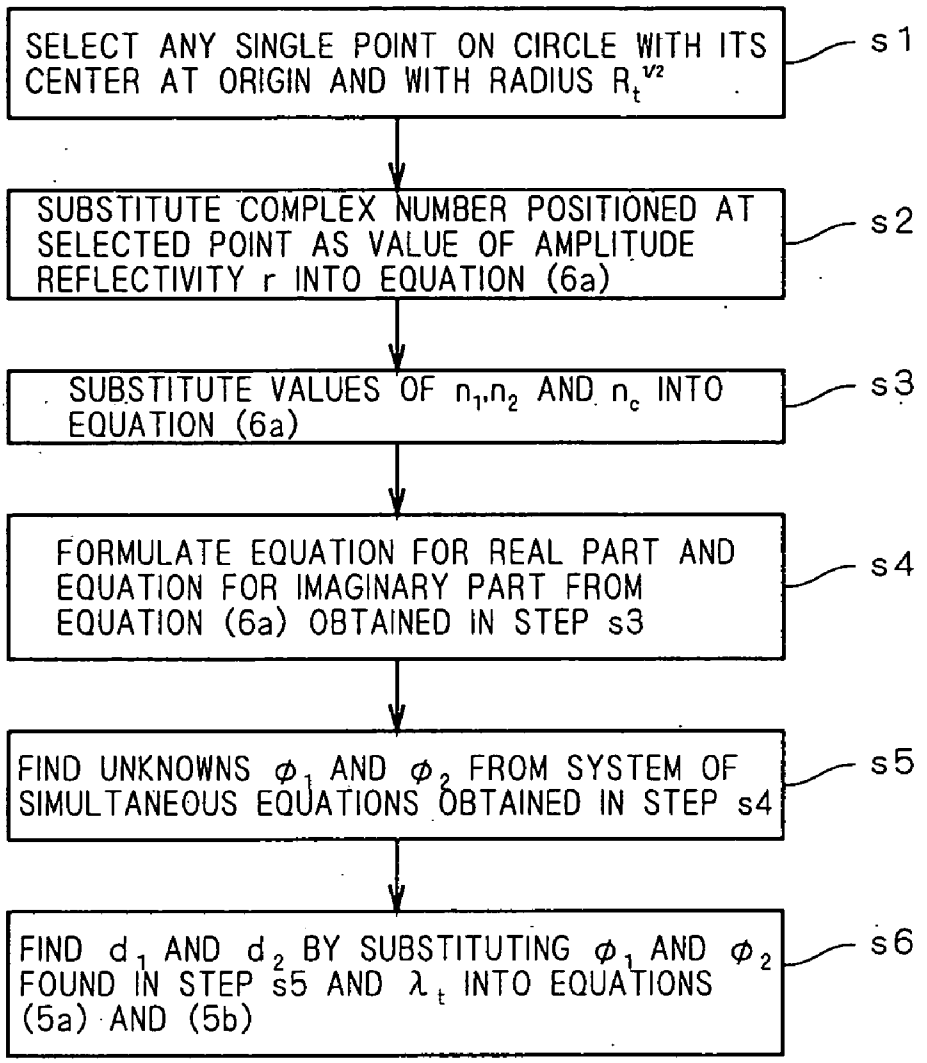

FIG. 1

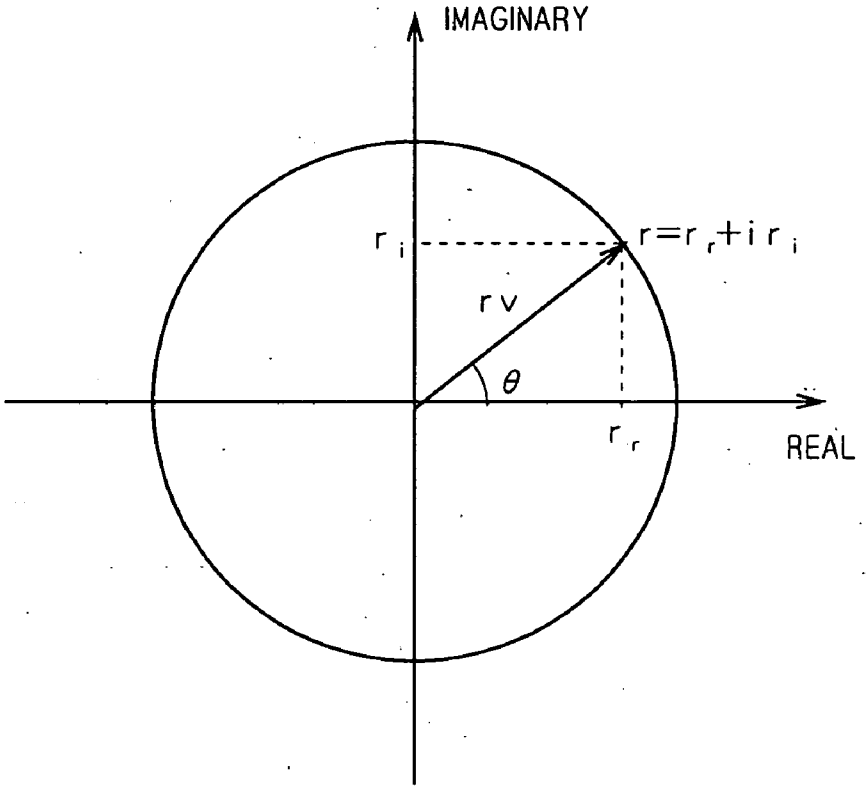

FIG. 2

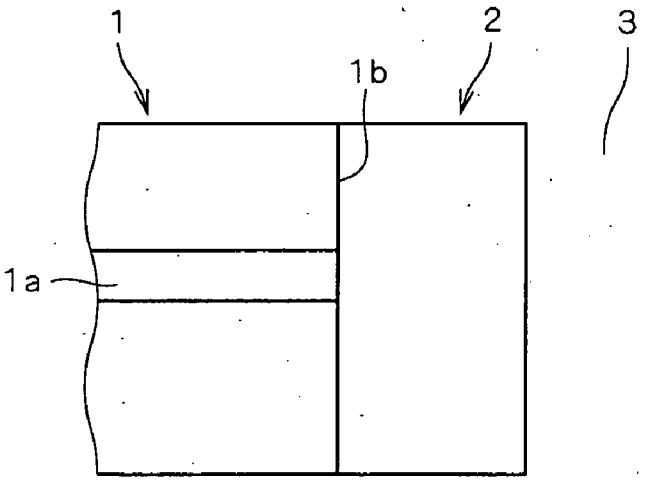

FIG. 3

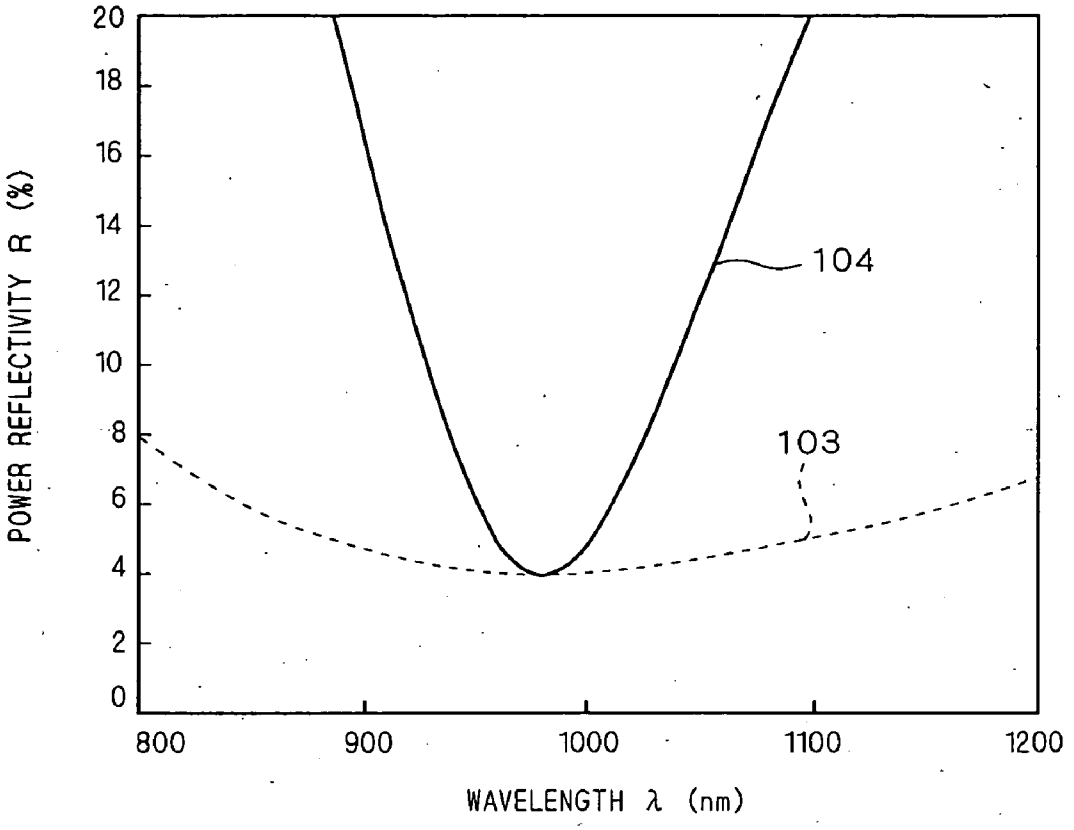
POWER REFLECTIVITY R (%)
20
18
16
14
12
10
8
6
4
2
0
800
900
1000
1100
1200
WAVELENGTH λ (nm)
104
103

FIG. 4

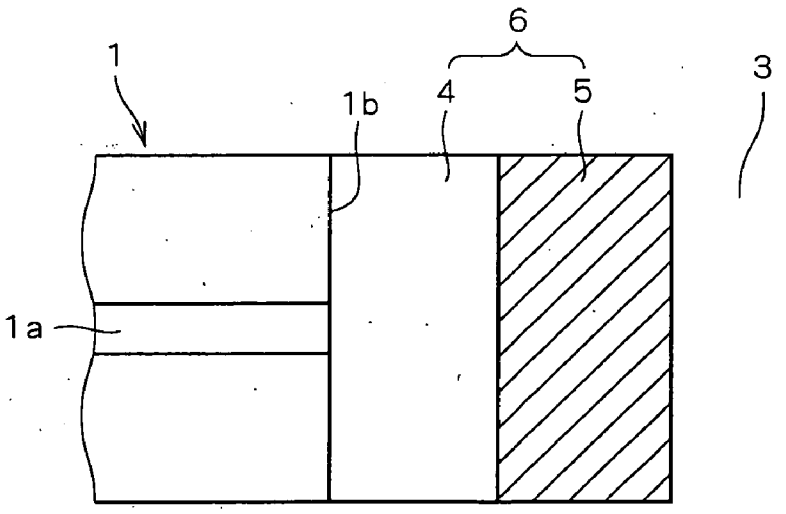
1
6
4
5
1b
3
1a

FIG. 5

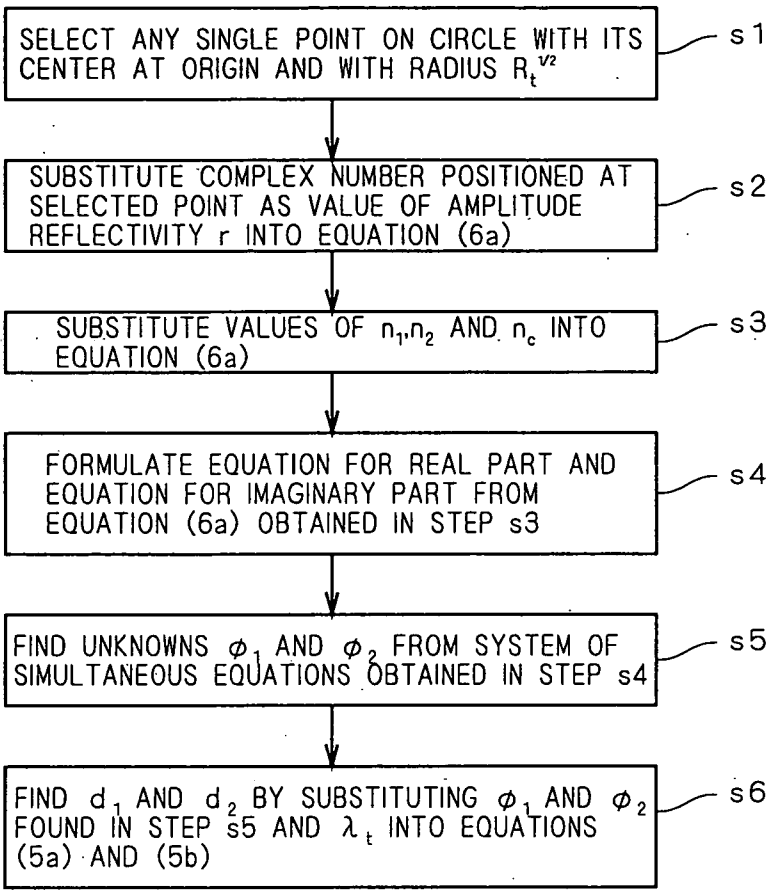
SELECT ANY SINGLE POINT ON CIRCLE WITH ITS CENTER AT ORIGIN AND WITH RADIUS R_t^{V2}
s1
SUBSTITUTE COMPLEX NUMBER POSITIONED AT SELECTED POINT AS VALUE OF AMPLITUDE REFLECTIVITY r INTO EQUATION (6a)
s2
SUBSTITUTE VALUES OF n_1,n_2 AND n_c INTO EQUATION (6a)
s3
FORMULATE EQUATION FOR REAL PART AND EQUATION FOR IMAGINARY PART FROM EQUATION (6a) OBTAINED IN STEP s3
s4
FIND UNKNOWNS ϕ_1 AND ϕ_2 FROM SYSTEM OF SIMULTANEOUS EQUATIONS OBTAINED IN STEP s4
s5
FIND d_1 AND d_2 BY SUBSTITUTING ϕ_1 AND ϕ_2 FOUND IN STEP s5 AND λ_t INTO EQUATIONS (5a) AND (5b)
s6

FIG. 6

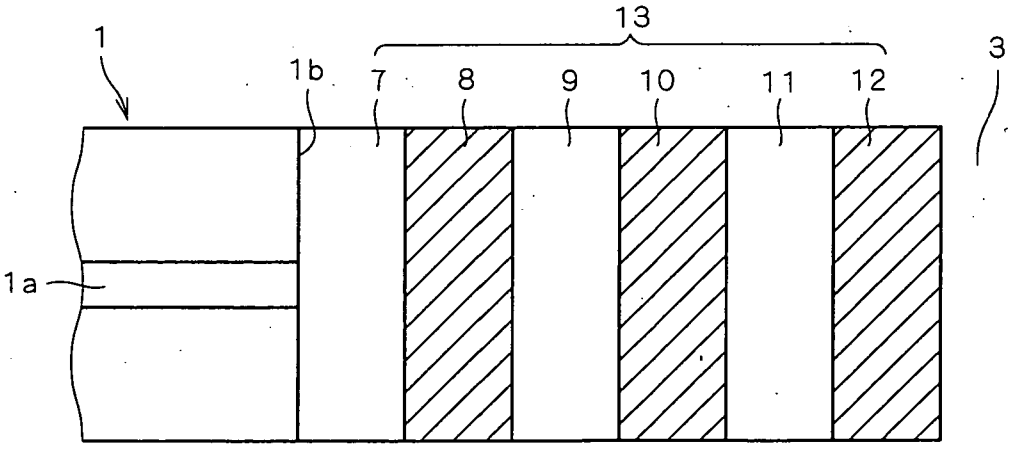
1
13
3
1b
7
8
9
10
11
12
1a

FIG. 7

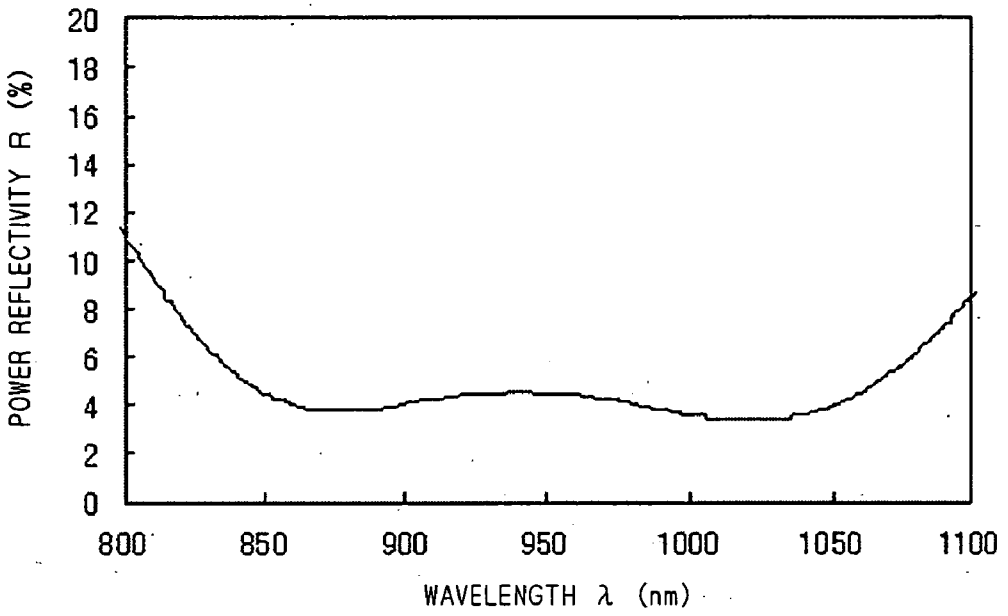
POWER REFLECTIVITY R (%)
20
18
16
14
12
10
8
6
4
2
0
800
850
900
950
1000
1050
1100
WAVELENGTH λ (nm)

FIG. 8

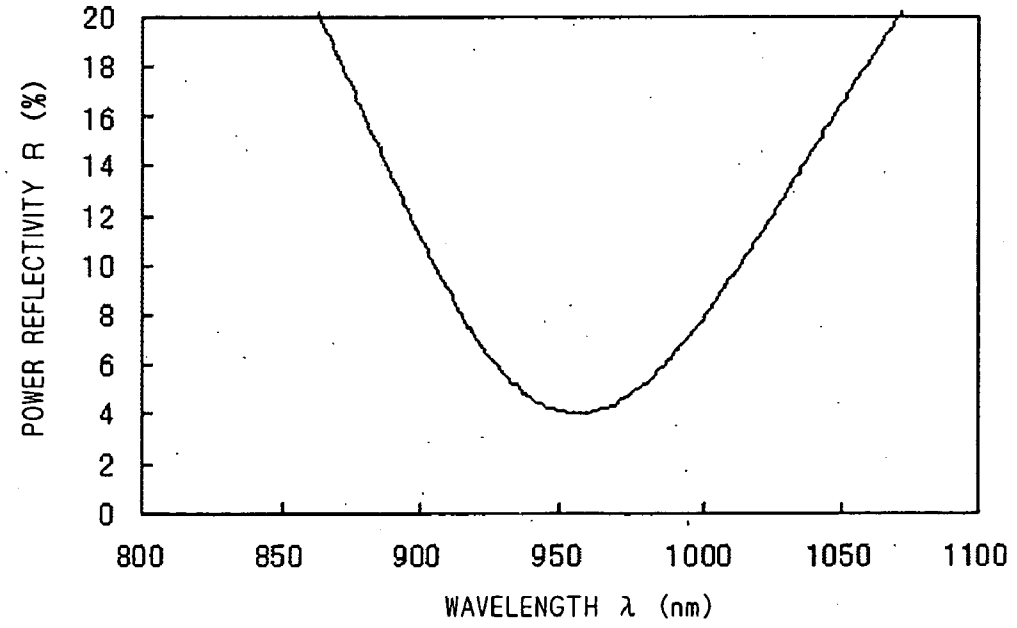
POWER REFLECTIVITY R (%)
20
18
16
14
12
10
8
6
4
2
0
800
850
900
950
1000
1050
1100
WAVELENGTH λ (nm)

FIG. 9

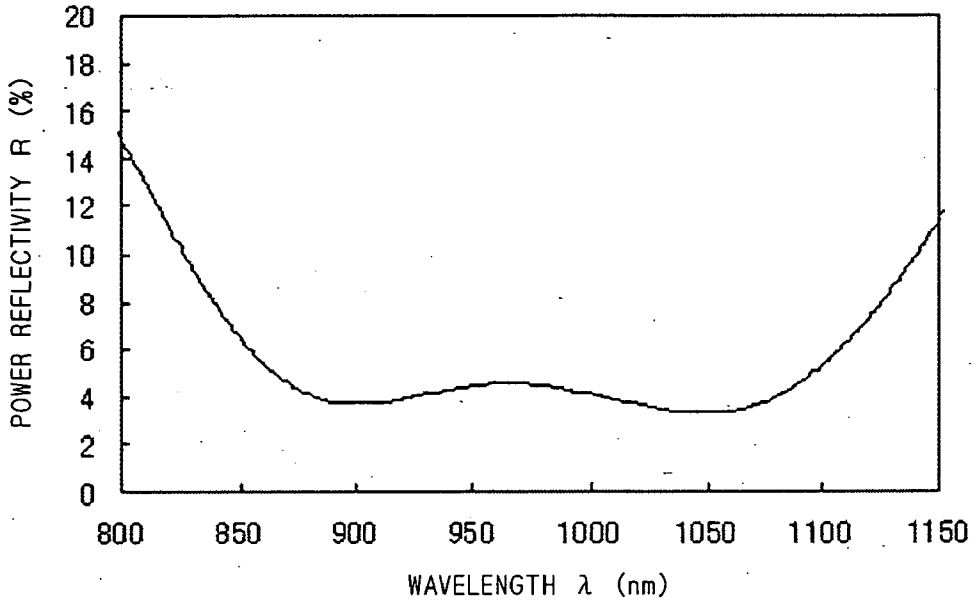
POWER REFLECTIVITY R (%)
20
18
16
14
12
10
8
6
4
2
0
800
850
900
950
1000
1050
1100
1150
WAVELENGTH λ (nm)

FIG. 10

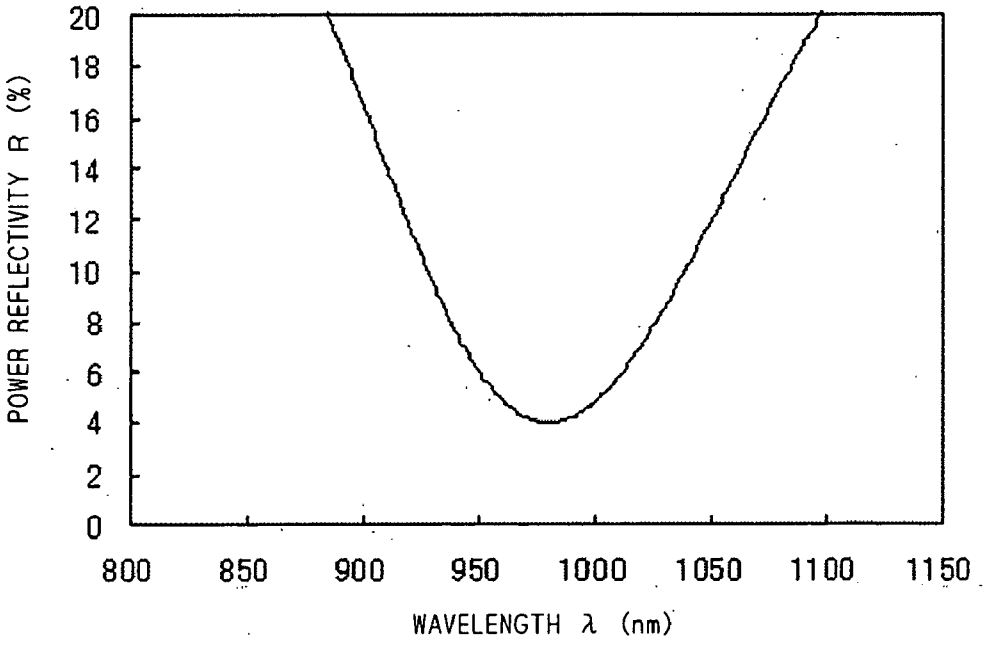
POWER REFLECTIVITY R (%)
20
18
16
14
12
10
8
6
4
2
0
800
850
900
950
1000
1050
1100
1150
WAVELENGTH λ (nm)

FIG. 11

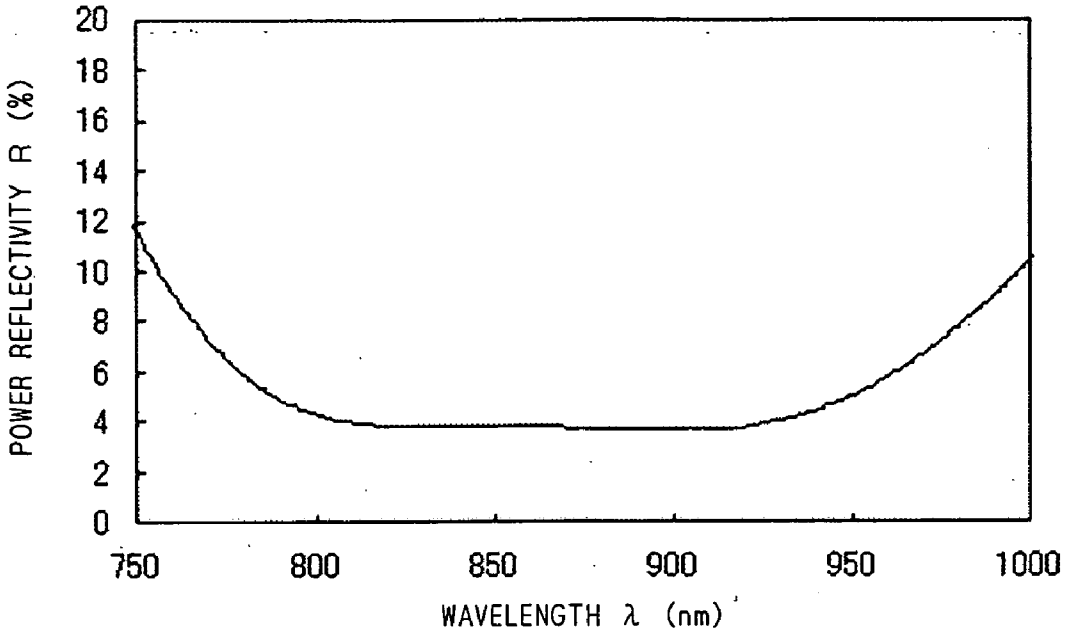
POWER REFLECTIVITY R (%)
20
18
16
14
12
10
8
6
4
2
0
750
800
850
900
950
1000
WAVELENGTH λ (nm)

FIG. 12

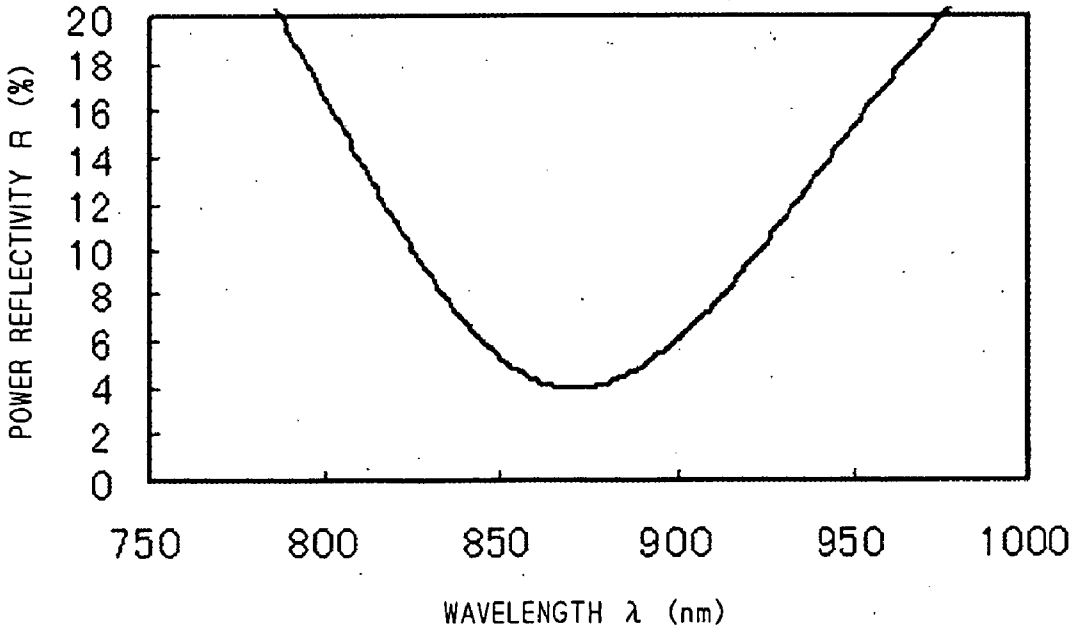
POWER REFLECTIVITY R (%)
20
18
16
14
12
10
8
6
4
2
0
750
800
850
900
950
1000
WAVELENGTH λ (nm)

FIG. 13

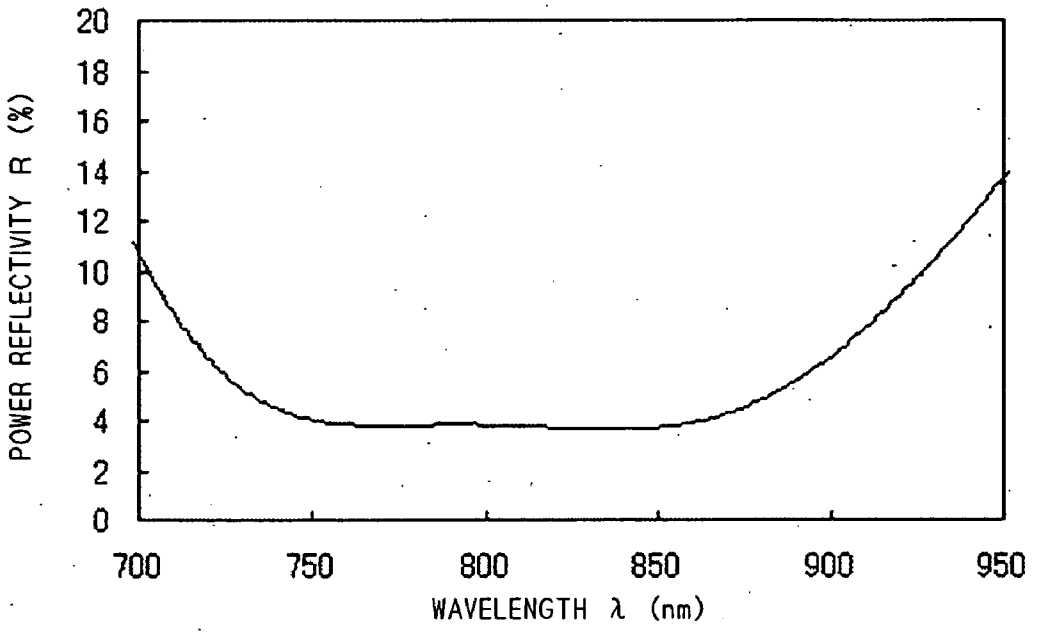
POWER REFLECTIVITY R (%)
20
18
16
14
12
10
8
6
4
2
0
700
750
800
850
900
950
WAVELENGTH λ (nm)

FIG. 14

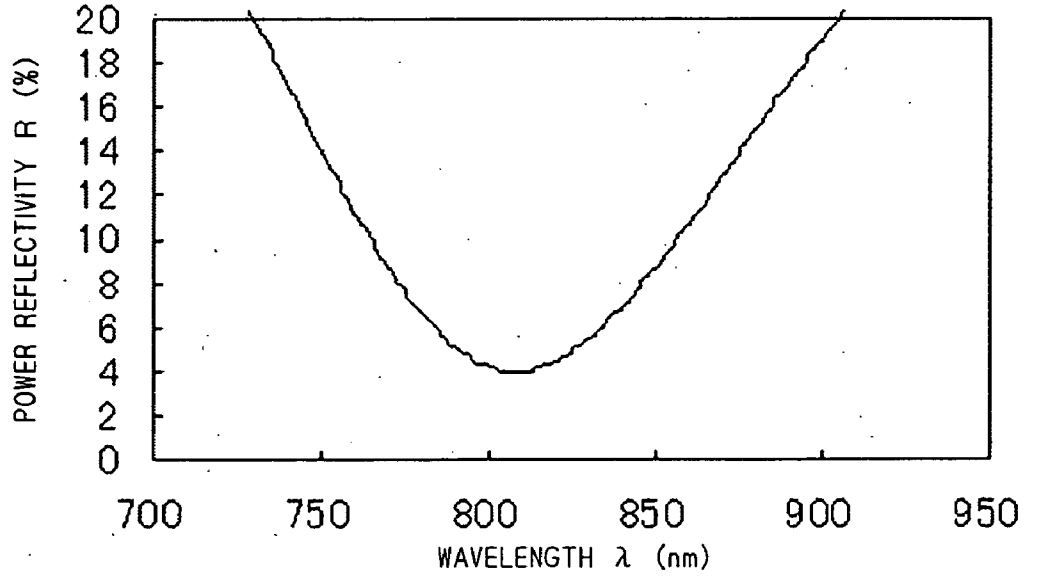
POWER REFLECTIVITY R (%)
20
18
16
14
12
10
8
6
4
2
0
700
750
800
850
900
950
WAVELENGTH λ (nm)

FIG. 15

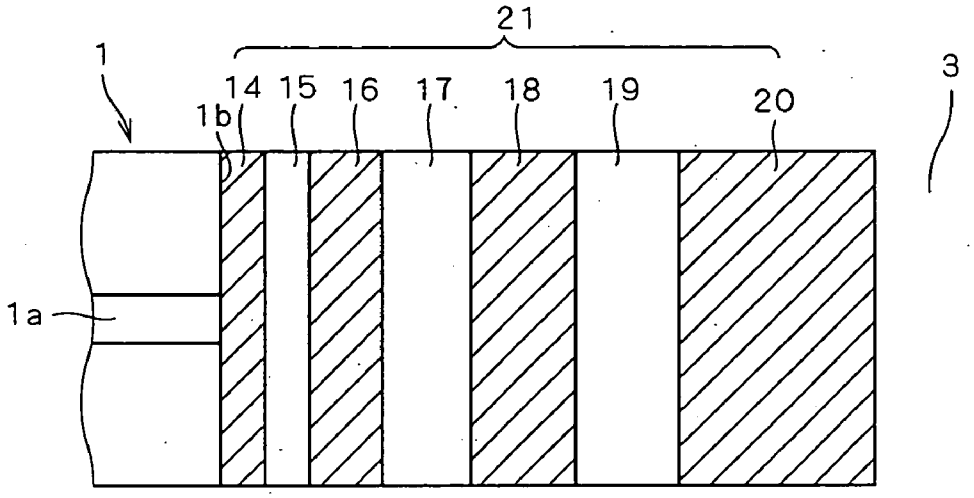
21
1
3
14
15
16
17
18
19
20
1b
1a

FIG. 16

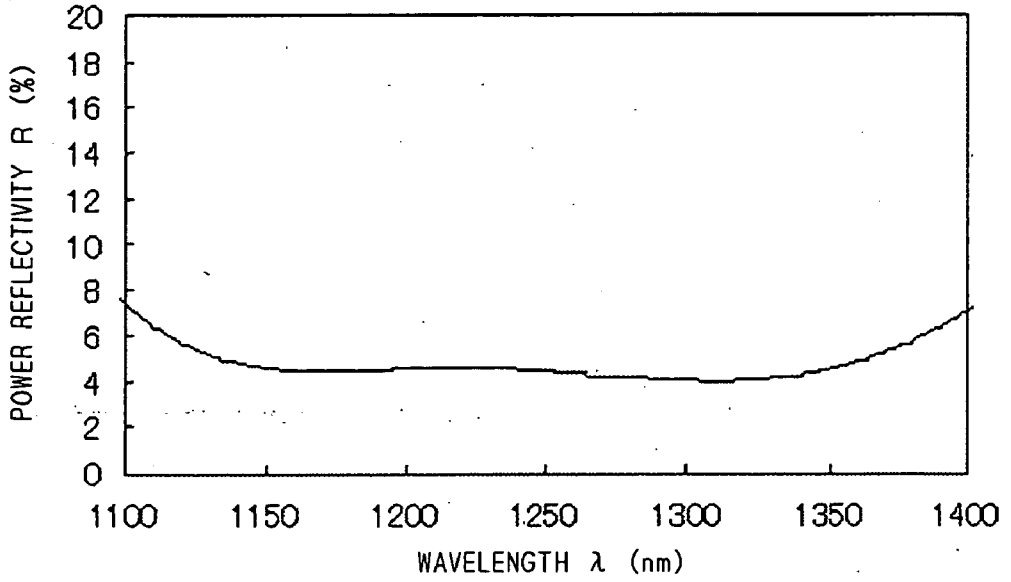
POWER REFLECTIVITY R (%)
20
18
16
14
12
10
8
6
4
2
0
1100
1150
1200
1250
1300
1350
1400
WAVELENGTH λ (nm)

FIG. 17

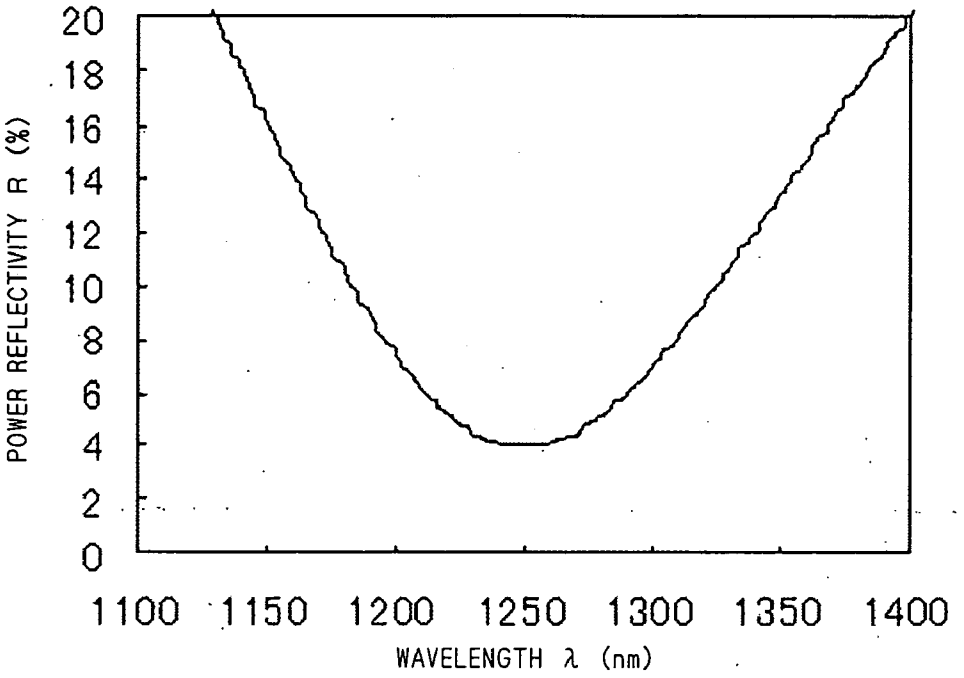
POWER REFLECTIVITY R (%)
20
18
16
14
12
10
8
6
4
2
0
1100
1150
1200
1250
1300
1350
1400
WAVELENGTH λ (nm)

FIG. 18

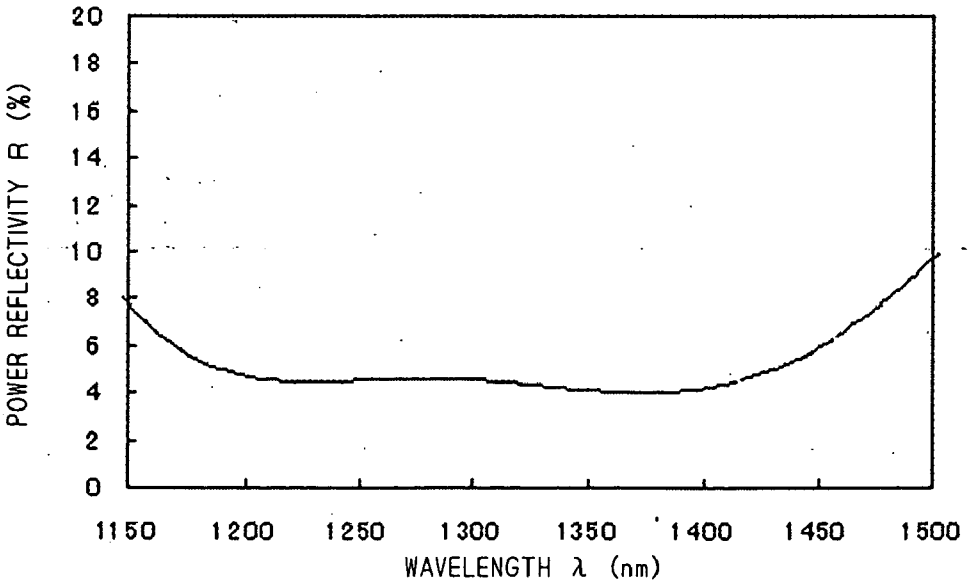
POWER REFLECTIVITY R (%)
20
18
16
14
12
10
8
6
4
2
0
1150
1200
1250
1300
1350
1400
1450
1500
WAVELENGTH λ (nm)

FIG. 19

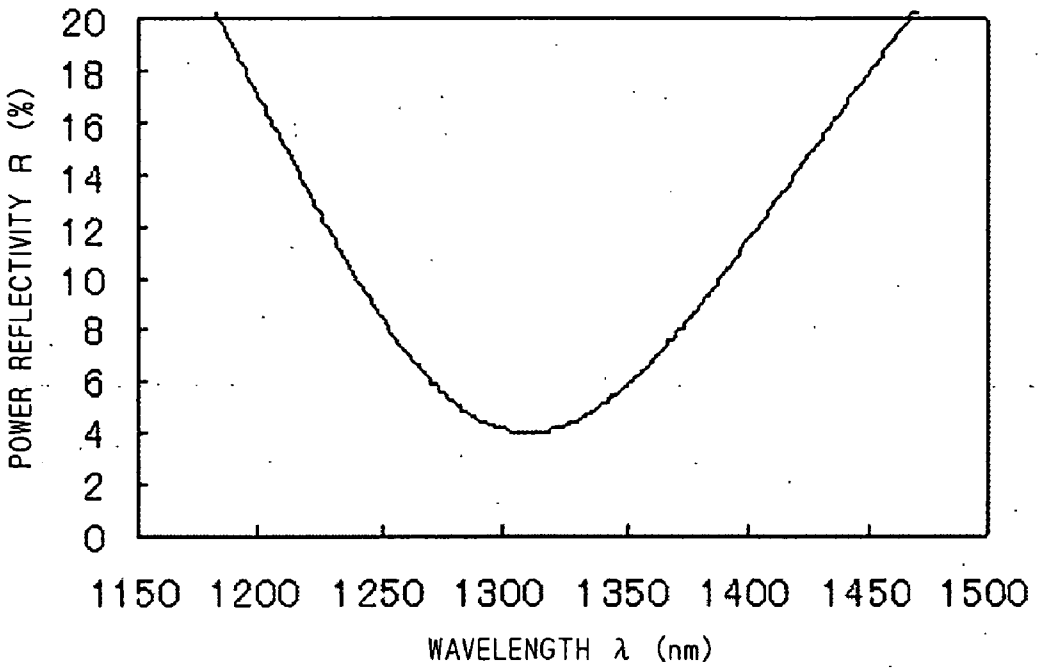
POWER REFLECTIVITY R (%)
20
18
16
14
12
10
8
6
4
2
0
1150 1200 1250 1300 1350 1400 1450 1500
WAVELENGTH λ (nm)

FIG. 20

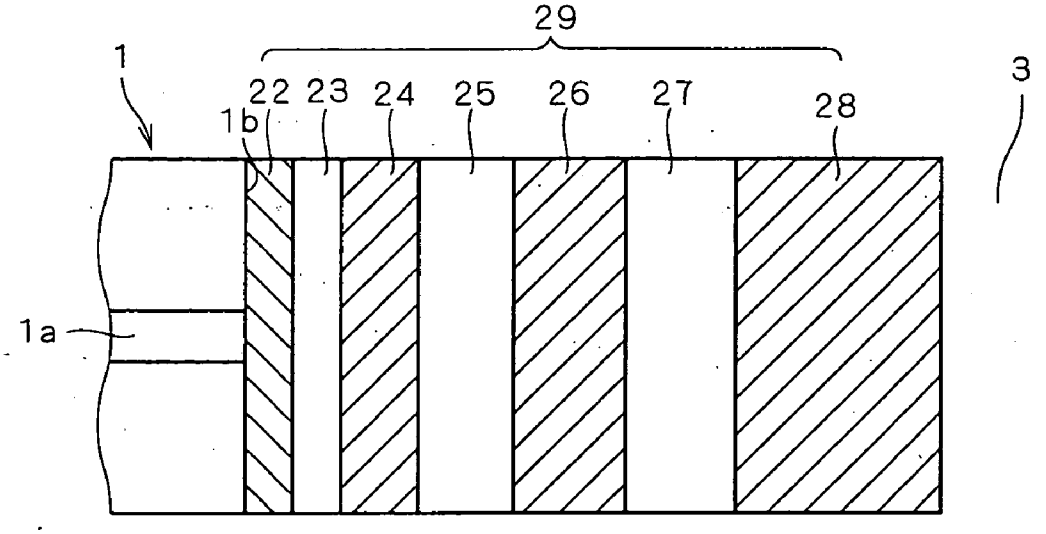
29
1
22 23 24 25 26 27 28
1b
3
1a

FIG. 21

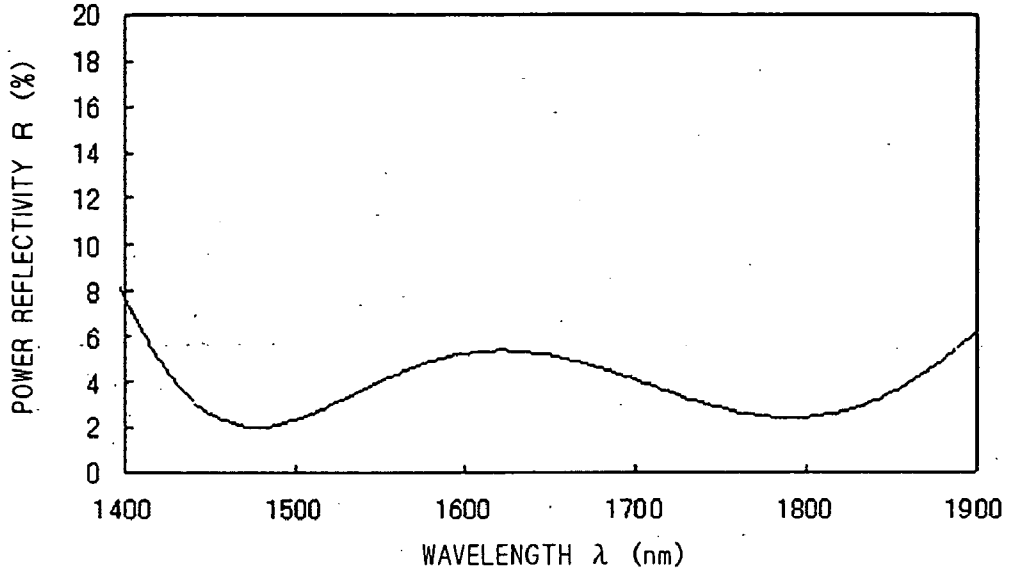
POWER REFLECTIVITY R (%)
20
18
16
14
12
10
8
6
4
2
0
1400
1500
1600
1700
1800
1900
WAVELENGTH λ (nm)

FIG. 22

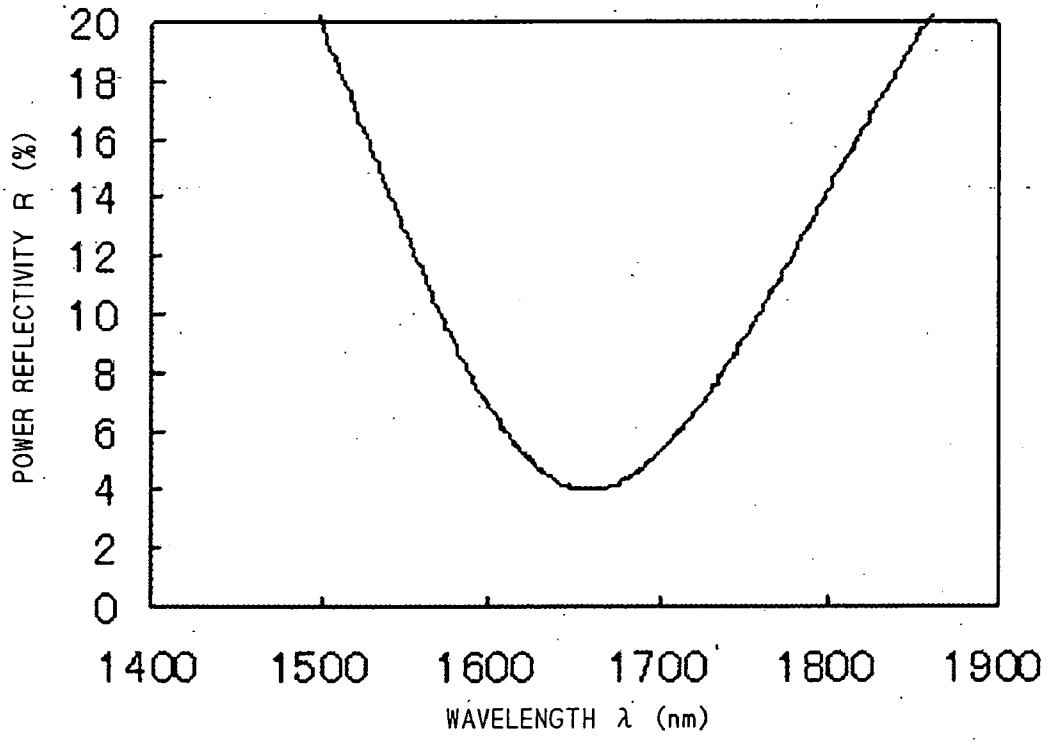
POWER REFLECTIVITY R (%)
20
18
16
14
12
10
8
6
4
2
0
1400
1500
1600
1700
1800
1900
WAVELENGTH λ (nm)

FIG. 23

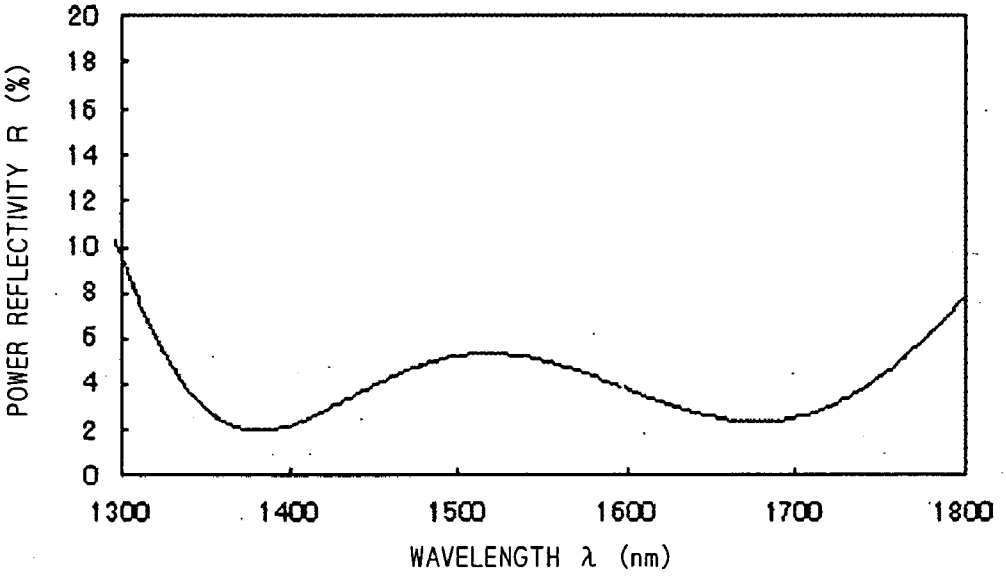
POWER REFLECTIVITY R (%)
20
18
16
14
12
10
8
6
4
2
0
1300
1400
1500
1600
1700
1800
WAVELENGTH λ (nm)

FIG. 24

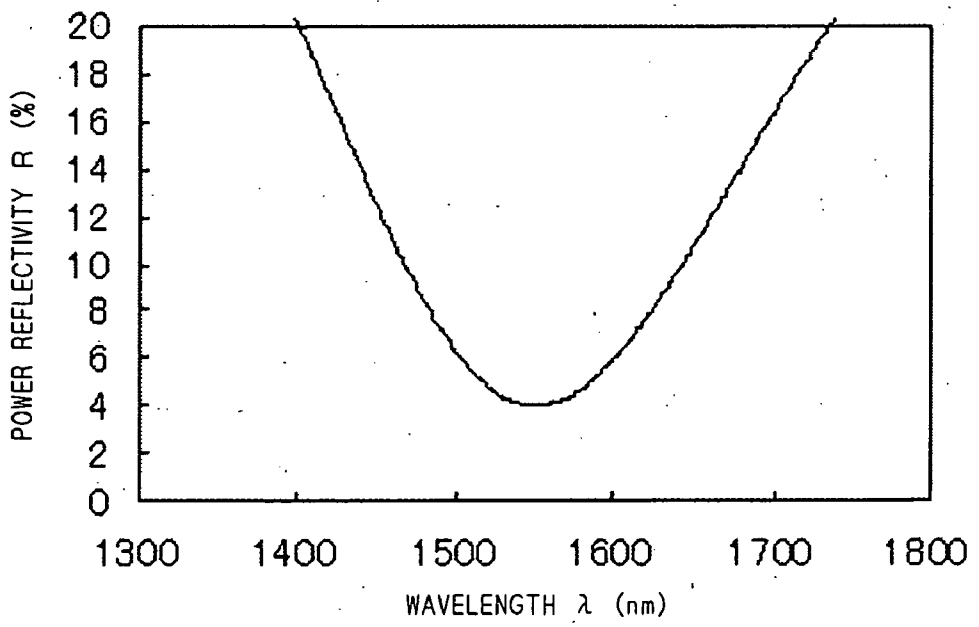
POWER REFLECTIVITY R (%)
20
18
16
14
12
10
8
6
4
2
0
1300
1400
1500
1600
1700
1800
WAVELENGTH λ (nm)

FIG. 25

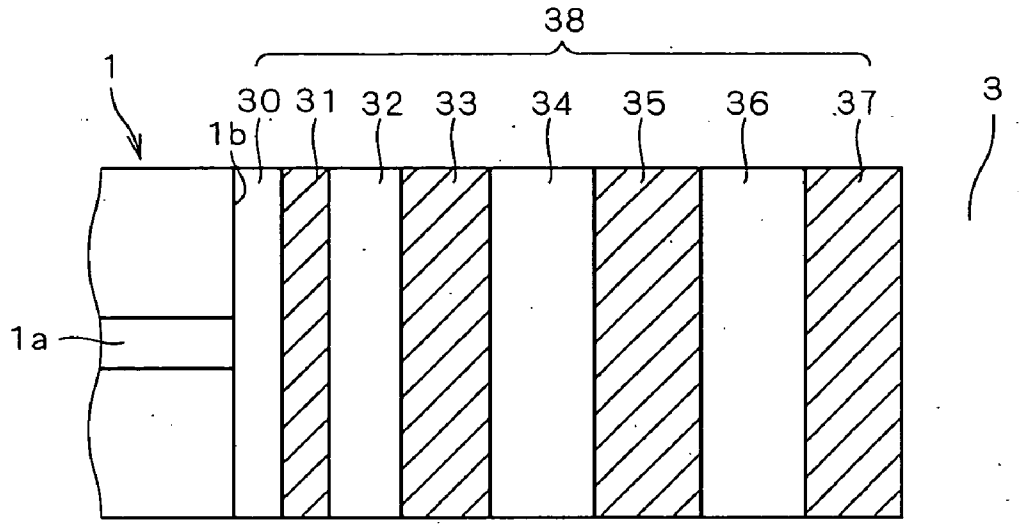
38
1
30
31
32
33
34
35
36
37
3
1b
1a

FIG. 26

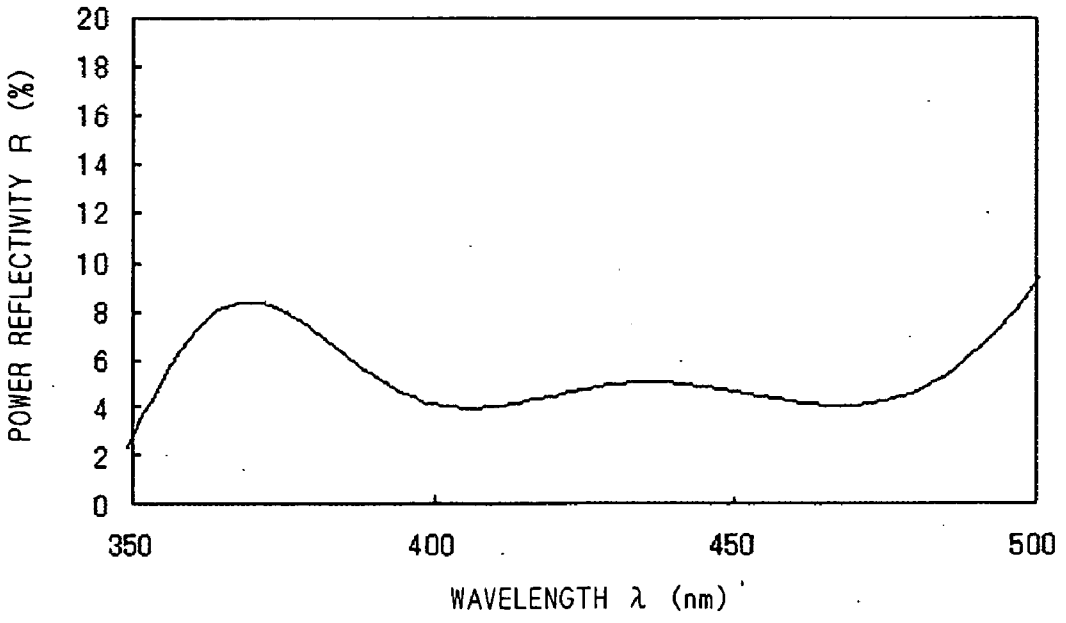
POWER REFLECTIVITY R (%)
20
18
16
14
12
10
8
6
4
2
0
350
400
450
500
WAVELENGTH λ (nm)

FIG. 27

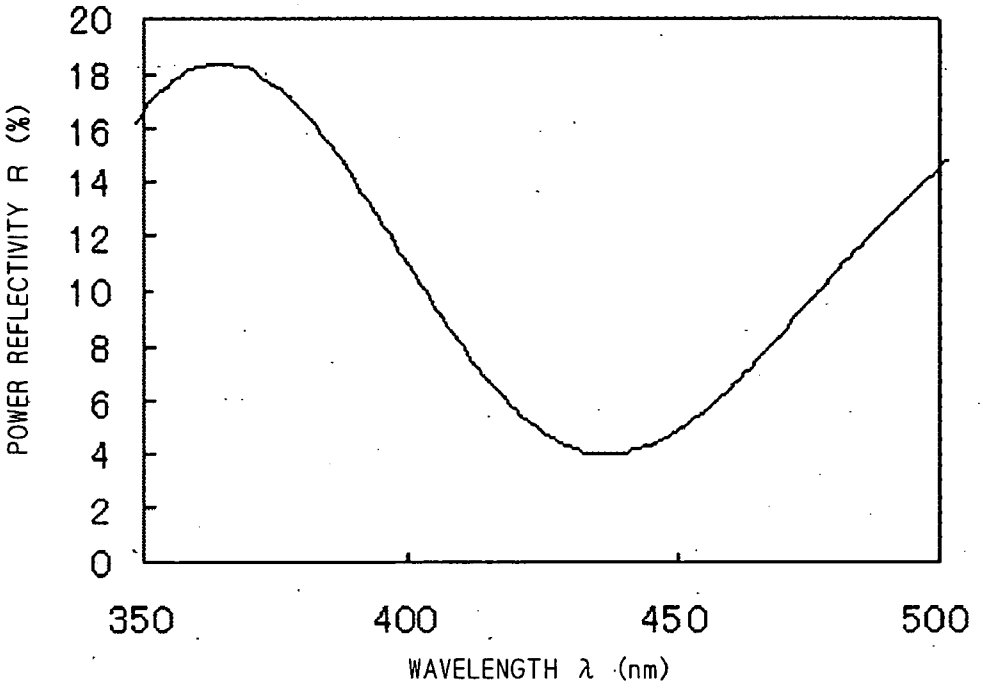
POWER REFLECTIVITY R (%)
20
18
16
14
12
10
8
6
4
2
0
350
400
450
500
WAVELENGTH λ (nm)

FIG. 28

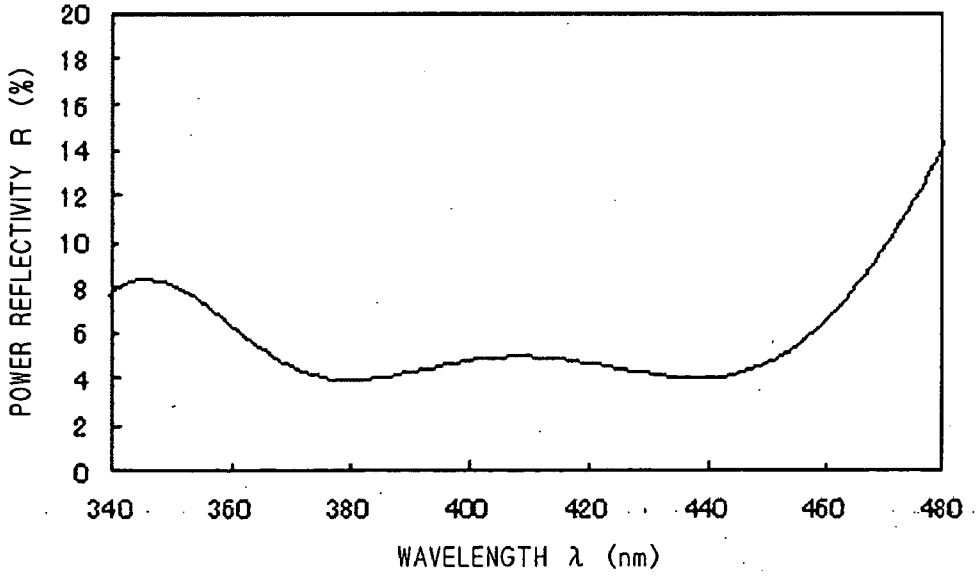
POWER REFLECTIVITY R (%)
20
18
16
14
12
10
8
6
4
2
0
340
360
380
400
420
440
460
480
WAVELENGTH λ (nm)

FIG. 29

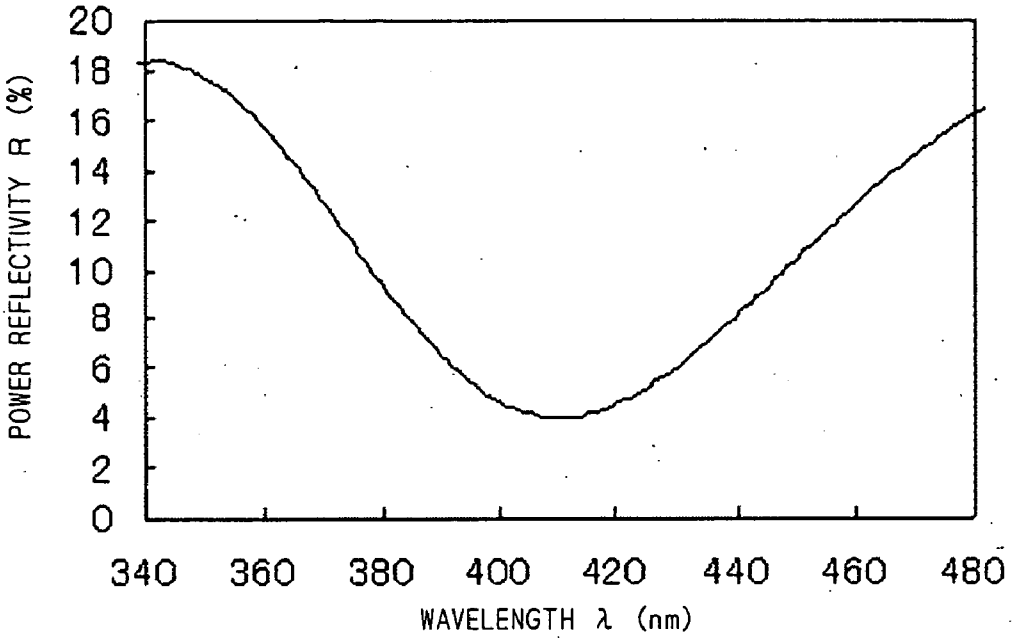
POWER REFLECTIVITY R (%)
20
18
16
14
12
10
8
6
4
2
0
340
360
380
400
420
440
460
480
WAVELENGTH λ (nm)

FIG. 30

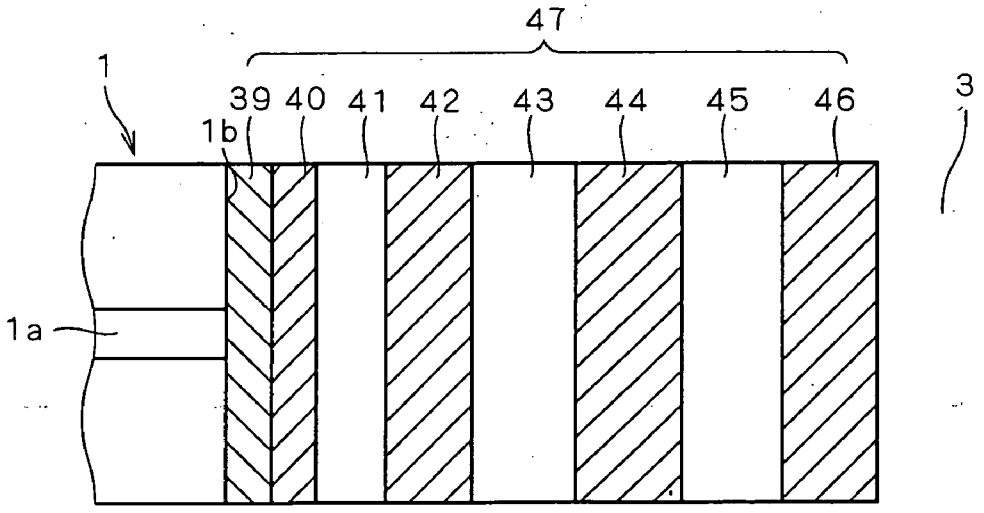
47
1
39
40
41
42
43
44
45
46
3
1b
1a

FIG. 31

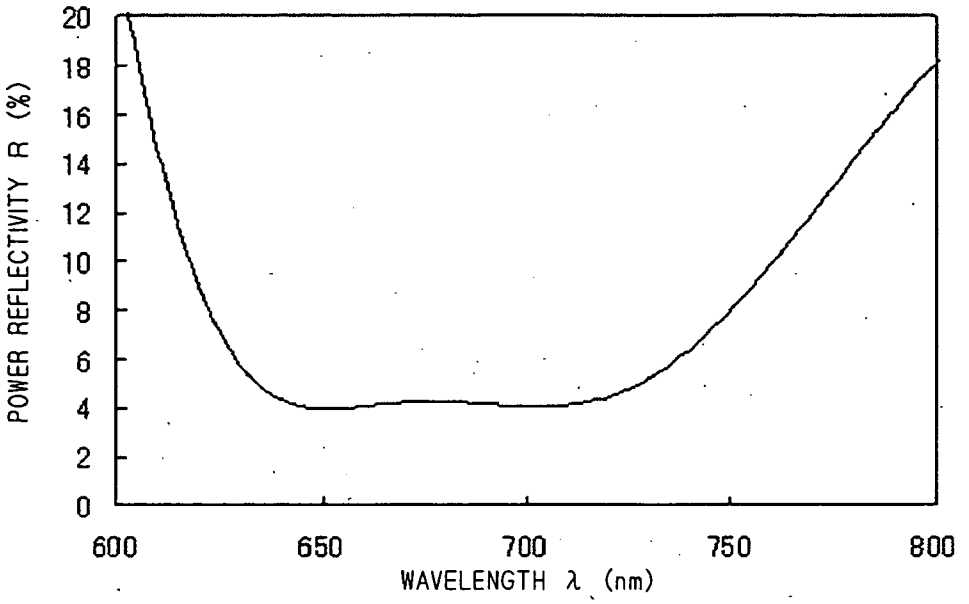
POWER REFLECTIVITY R (%)
20
18
16
14
12
10
8
6
4
2
0
600
650
700
750
800
WAVELENGTH λ (nm)

FIG. 32

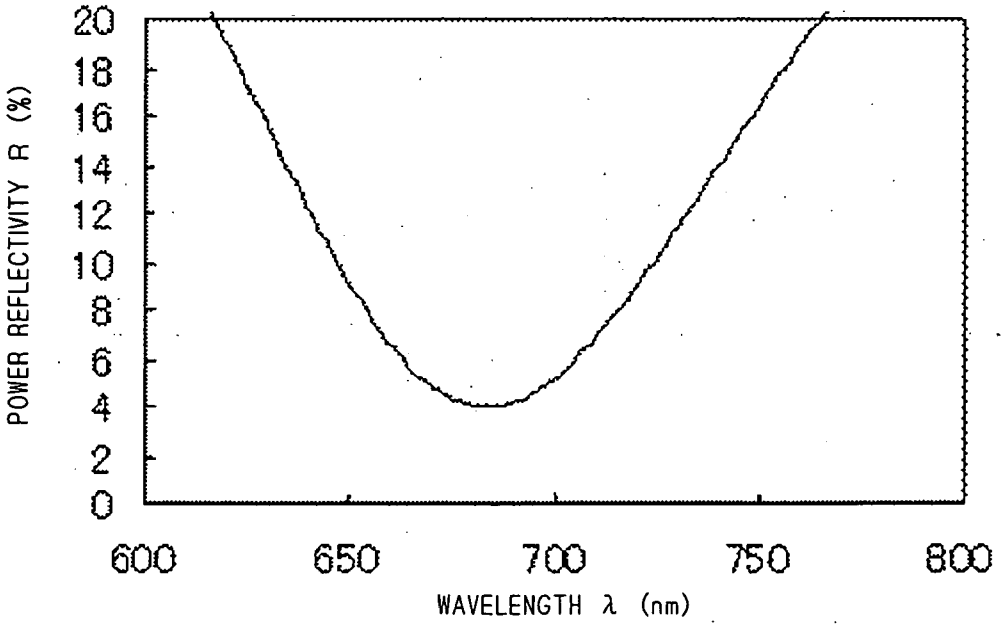
POWER REFLECTIVITY R (%)
20
18
16
14
12
10
8
6
4
2
0
600
650
700
750
800
WAVELENGTH λ (nm)

FIG. 33

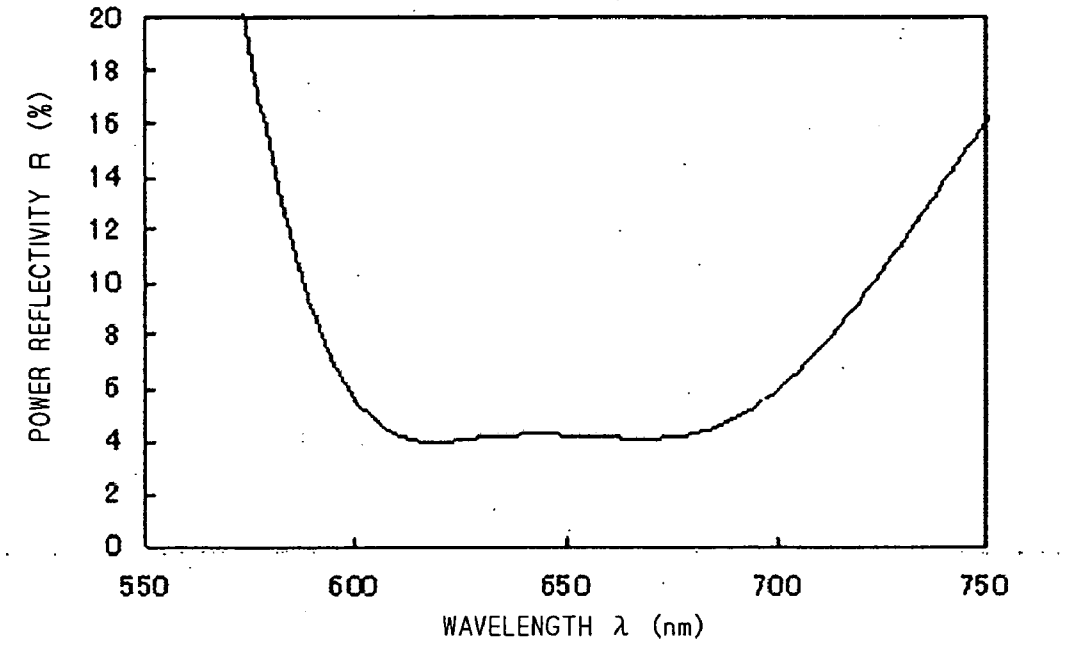
POWER REFLECTIVITY R (%)
20
18
16
14
12
10
8
6
4
2
0
550
600
650
700
750
WAVELENGTH λ (nm)

FIG. 34

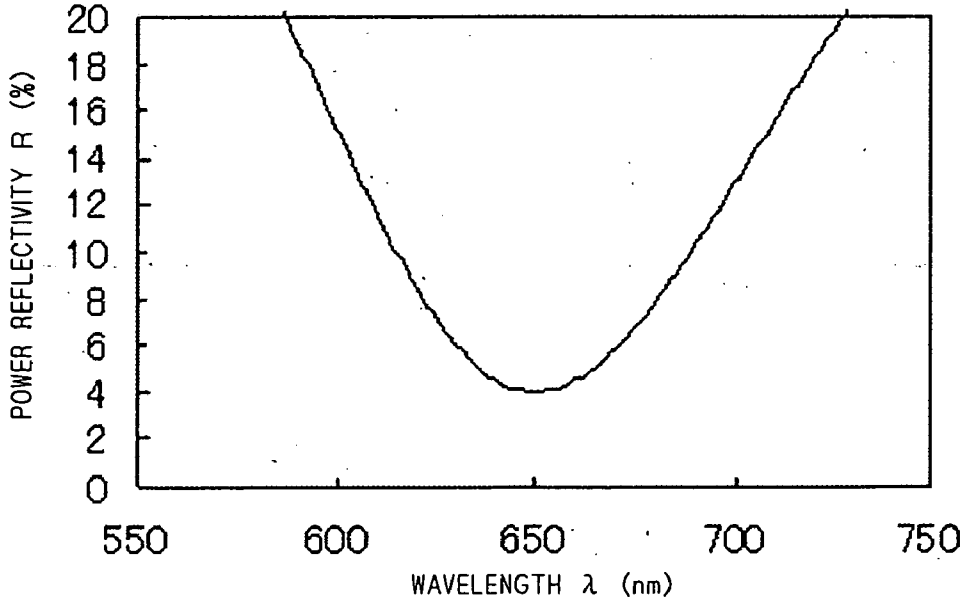
POWER REFLECTIVITY R (%)
20
18
16
14
12
10
8
6
4
2
0
550
600
650
700
750
WAVELENGTH λ (nm)

FIG. 35

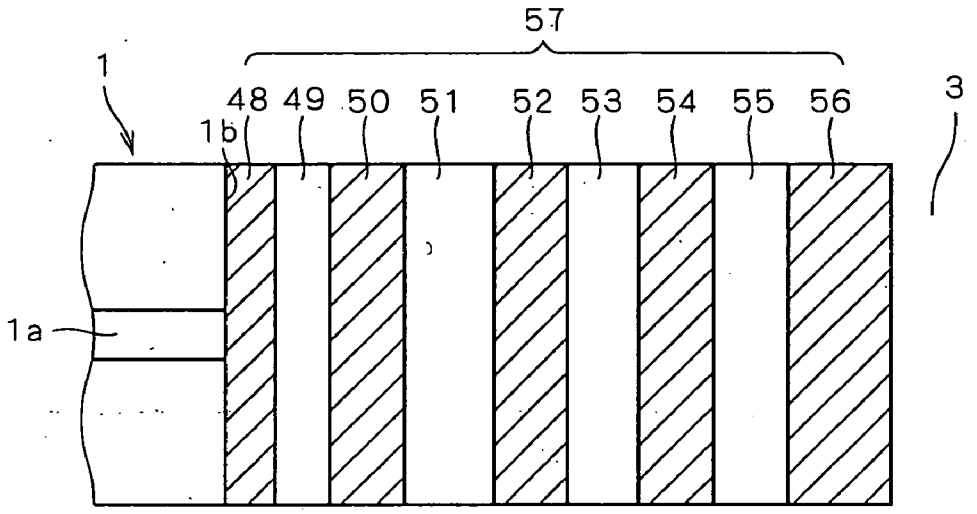
57
1
48 49 50 51 52 53 54 55 56
3
1b
1a

FIG. 36

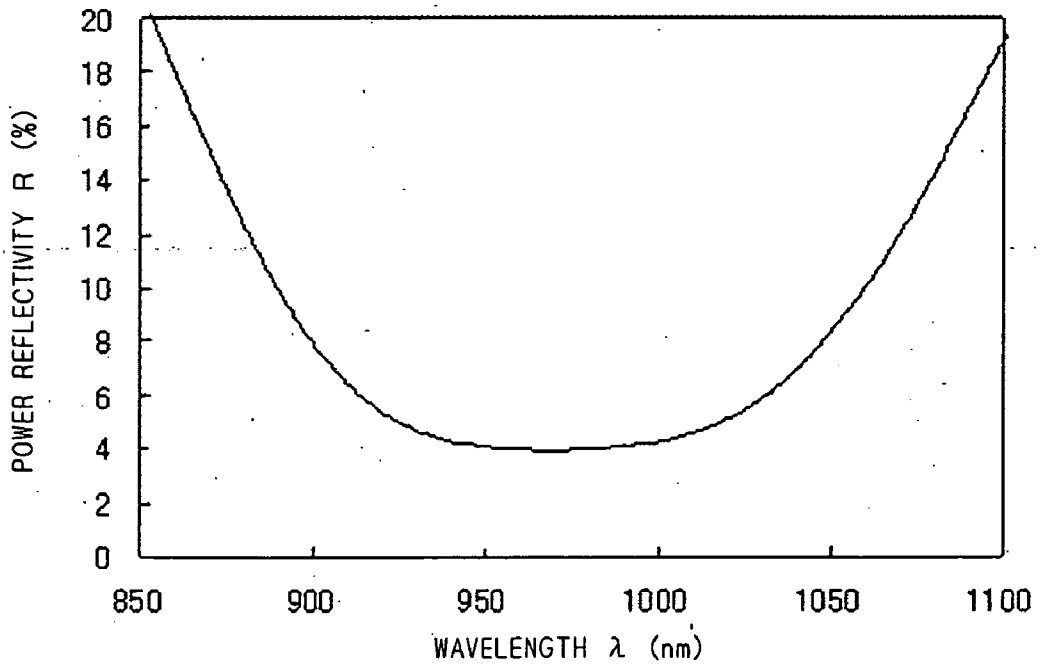
POWER REFLECTIVITY R (%)
20
18
16
14
12
10
8
6
4
2
0
850
900
950
1000
1050
1100
WAVELENGTH λ (nm)

FIG. 37

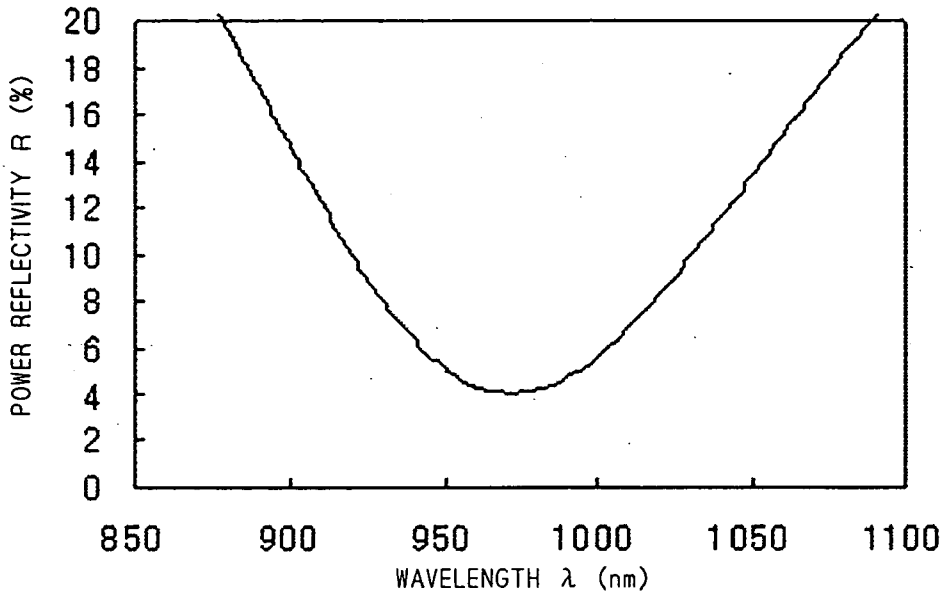
POWER REFLECTIVITY R (%)
20
18
16
14
12
10
8
6
4
2
0
850
900
950
1000
1050
1100
WAVELENGTH λ (nm)

FIG. 38

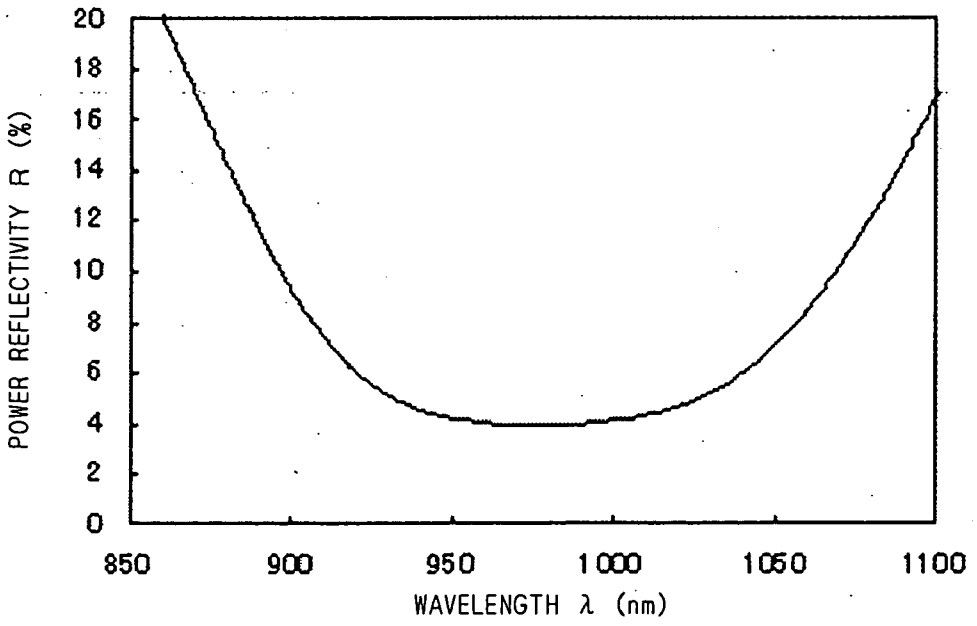
POWER REFLECTIVITY R (%)
20
18
16
14
12
10
8
6
4
2
0
850
900
950
1000
1050
1100
WAVELENGTH λ (nm)

FIG. 39

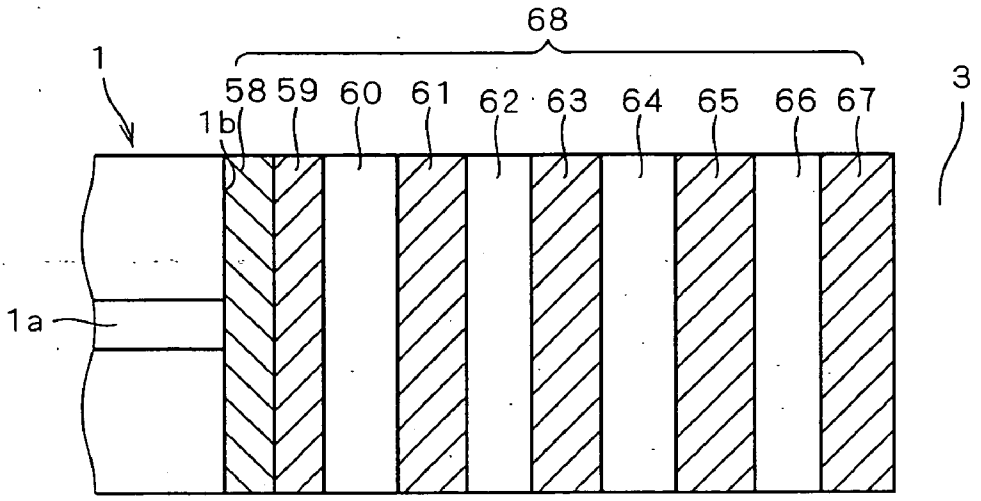
68
1
58 59 60 61 62 63 64 65 66 67
3
1b
1a

FIG. 40

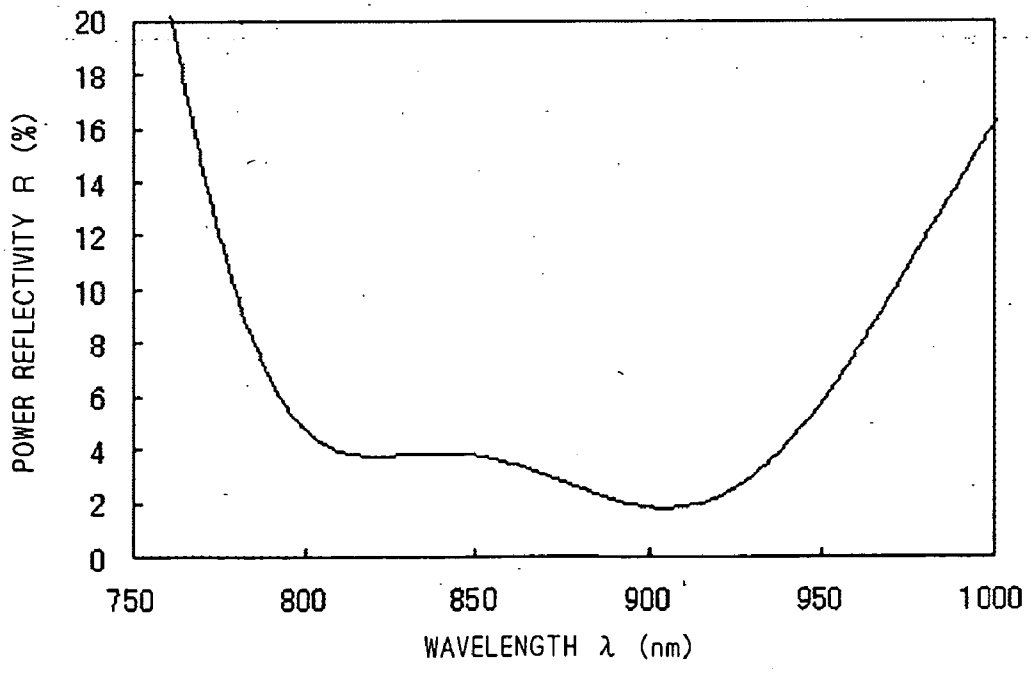
20
18
16
14
12
10
8
6
4
2
0
POWER REFLECTIVITY R (%)
750
800
850
900
950
1000
WAVELENGTH λ (nm)

FIG. 41

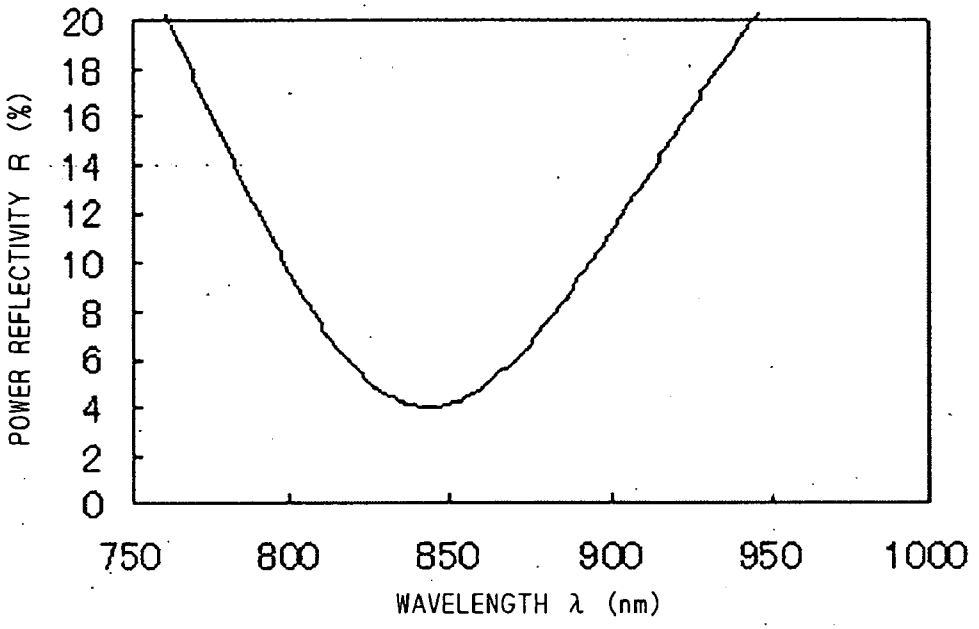
POWER REFLECTIVITY R (%)
20
18
16
14
12
10
8
6
4
2
0
750
800
850
900
950
1000
WAVELENGTH λ (nm)

FIG. 42

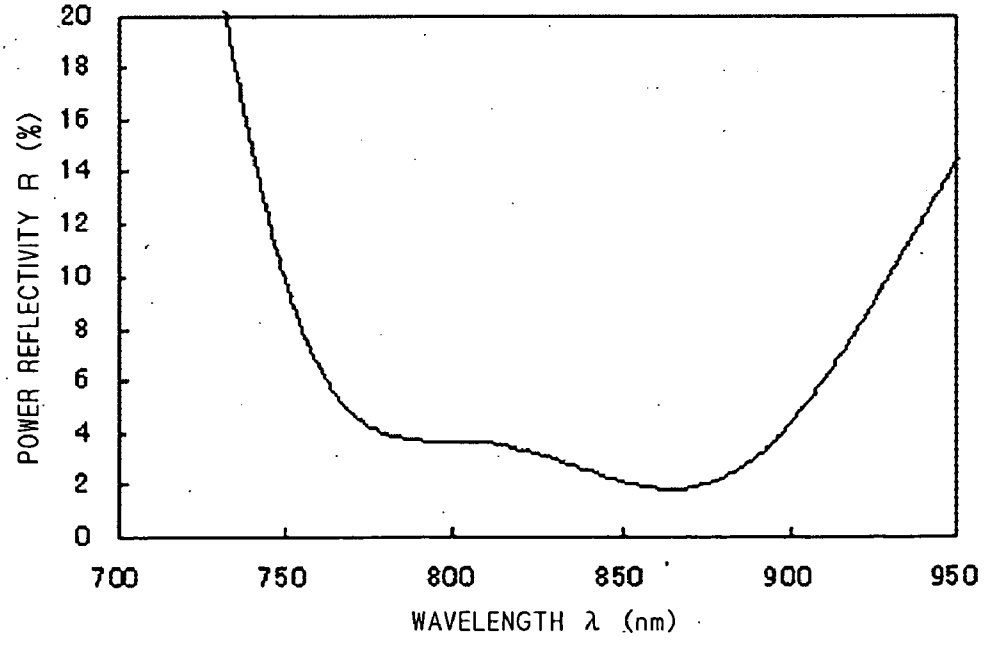
POWER REFLECTIVITY R (%)
20
18
16
14
12
10
8
6
4
2
0
700
750
800
850
900
950
WAVELENGTH λ (nm)

FIG. 43

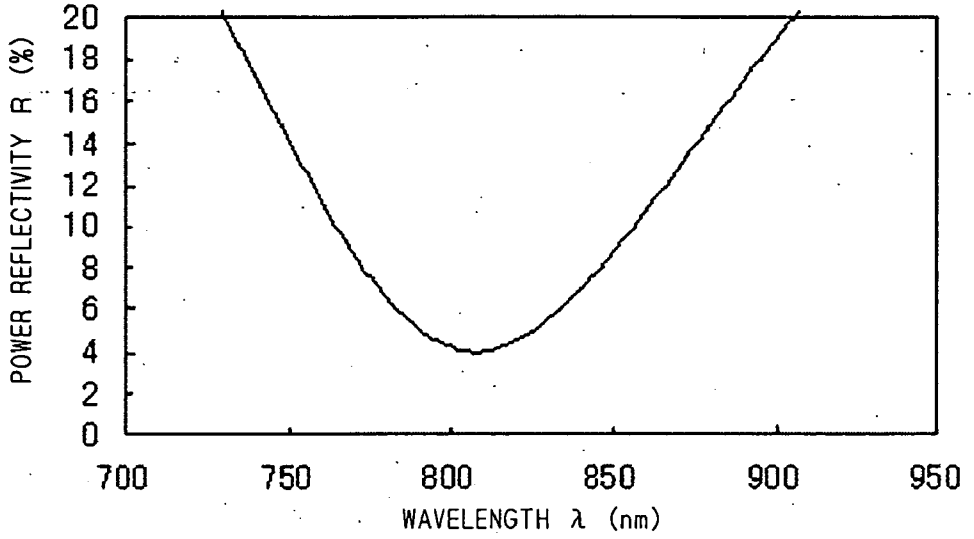
POWER REFLECTIVITY R (%)
20
18
16
14
12
10
8
6
4
2
0
700
750
800
850
900
950
WAVELENGTH λ (nm)

FIG. 44

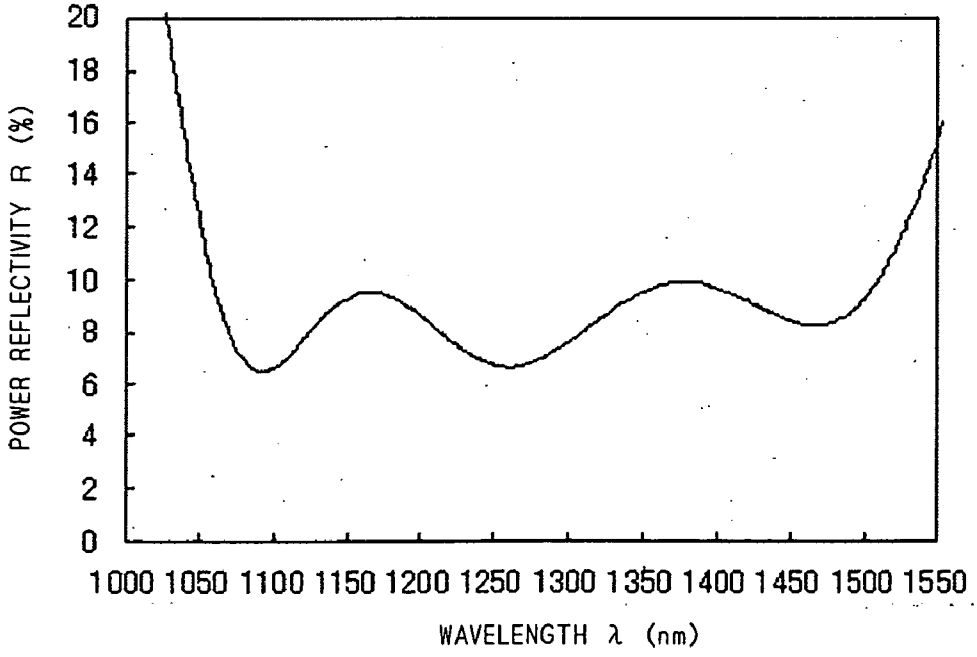
POWER REFLECTIVITY R (%)
20
18
16
14
12
10
8
6
4
2
0
1000 1050 1100 1150 1200 1250 1300 1350 1400 1450 1500 1550
WAVELENGTH λ (nm)

FIG. 45

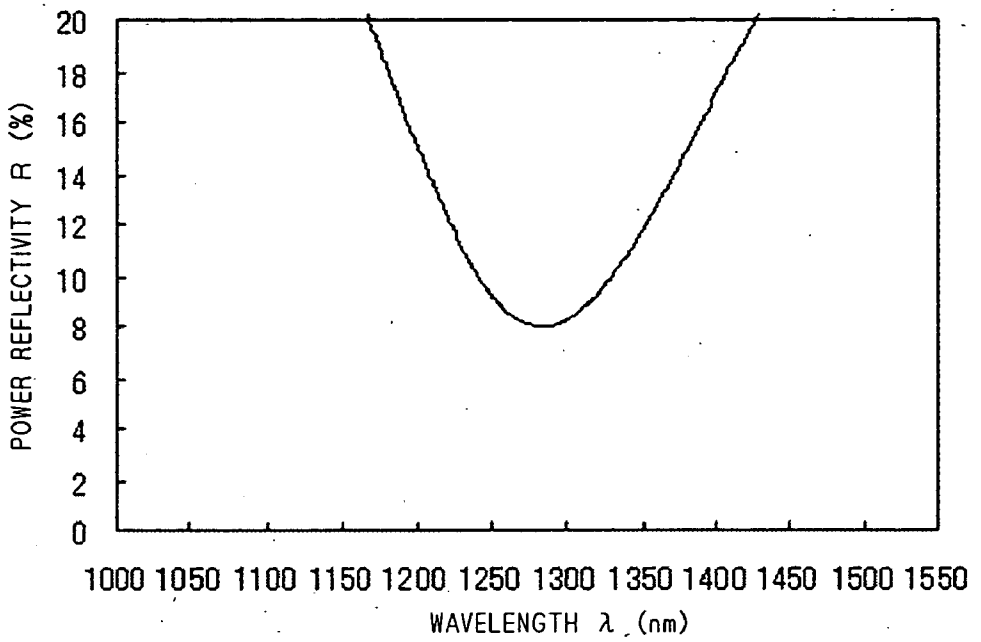
POWER REFLECTIVITY R (%)
20
18
16
14
12
10
8
6
4
2
0
1000 1050 1100 1150 1200 1250 1300 1350 1400 1450 1500 1550
WAVELENGTH λ (nm)

FIG. 46

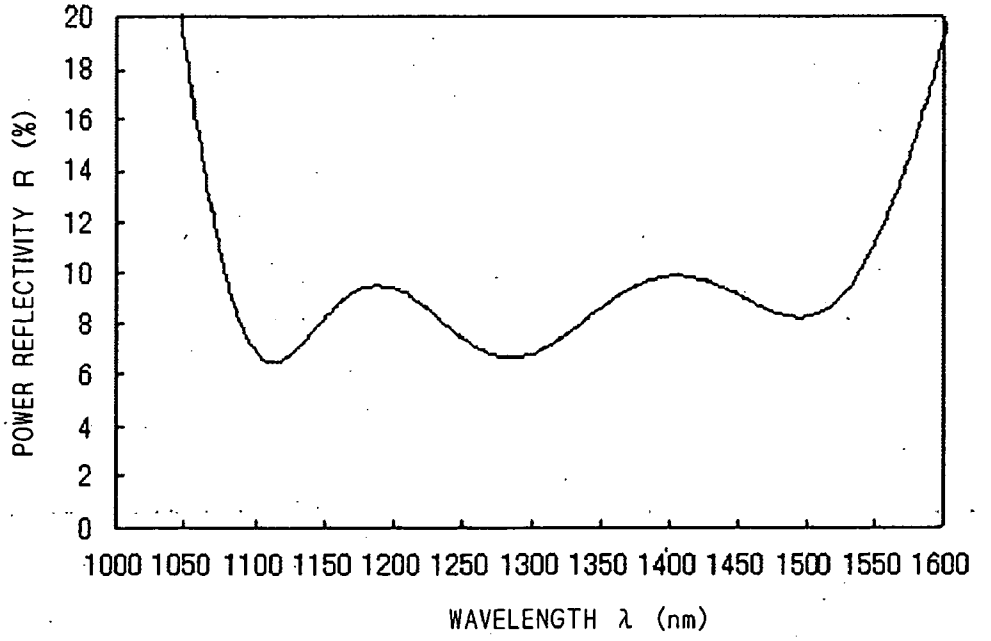
POWER REFLECTIVITY R (%)
20
18
16
14
12
10
8
6
4
2
0
1000 1050 1100 1150 1200 1250 1300 1350 1400 1450 1500 1550 1600
WAVELENGTH λ (nm)

FIG. 47

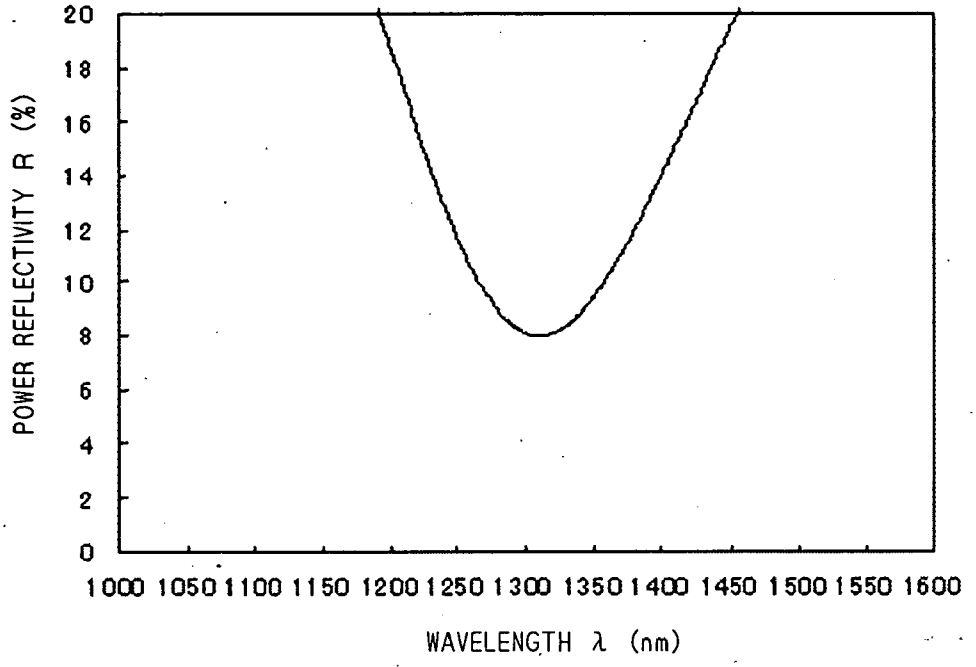
POWER REFLECTIVITY R (%)
20
18
16
14
12
10
8
6
4
2
0
1000 1050 1100 1150 1200 1250 1300 1350 1400 1450 1500 1550 1600
WAVELENGTH λ (nm)

FIG. 48

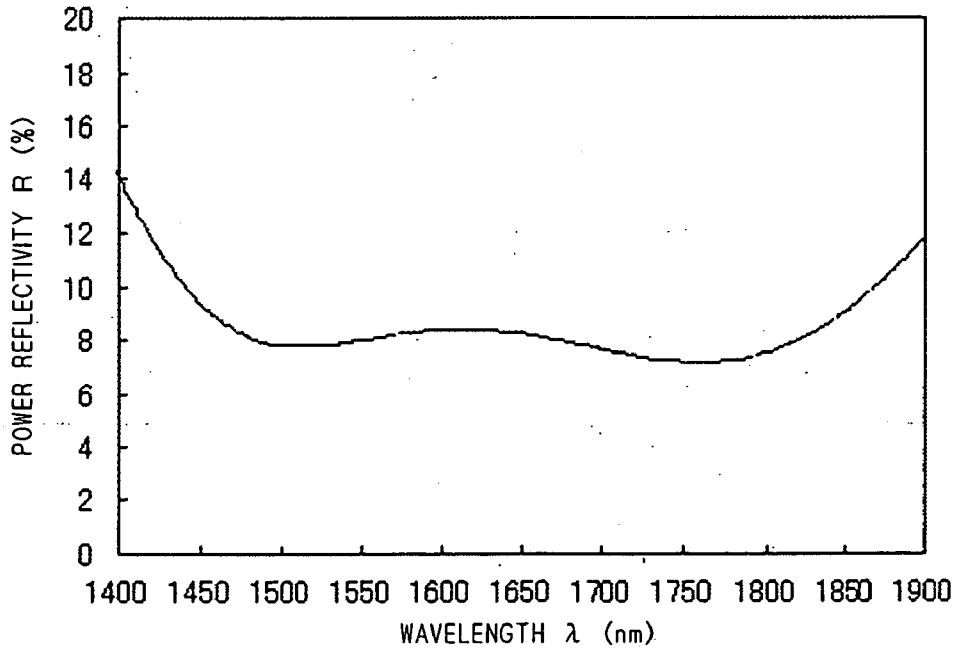
POWER REFLECTIVITY R (%)
20
18
16
14
12
10
8
6
4
2
0
1400 1450 1500 1550 1600 1650 1700 1750 1800 1850 1900
WAVELENGTH λ (nm)

FIG. 49

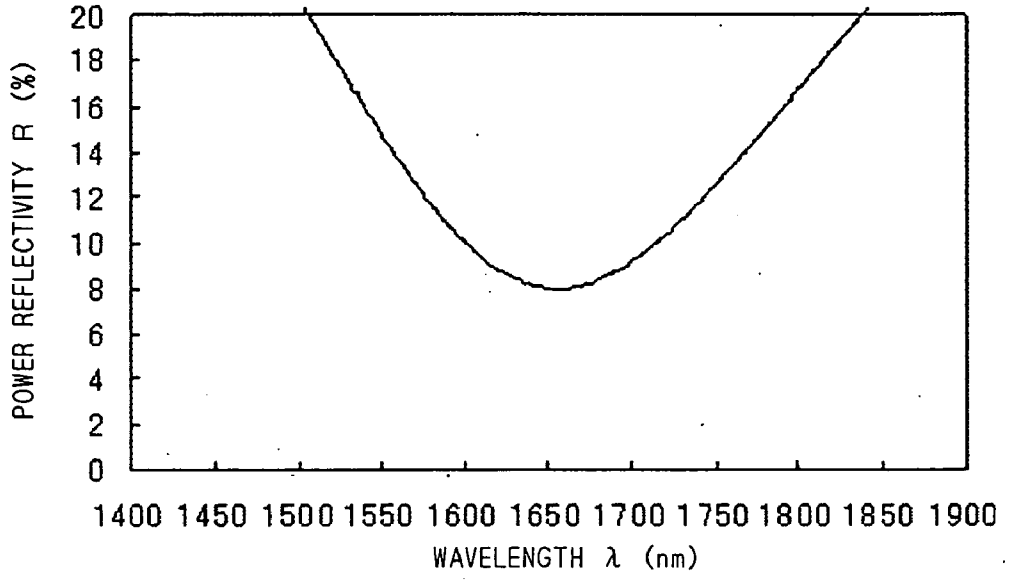
POWER REFLECTIVITY R (%)
20
18
16
14
12
10
8
6
4
2
0
1400 1450 1500 1550 1600 1650 1700 1750 1800 1850 1900
WAVELENGTH λ (nm)

FIG. 50

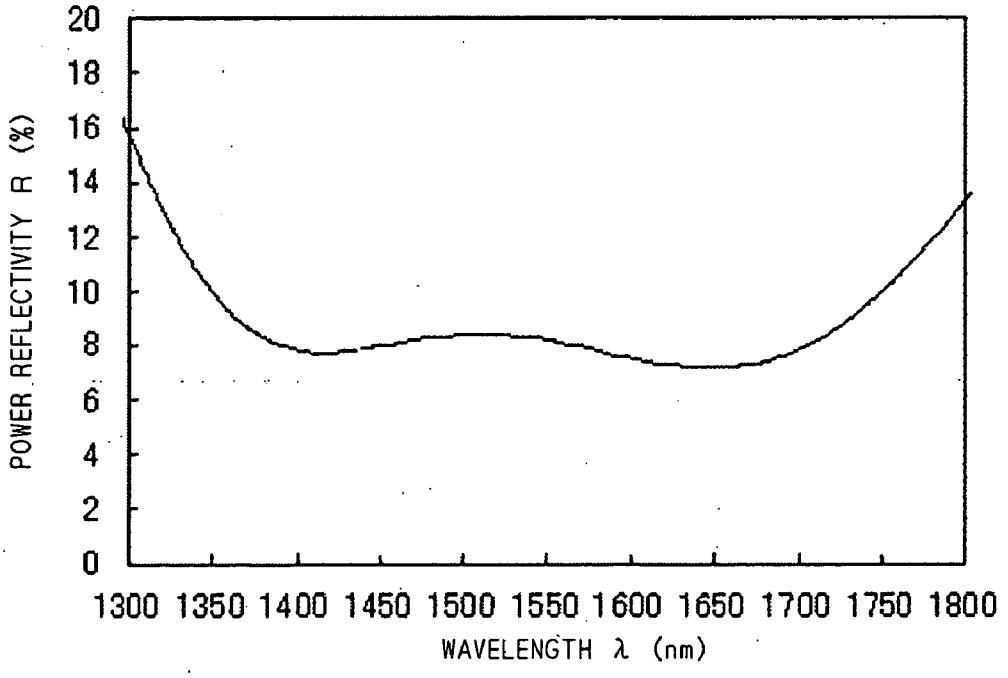
POWER REFLECTIVITY R (%)
20
18
16
14
12
10
8
6
4
2
0
1300 1350 1400 1450 1500 1550 1600 1650 1700 1750 1800
WAVELENGTH λ (nm)

FIG. 51

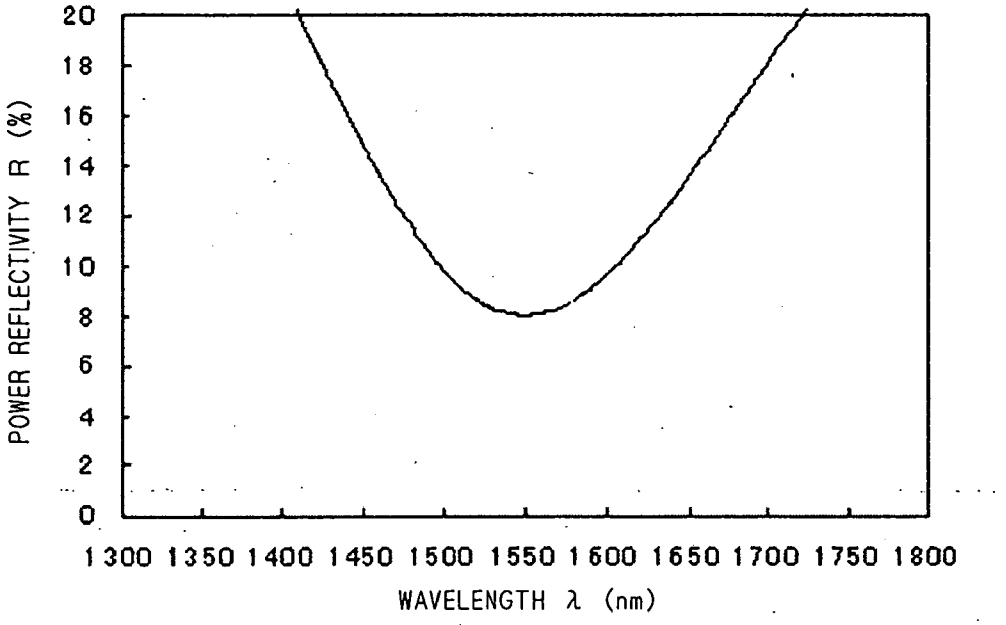
POWER REFLECTIVITY R (%)
20
18
16
14
12
10
8
6
4
2
0
1300 1350 1400 1450 1500 1550 1600 1650 1700 1750 1800
WAVELENGTH λ (nm)

FIG. 52

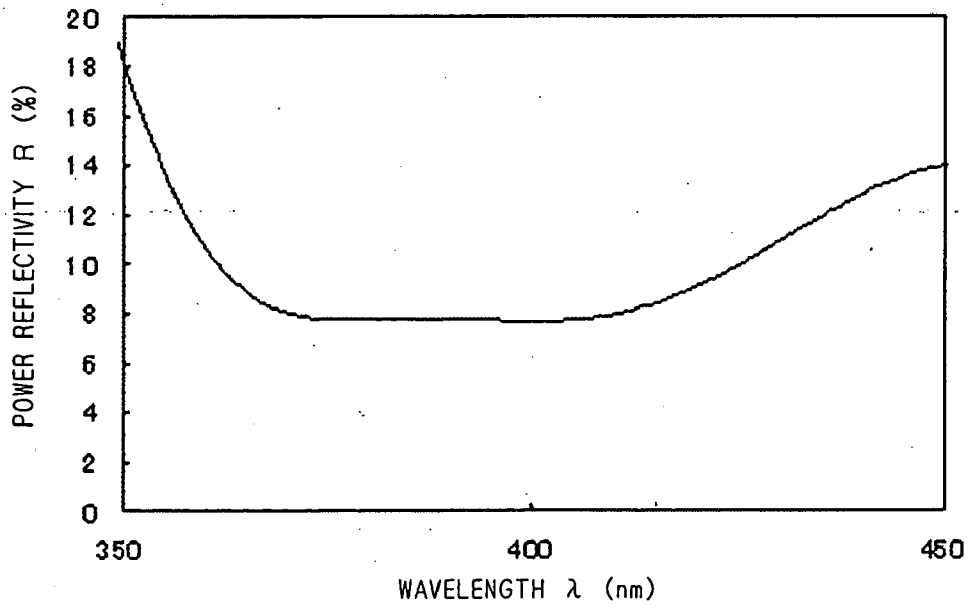
POWER REFLECTIVITY R (%)
20
18
16
14
12
10
8
6
4
2
0
350
400
450
WAVELENGTH λ (nm)

FIG. 53

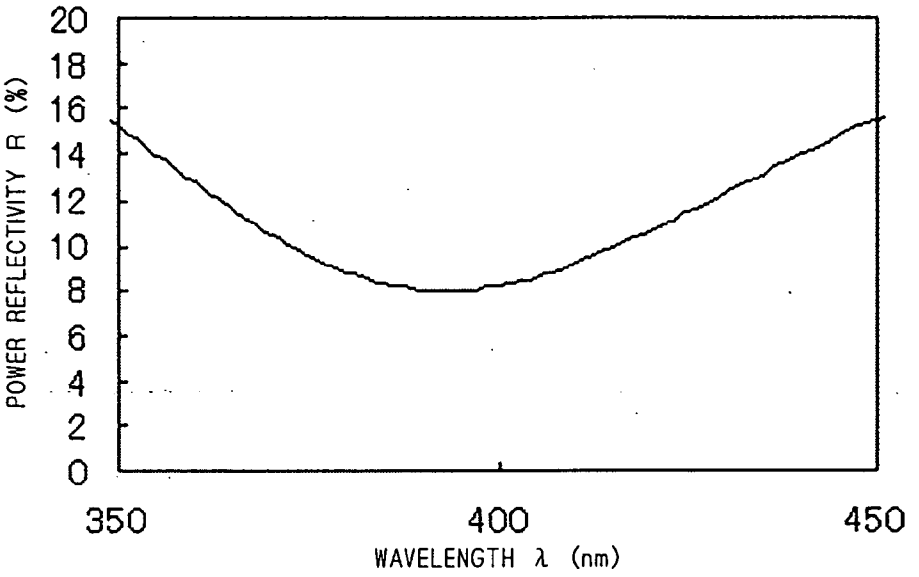
POWER REFLECTIVITY R (%)
20
18
16
14
12
10
8
6
4
2
0
350
400
450
WAVELENGTH λ (nm)

FIG. 54

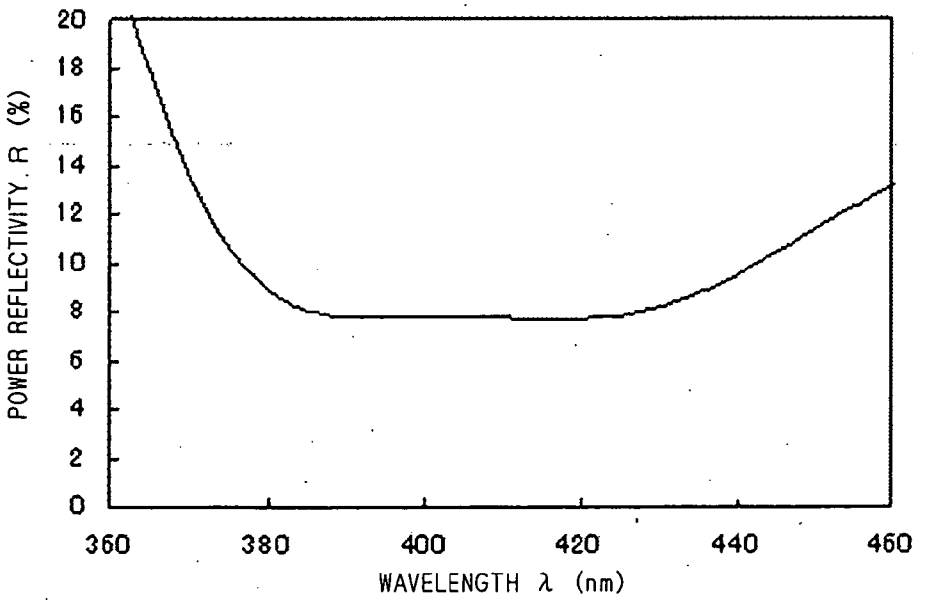
POWER REFLECTIVITY R (%)
20
18
16
14
12
10
8
6
4
2
0
360
380
400
420
440
460
WAVELENGTH λ (nm)

FIG. 55

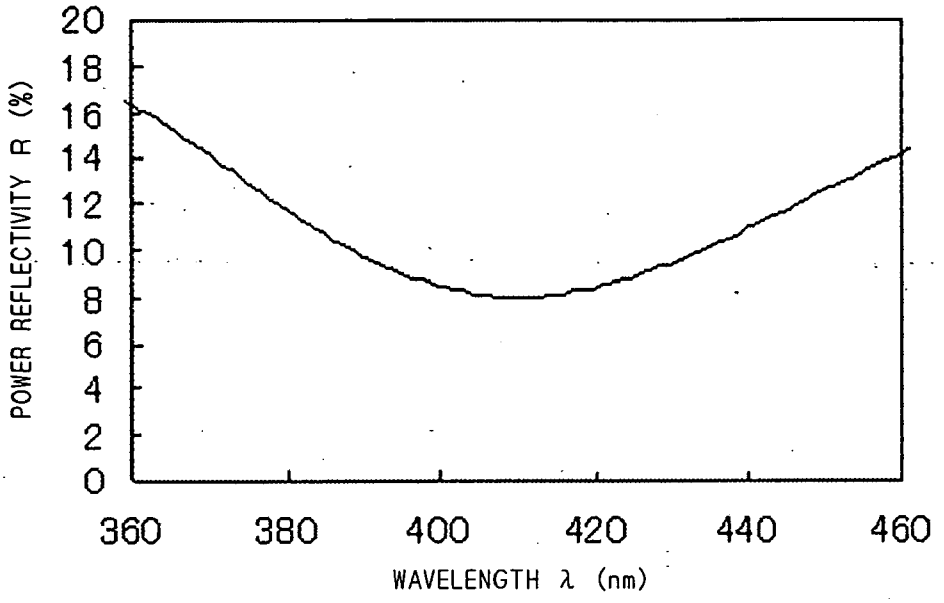
POWER REFLECTIVITY R (%)
20
18
16
14
12
10
8
6
4
2
0
360
380
400
420
440
460
WAVELENGTH λ (nm)

FIG. 56

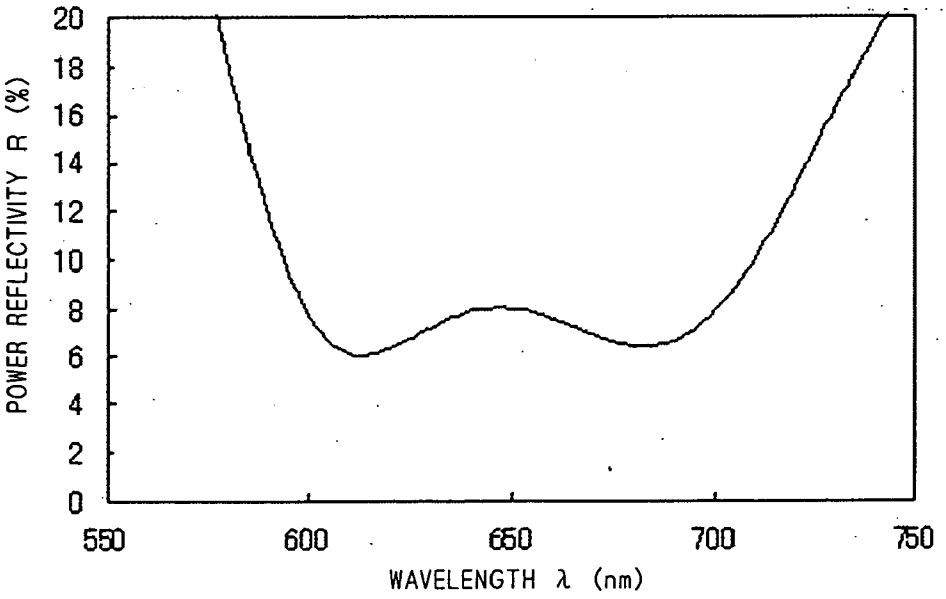
POWER REFLECTIVITY R (%)
20
18
16
14
12
10
8
6
4
2
0
550
600
650
700
750
WAVELENGTH λ (nm)

FIG. 57

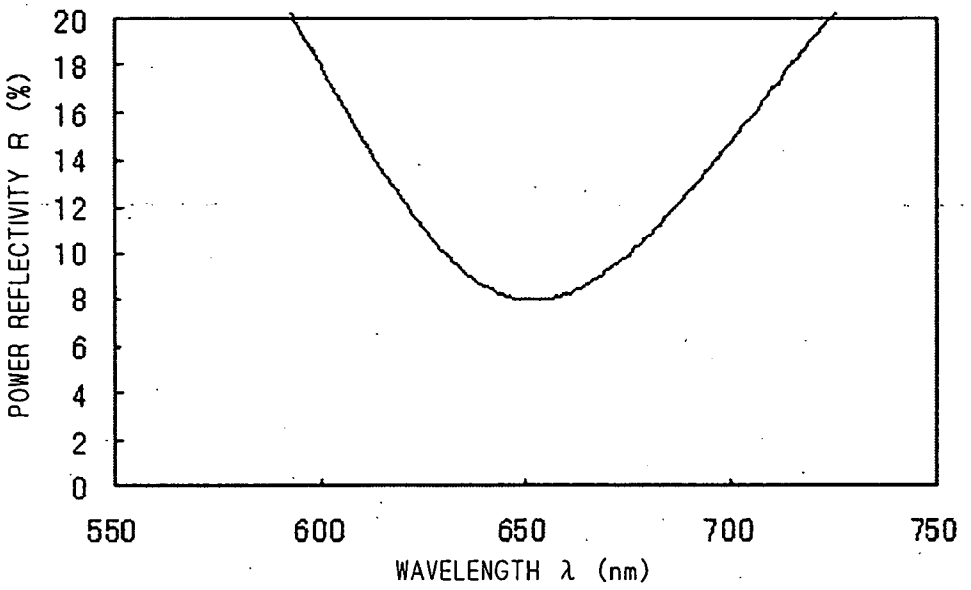
POWER REFLECTIVITY R (%)
20
18
16
14
12
10
8
6
4
2
0
550
600
650
700
750
WAVELENGTH λ (nm)

FIG. 58

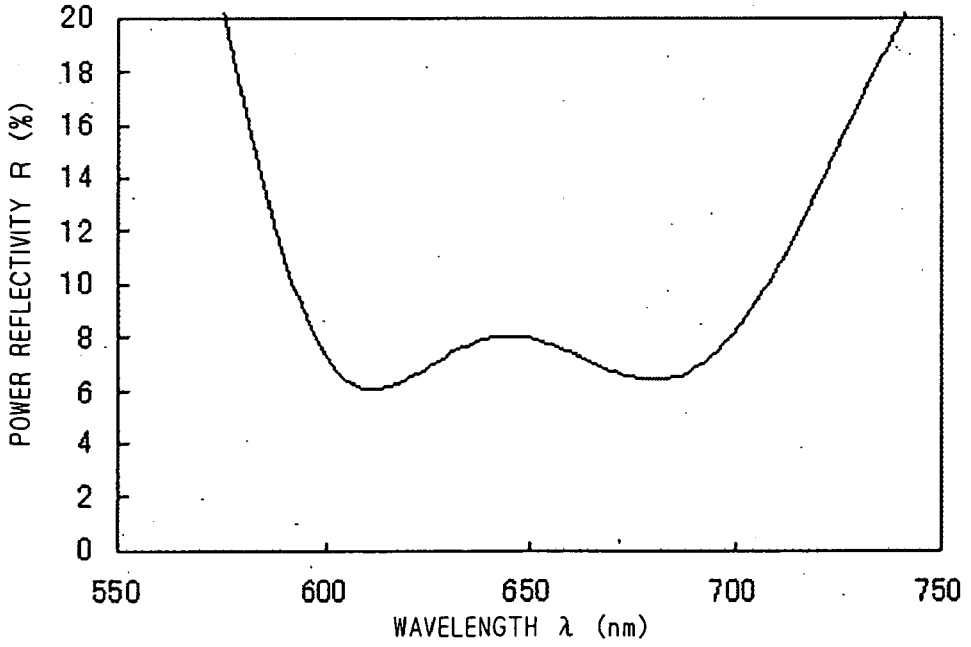
POWER REFLECTIVITY R (%)
20
18
16
14
12
10
8
6
4
2
0
550
600
650
700
750
WAVELENGTH λ (nm)

FIG. 59

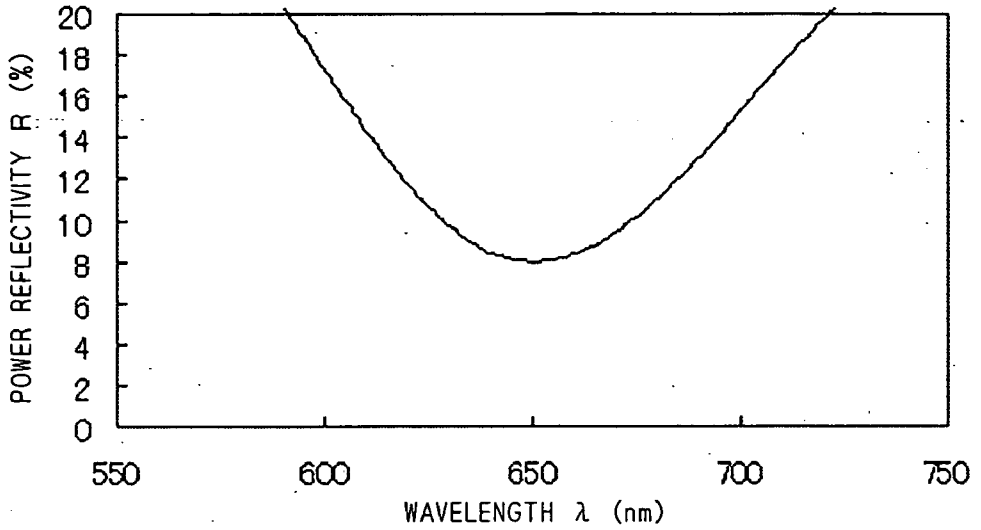
POWER REFLECTIVITY R (%)
20
18
16
14
12
10
8
6
4
2
0
550
600
650
700
750
WAVELENGTH λ (nm)

FIG. 60

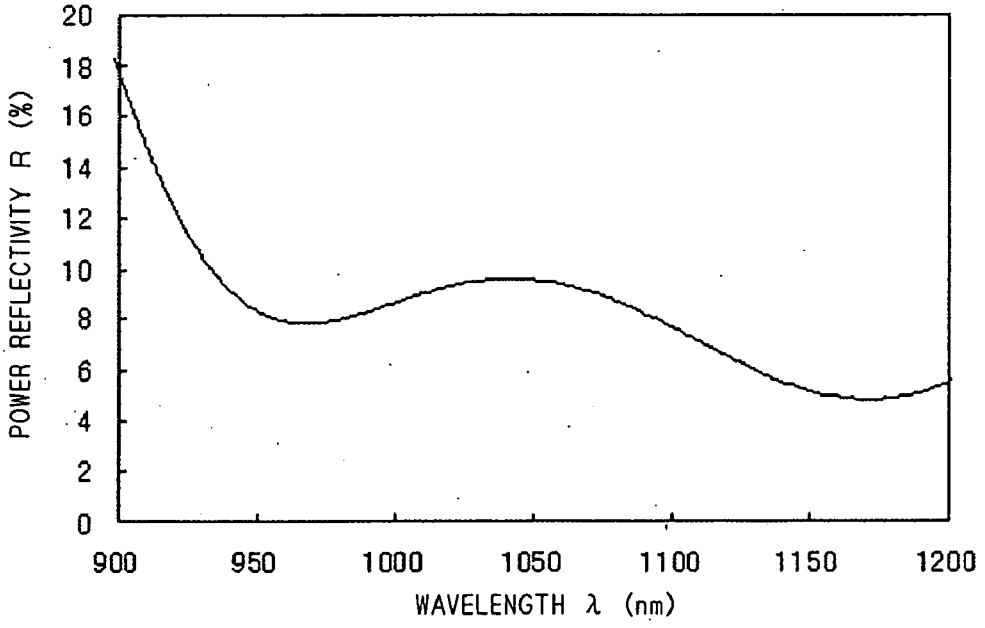
POWER REFLECTIVITY R (%)
20
18
16
14
12
10
8
6
4
2
0
900
950
1000
1050
1100
1150
1200
WAVELENGTH λ (nm)

FIG. 61

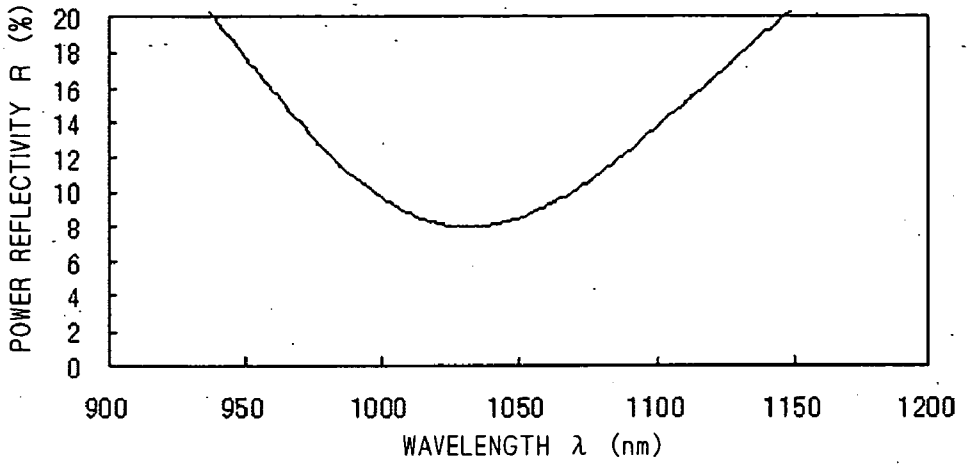
POWER REFLECTIVITY R (%)
20
18
16
14
12
10
8
6
4
2
0
900
950
1000
1050
1100
1150
1200
WAVELENGTH λ (nm)

FIG. 62

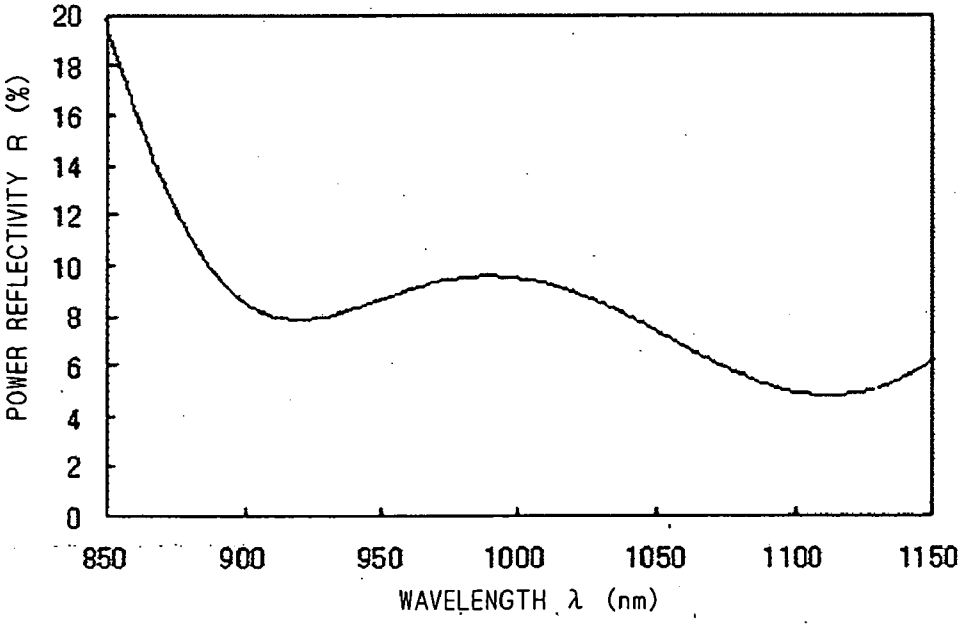
POWER REFLECTIVITY R (%)
20
18
16
14
12
10
8
6
4
2
0
850
900
950
1000
1050
1100
1150
WAVELENGTH λ (nm)

FIG. 63

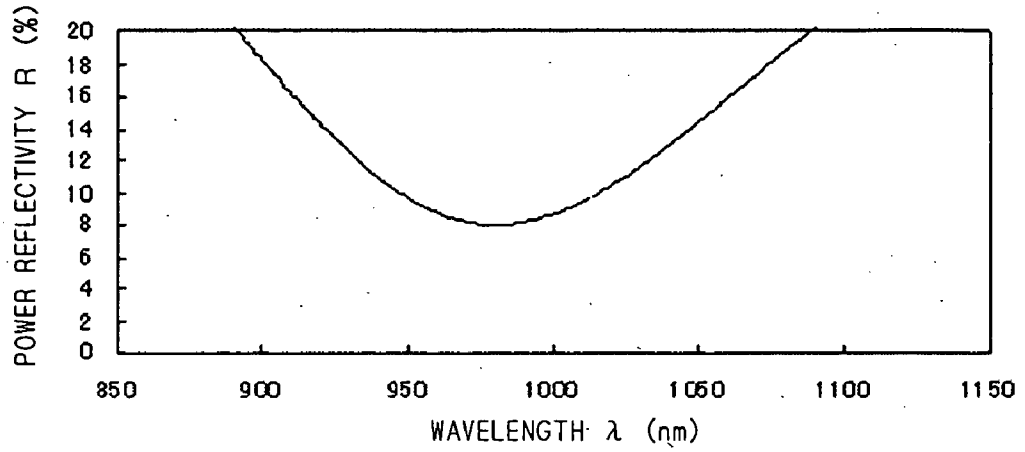
POWER REFLECTIVITY R (%)
20
18
16
14
12
10
8
6
4
2
0
850
900
950
1000
1050
1100
1150
WAVELENGTH λ (nm)

FIG. 64

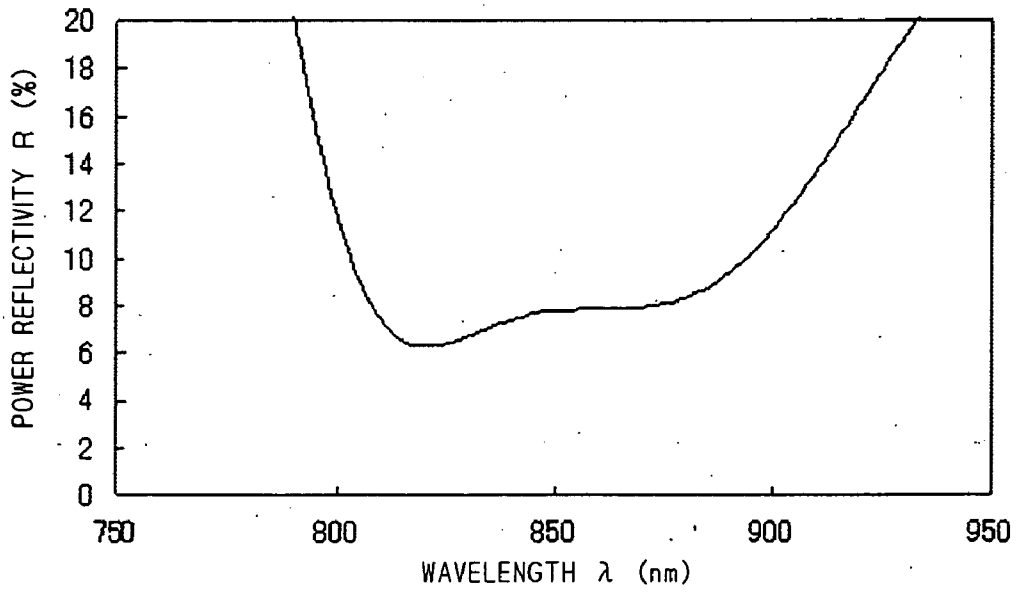
POWER REFLECTIVITY R (%)
20
18
16
14
12
10
8
6
4
2
0
750
800
850
900
950
WAVELENGTH λ (nm)

FIG. 65

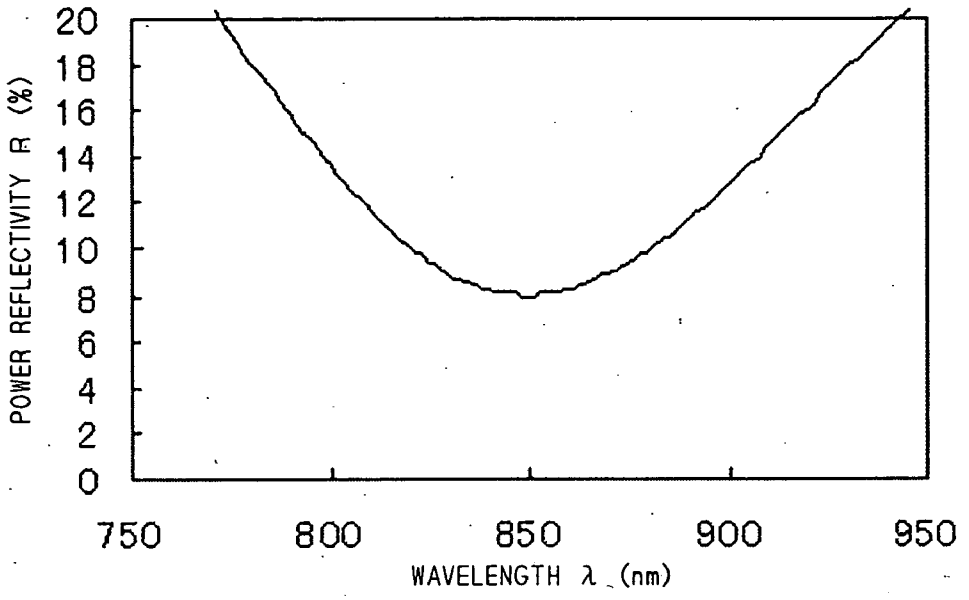
POWER REFLECTIVITY R (%)
20
18
16
14
12
10
8
6
4
2
0
750
800
850
900
950
WAVELENGTH λ (nm)

FIG. 66

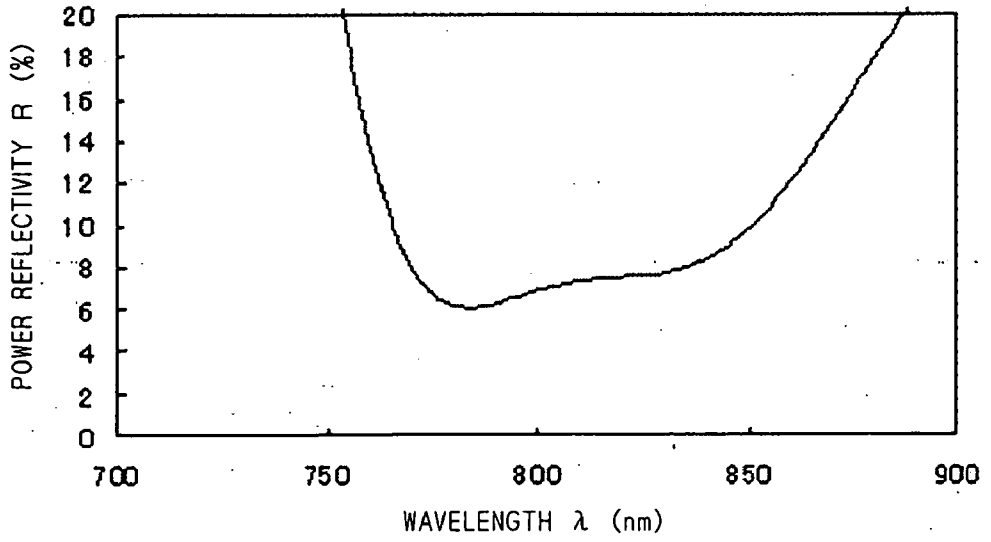
POWER REFLECTIVITY R (%)
20
18
16
14
12
10
8
6
4
2
0
700
750
800
850
900
WAVELENGTH λ (nm)

FIG. 67

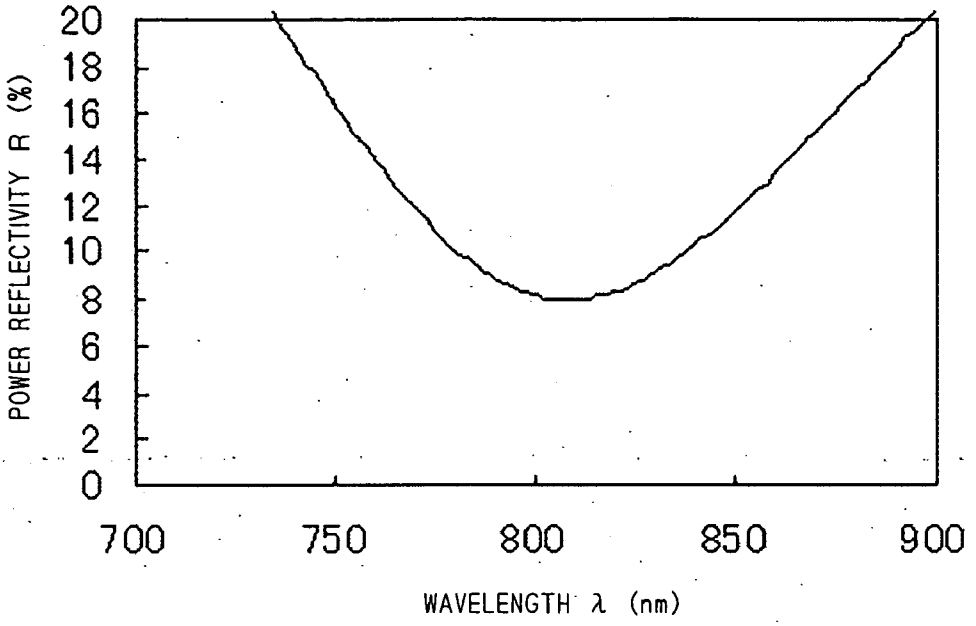
POWER REFLECTIVITY R (%)
20
18
16
14
12
10
8
6
4
2
0
700
750
800
850
900
WAVELENGTH λ (nm)

FIG. 68

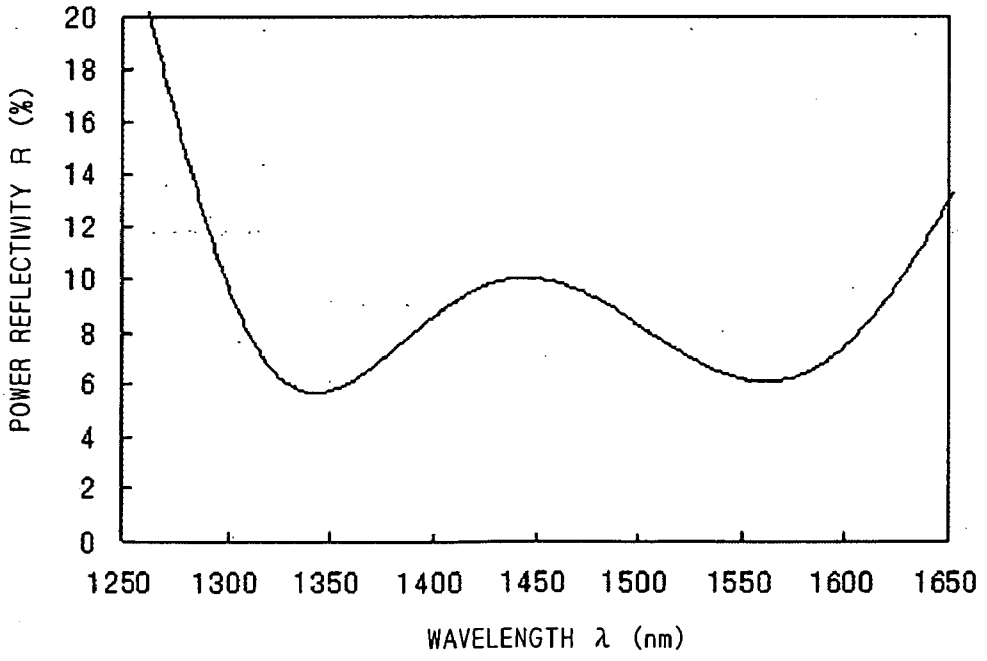
POWER REFLECTIVITY R (%)
20
18
16
14
12
10
8
6
4
2
0
1250
1300
1350
1400
1450
1500
1550
1600
1650
WAVELENGTH λ (nm)

FIG. 69

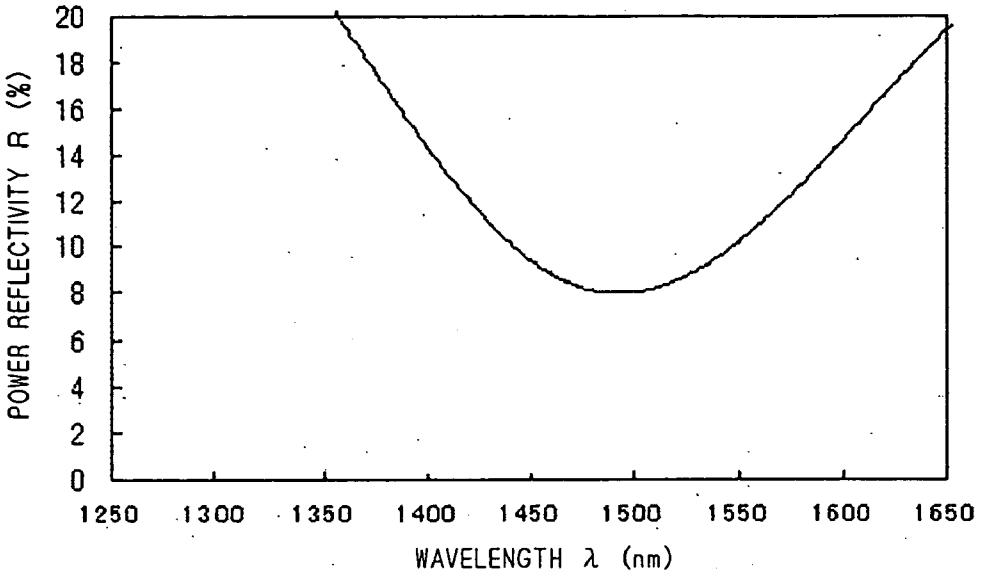
POWER REFLECTIVITY R (%)
20
18
16
14
12
10
8
6
4
2
0
1250
1300
1350
1400
1450
1500
1550
1600
1650
WAVELENGTH λ (nm)

FIG. 70

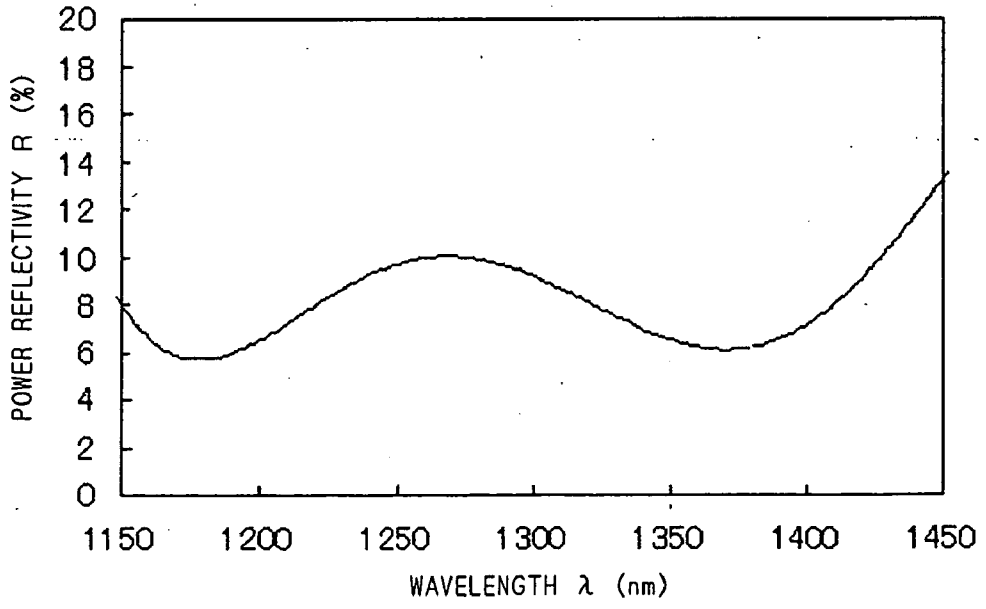
POWER REFLECTIVITY R (%)
20
18
16
14
12
10
8
6
4
2
0
1150
1200
1250
1300
1350
1400
1450
WAVELENGTH λ (nm)

FIG. 71

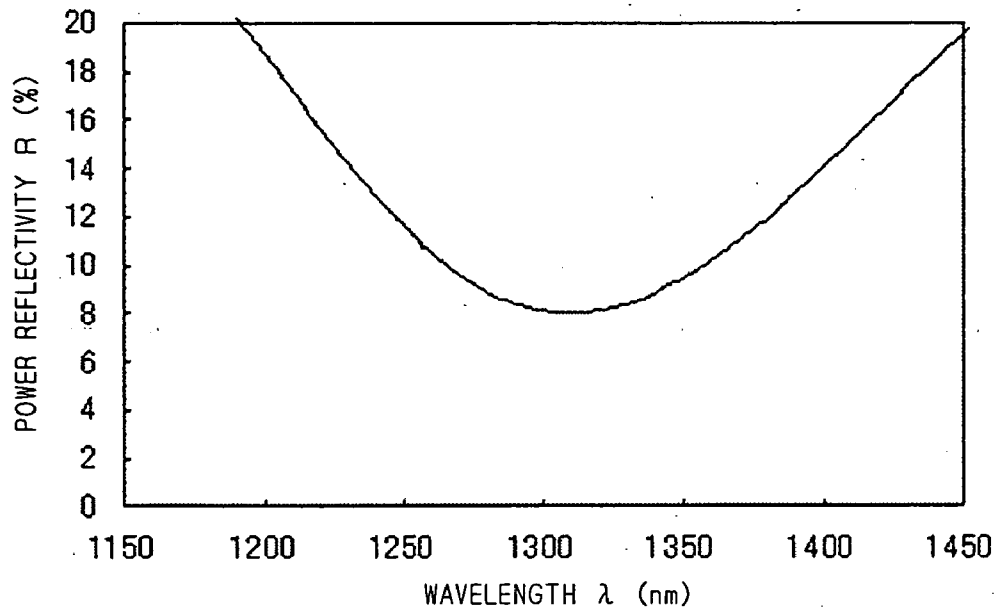
POWER REFLECTIVITY R (%)
20
18
16
14
12
10
8
6
4
2
0
1150
1200
1250
1300
1350
1400
1450
WAVELENGTH λ (nm)

FIG. 72

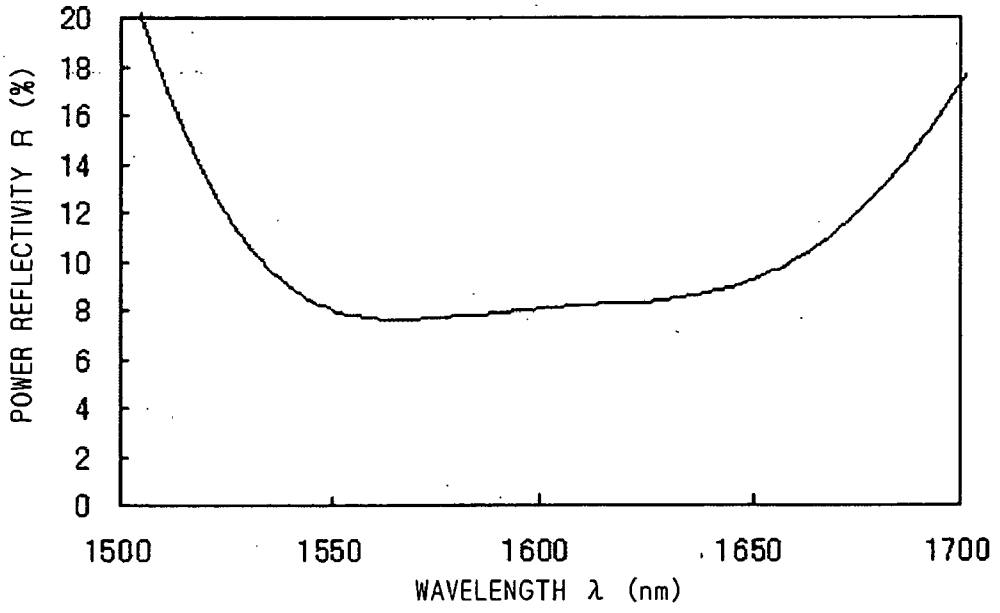
POWER REFLECTIVITY R (%)
20
18
16
14
12
10
8
6
4
2
0
1500
1550
1600
1650
1700
WAVELENGTH λ (nm)

FIG. 73

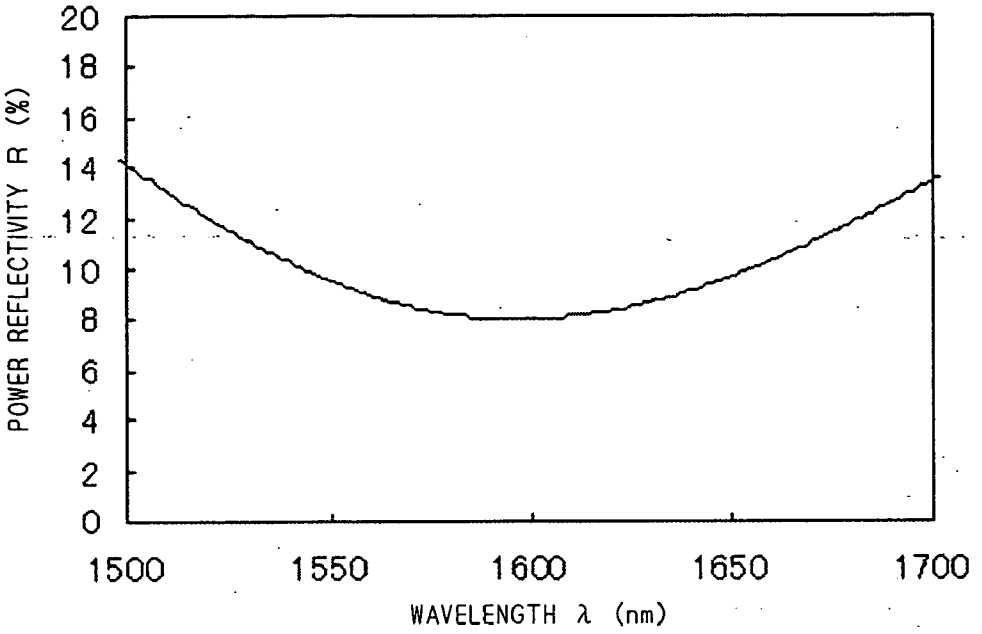
20
18
16
14
12
10
8
6
4
2
0
POWER REFLECTIVITY R (%)
1500
1550
1600
1650
1700
WAVELENGTH λ (nm)

FIG. 74

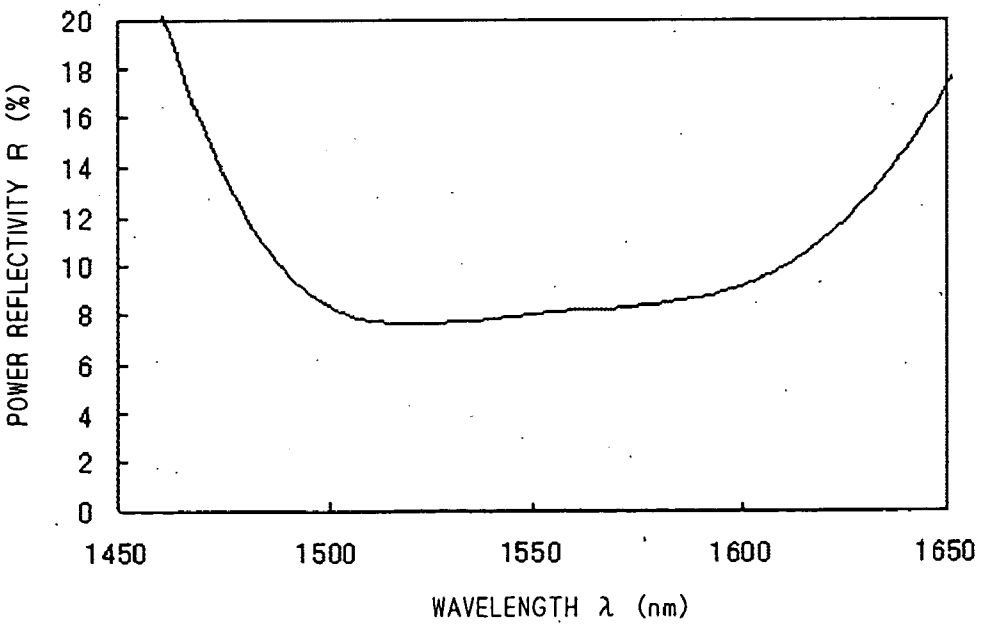
20
18
16
14
12
10
8
6
4
2
0
POWER REFLECTIVITY R (%)
1450
1500
1550
1600
1650
WAVELENGTH λ (nm)

FIG. 75

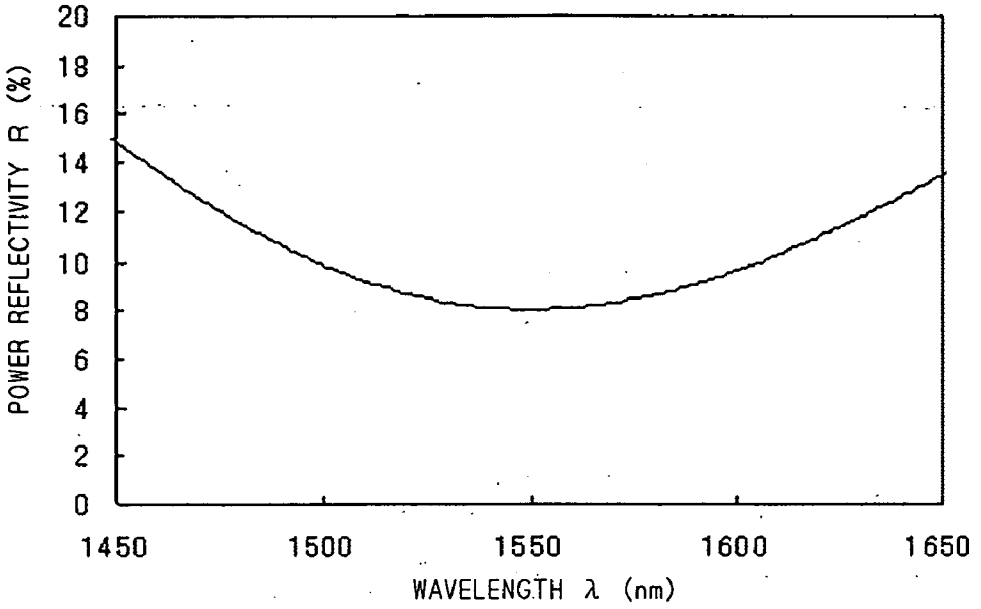
POWER REFLECTIVITY R (%)
20
18
16
14
12
10
8
6
4
2
0
1450
1500
1550
1600
1650
WAVELENGTH λ (nm)

FIG. 76

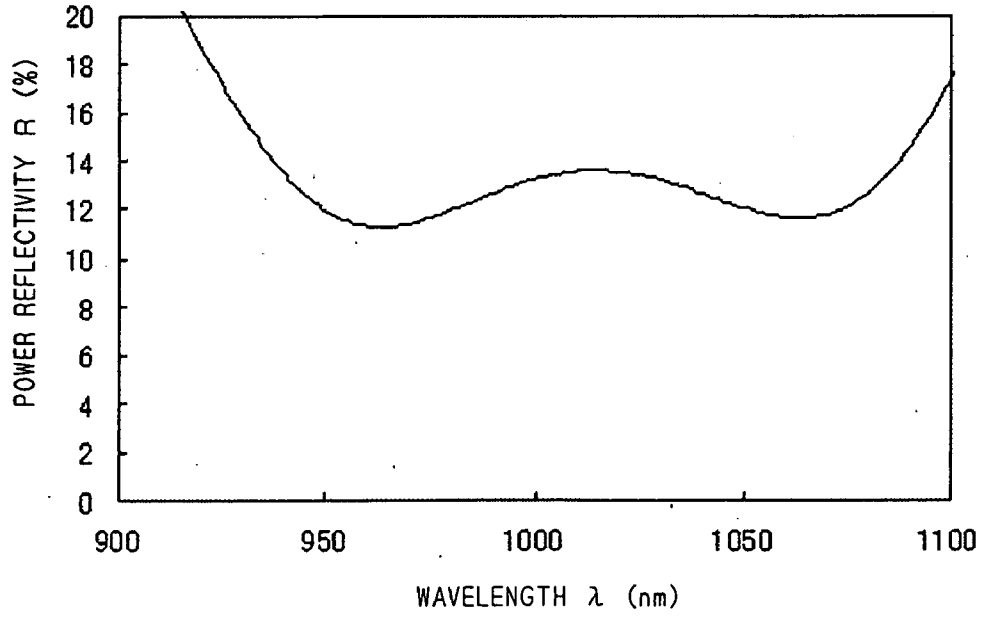
POWER REFLECTIVITY R (%)
20
18
16
14
12
10
8
6
4
2
0
900
950
1000
1050
1100
WAVELENGTH λ (nm)

FIG. 77

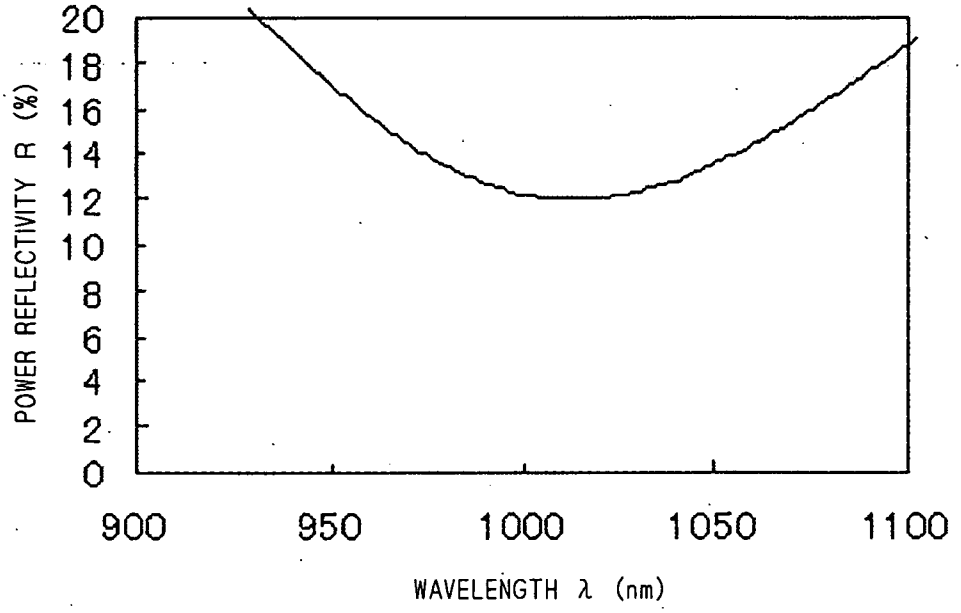
POWER REFLECTIVITY R (%)
20
18
16
14
12
10
8
6
4
2
0
900
950
1000
1050
1100
WAVELENGTH λ (nm)

FIG. 78

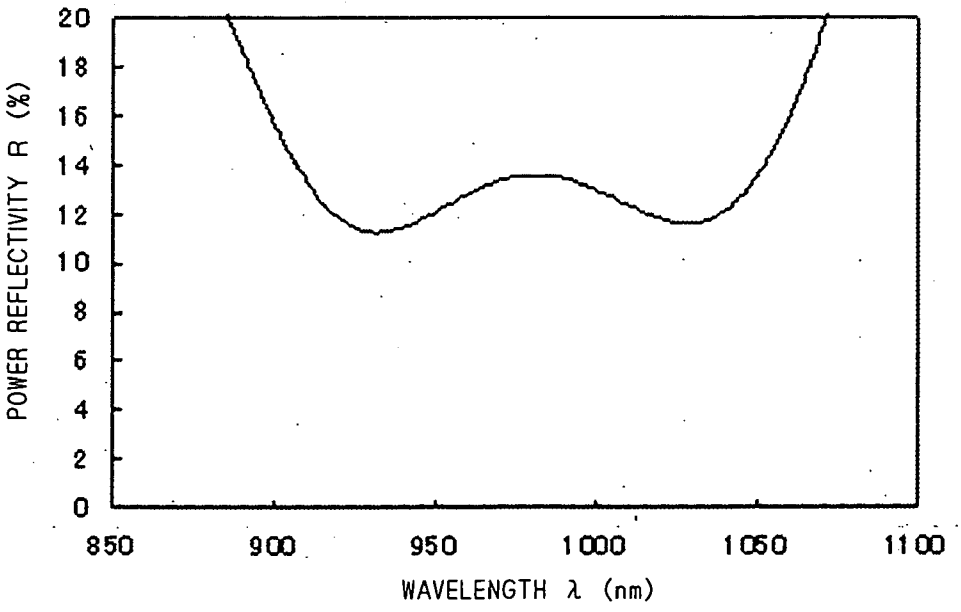
POWER REFLECTIVITY R (%)
20
18
16
14
12
10
8
6
4
2
0
850
900
950
1000
1050
1100
WAVELENGTH λ (nm)

FIG. 79

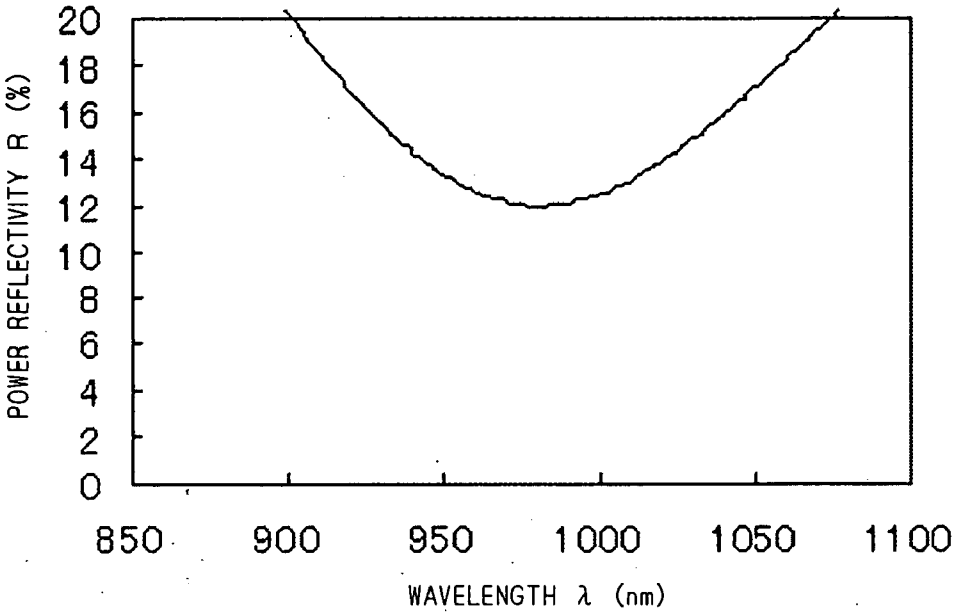
POWER REFLECTIVITY R (%)
20
18
16
14
12
10
8
6
4
2
0
850
900
950
1000
1050
1100
WAVELENGTH λ (nm)

FIG. 80

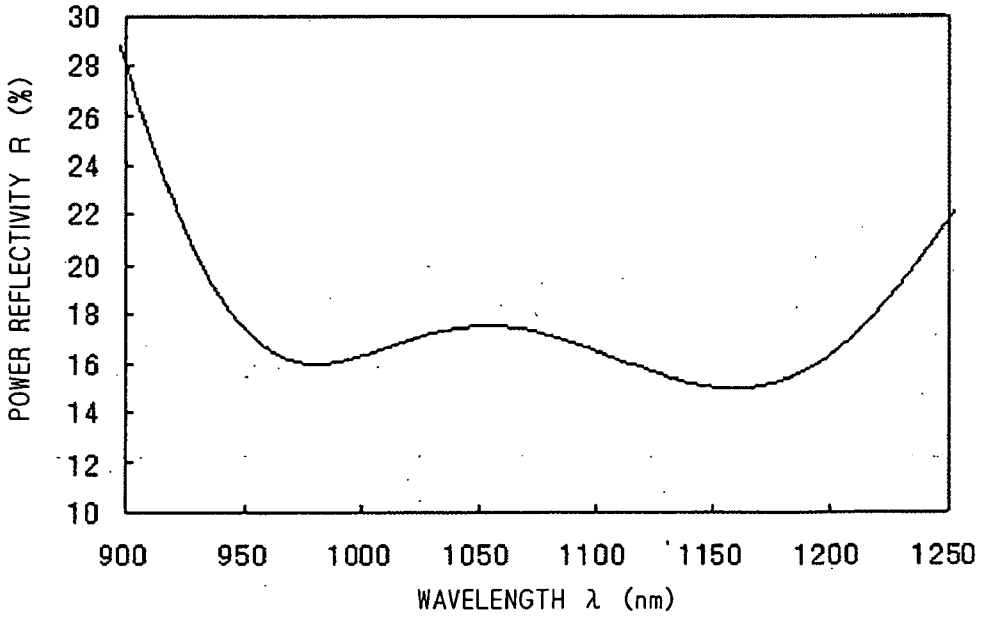
POWER REFLECTIVITY R (%)
30
28
26
24
22
20
18
16
14
12
10
900
950
1000
1050
1100
1150
1200
1250
WAVELENGTH λ (nm)

FIG. 81

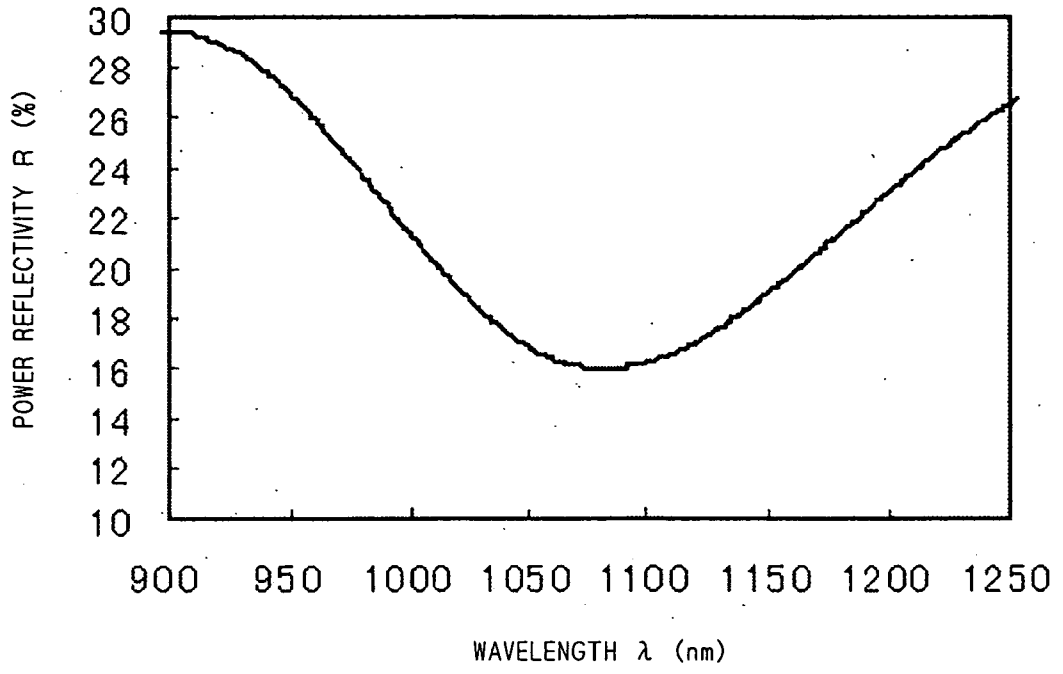
30
28
26
24
22
20
18
16
14
12
10
POWER REFLECTIVITY R (%)
900
950
1000
1050
1100
1150
1200
1250
WAVELENGTH λ (nm)

FIG. 82

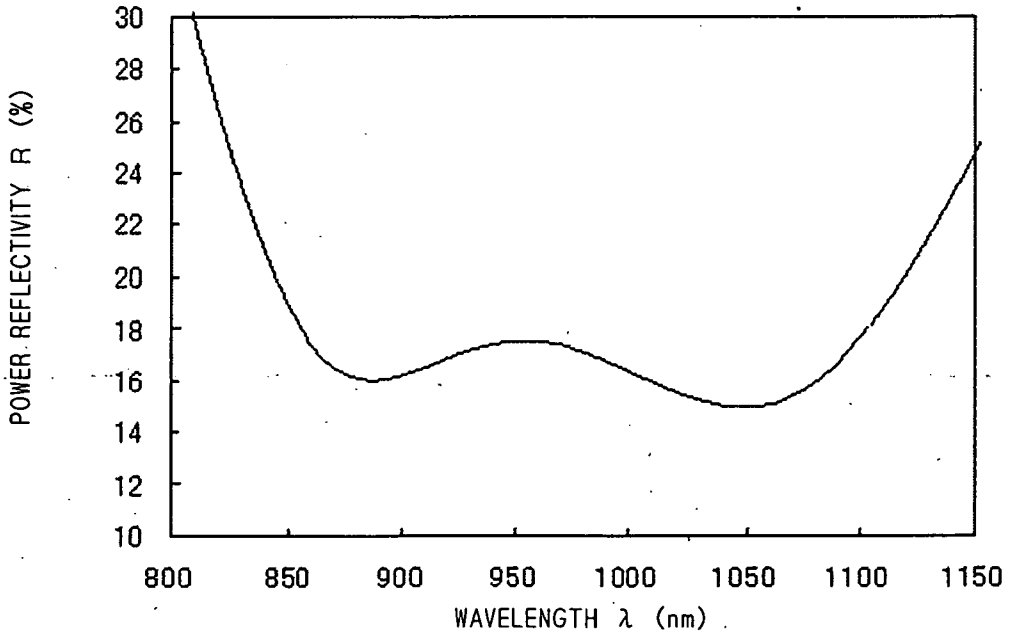
30
28
26
24
22
20
18
16
14
12
10
POWER REFLECTIVITY R (%)
800
850
900
950
1000
1050
1100
1150
WAVELENGTH λ (nm)

FIG. 83

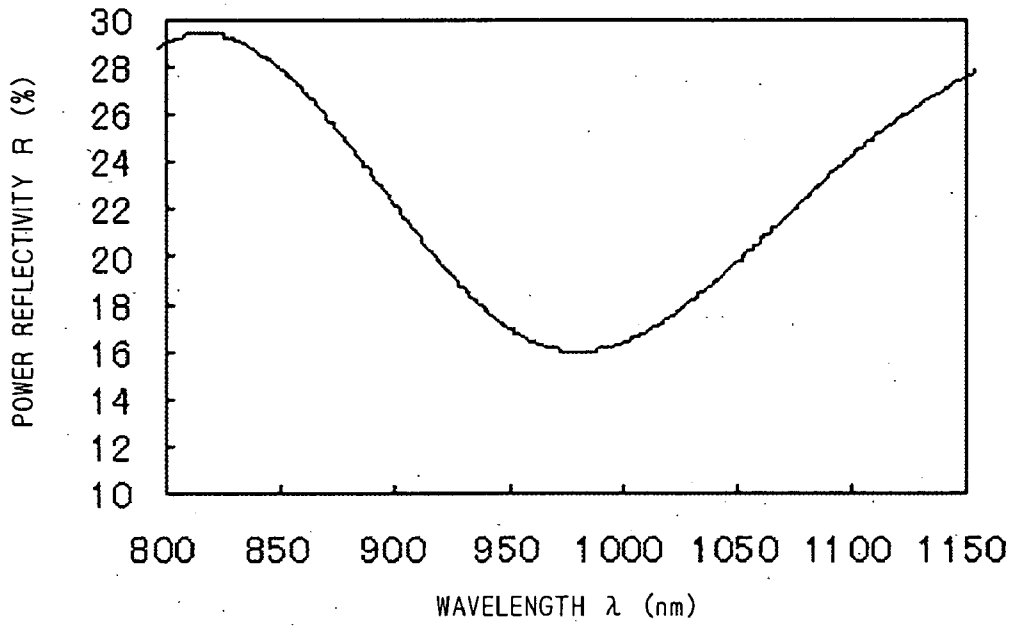
POWER REFLECTIVITY R (%)
30
28
26
24
22
20
18
16
14
12
10
800 850 900 950 1000 1050 1100 1150
WAVELENGTH λ (nm)

FIG. 84

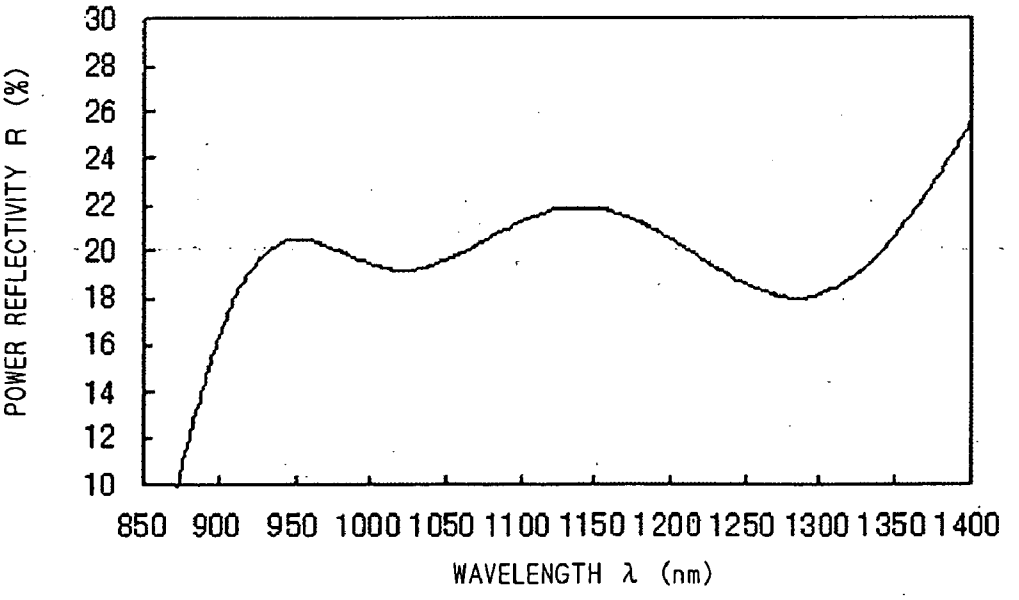
POWER REFLECTIVITY R (%)
30
28
26
24
22
20
18
16
14
12
10
850 900 950 1000 1050 1100 1150 1200 1250 1300 1350 1400
WAVELENGTH λ (nm)

FIG. 85

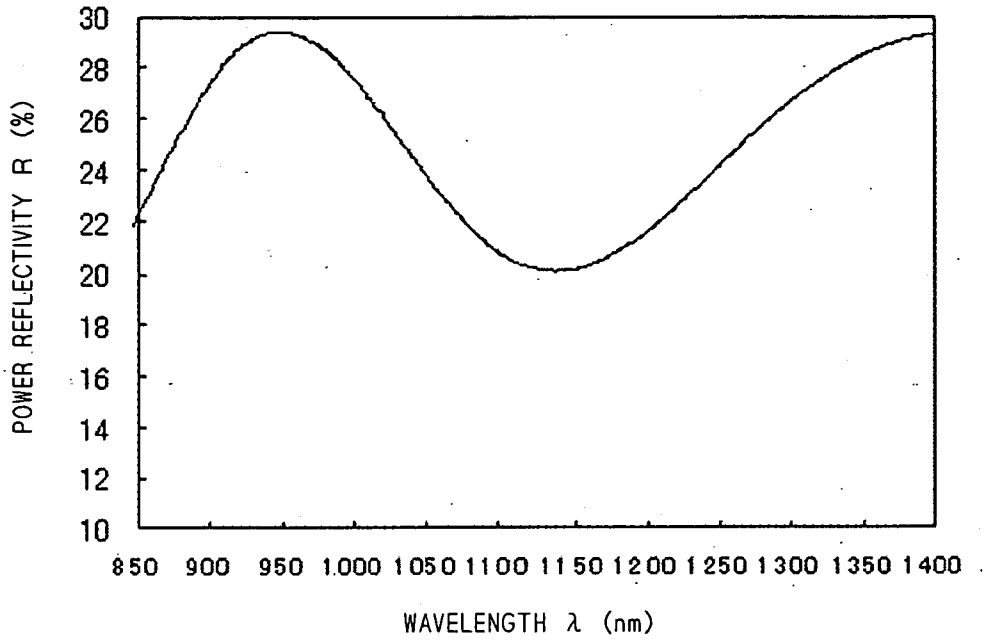
POWER REFLECTIVITY R (%)
30
28
26
24
22
20
18
16
14
12
10
850 900 950 1000 1050 1100 1150 1200 1250 1300 1350 1400
WAVELENGTH λ (nm)

FIG. 86

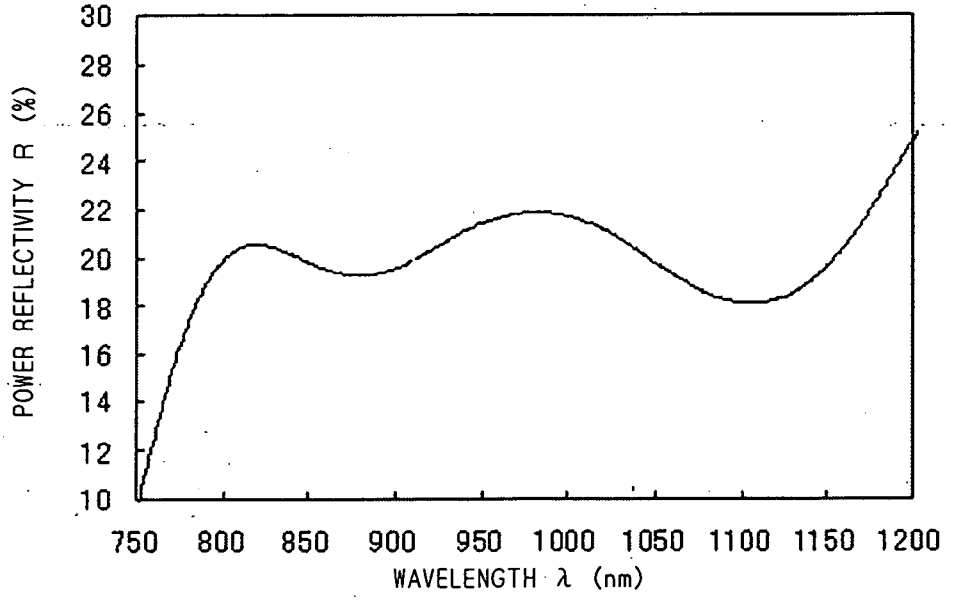
POWER REFLECTIVITY R (%)
30
28
26
24
22
20
18
16
14
12
10
750 800 850 900 950 1000 1050 1100 1150 1200
WAVELENGTH λ (nm)

FIG. 87

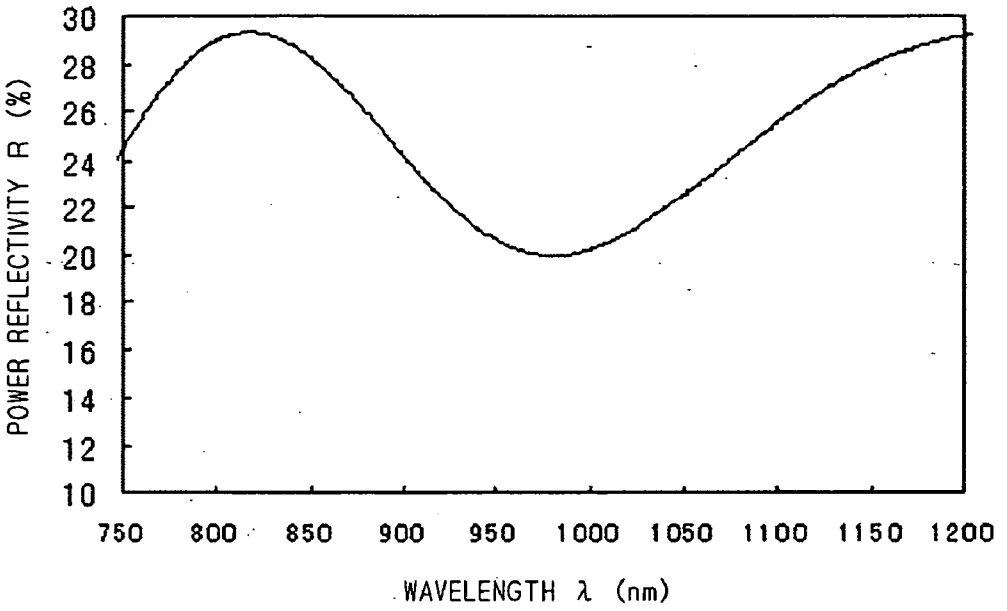
POWER REFLECTIVITY R (%)
30
28
26
24
22
20
18
16
14
12
10
750
800
850
900
950
1000
1050
1100
1150
1200
WAVELENGTH λ (nm)

FIG. 88

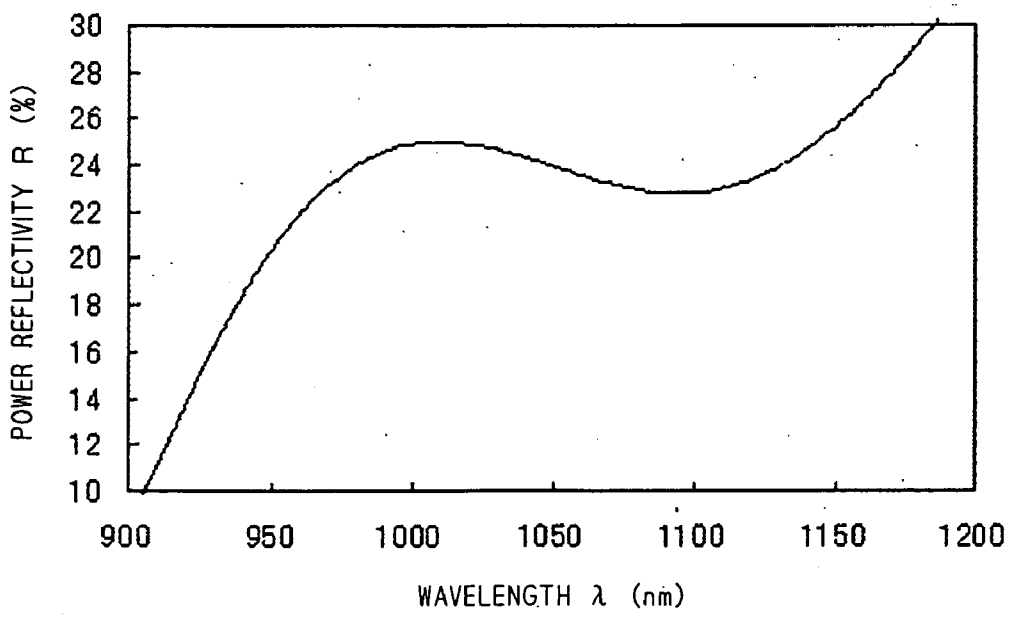
POWER REFLECTIVITY R (%)
30
28
26
24
22
20
18
16
14
12
10
900
950
1000
1050
1100
1150
1200
WAVELENGTH λ (nm)

FIG. 89

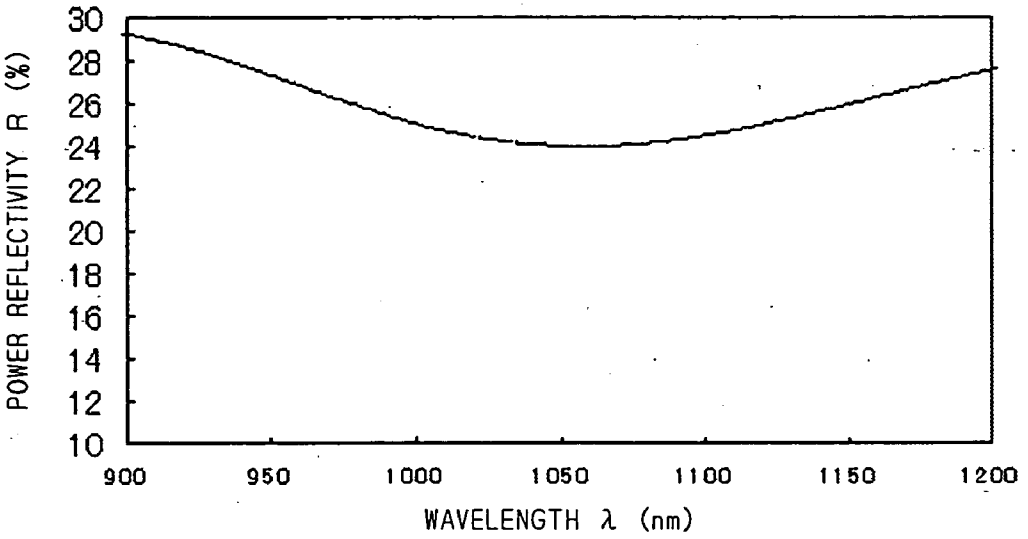
POWER REFLECTIVITY R (%)
30
28
26
24
22
20
18
16
14
12
10
900
950
1000
1050
1100
1150
1200
WAVELENGTH λ (nm)

FIG. 90

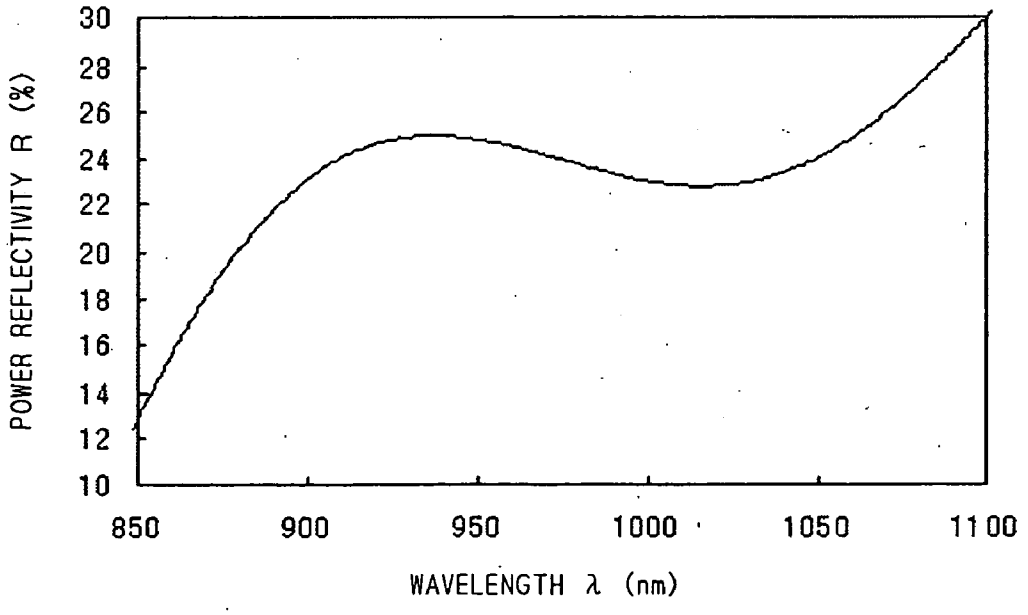
POWER REFLECTIVITY R (%)
30
28
26
24
22
20
18
16
14
12
10
850
900
950
1000
1050
1100
WAVELENGTH λ (nm)

FIG. 91

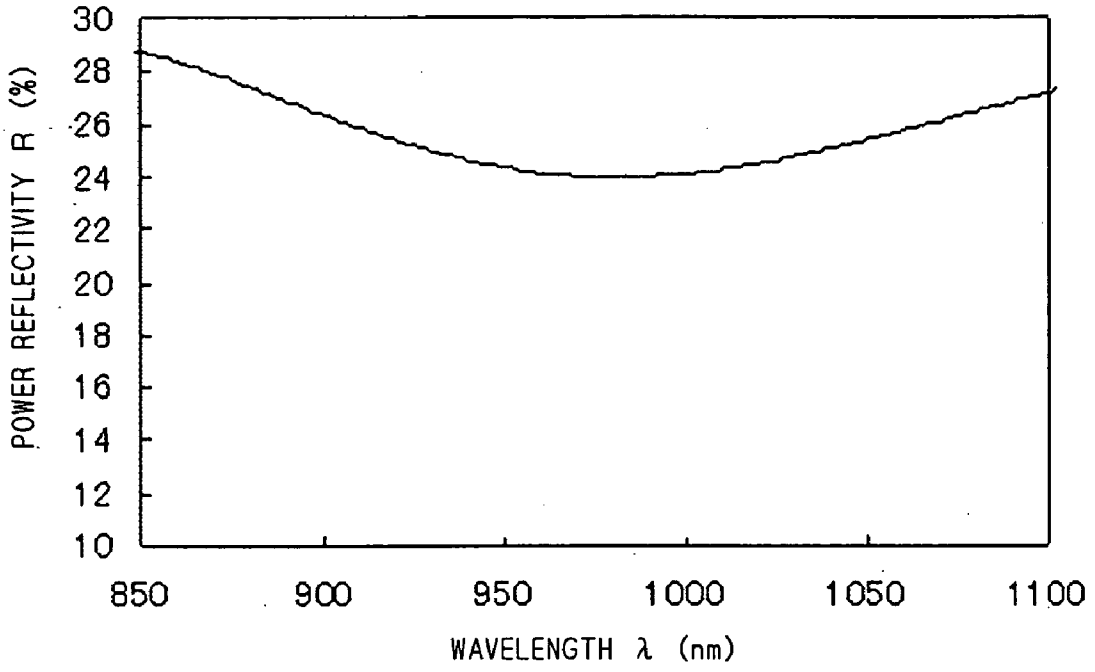
30
28
26
24
22
20
18
16
14
12
10
POWER REFLECTIVITY R (%)
850
900
950
1000
1050
1100
WAVELENGTH λ (nm)

FIG. 92

PREFERRED EMBODIMENT	ALLOWABLE REFLECTIVITY RANGE	TOTAL NUMBER OF LAYERS	NUMBER OF MATERIAL LAYERS	COATING FILM STRUCTURE	QUADRANT	θ (°)	DESIGN WAVELENGTH (nm)
1	4%±2%	6	2	$Ta_2O_5/SiO_2/Ta_2O_5/SiO_2/Ta_2O_5/SiO_2$	1	60	980
2	4%±2%	6	2	$Ta_2O_5/Al_2O_3/Ta_2O_5/Al_2O_3/Ta_2O_5/Al_2O_3$	2	150	808
3	4%±2%	7	2	$Al_2O_3/Ta_2O_5/Al_2O_3/Ta_2O_5/Al_2O_3/Ta_2O_5/Al_2O_3$	3	225	1310
4	4%±2%	7	3	$AlN/Ta_2O_5/Al_2O_3/Ta_2O_5/Al_2O_3/Ta_2O_5/Al_2O_3$	4	330	1550
5	4%±2%	8	2	$Ta_2O_5/SiO_2/Ta_2O_5/SiO_2/Ta_2O_5/SiO_2/Ta_2O_5/SiO_2$	1	45	410
6	4%±2%	8	3	$AlN/SiO_2/Ta_2O_5/SiO_2/Ta_2O_5/SiO_2/Ta_2O_5/SiO_2$	2	135	650
7	4%±2%	9	2	$Al_2O_3/Ta_2O_5/Al_2O_3/Ta_2O_5/Al_2O_3/Ta_2O_5/Al_2O_3/Ta_2O_5/Al_2O_3$	3	240	980
8	4%±2%	10	3	$Al_2O_3/SiO_2/AlN/SiO_2/AlN/SiO_2/AlN/SiO_2/AlN/SiO_2$	4	315	808
9	8%±2%	6	2	$Ta_2O_5/SiO_2/Ta_2O_5/SiO_2/Ta_2O_5/SiO_2$	1	30	1310
10	8%±2%	6	2	$Ta_2O_5/Al_2O_3/Ta_2O_5/Al_2O_3/Ta_2O_5/Al_2O_3$	2	120	1550
11	8%±2%	7	2	$SiO_2/Ta_2O_5/SiO_2/Ta_2O_5/SiO_2/Ta_2O_5/SiO_2$	3	210	410
12	8%±2%	7	3	$AlN/Ta_2O_5/Al_2O_3/Ta_2O_5/Al_2O_3/Ta_2O_5/Al_2O_3$	4	300	650
13	8%±2%	8	2	$Ta_2O_5/SiO_2/Ta_2O_5/SiO_2/Ta_2O_5/SiO_2/Ta_2O_5/SiO_2$	1	15	980
14	8%±2%	8	3	$AlN/Ta_2O_5/SiO_2/Ta_2O_5/SiO_2/Ta_2O_5/SiO_2/Ta_2O_5$	2	105	808
15	8%±2%	9	2	$Ta_2O_5/Al_2O_3/Ta_2O_5/Al_2O_3/Ta_2O_5/Al_2O_3/Ta_2O_5/Al_2O_3/Ta_2O_5$	3	195	1310
16	8%±2%	10	3	$AlN/SiO_2/Ta_2O_5/SiO_2/Ta_2O_5/SiO_2/Ta_2O_5/SiO2/Ta_2O_5/SiO_2$	4	285	1550
17	12%±2%	7	2	$Ta_2O_5/SiO_2/Ta_2O_5/SiO_2/Ta_2O_5/SiO_2/Ta_2O_5$	1	75	980
18	16%±2%	7	2	$Ta_2O_5/SiO_2/Ta_2O_5/SiO_2/Ta_2O_5/SiO_2/Ta_2O_5$	2	165	980
19	20%±2%	7	2	$Ta_2O_5/SiO_2/Ta_2O_5/SiO_2/Ta_2O_5/SiO_2/Ta_2O_5$	3	255	980
20	24%±2%	7	2	$Ta_2O_5/SiO_2/Ta_2O_5/SiO_2/Ta_2O_5/SiO_2/Ta_2O_5$	4	345	980

FIG. 93

PREFERRED EMBODIMENT	CENTER WAVELENGTH λ_c (nm)	WAVELENGTH BANDWIDTH W (nm)	W/λ_c	WAVELENGTH BANDWIDTH W_r (nm)	FILM THICKNESS RATIO t/t_r
1	956	245	0.256	58	6.19
	981	252	0.257	60	6.20
2	871	183	0.210	54	5.93
	809	170	0.210	50	5.95
3	1250	267	0.216	77	5.94
	1311	281	0.214	81	5.95
4	1659	478	0.288	103	5.88
	1550	455	0.294	97	5.89
5	437	102	0.233	38	9.63
	410	95	0.224	36	9.55
6	683	106	0.155	42	7.70
	650	101	0.155	39	7.68
7	972	118	0.121	60	8.07
	980	118	0.120	60	8.07
8	843	100	0.119	52	7.78
	808	90	0.111	60	7.77
9	1284	450	0.356	89	9.02
	1310	459	0.350	91	9.00
10	1655	427	0.258	114	5.92
	1550	400	0.258	108	5.92
11	393	62	0.158	42	9.70
	410	65	0.159	44	9.61
12	652	115	0.176	45	9.95
	650	115	0.177	44	9.92
13	1032	195	0.189	71	6.17
	980	186	0.190	68	6.17
14	849	89	0.105	58	11.59
	808	84	0.104	56	11.58
15	1492	268	0.180	103	7.66
	1310	235	0.179	91	7.65
16	1597	125	0.078	110	12.14
	1550	121	0.078	108	12.11
17	1013	149	0.147	79	10.13
	980	145	0.148	77	10.12
18	1082	274	0.253	100	5.85
	980	247	0.252	90	5.86
19	1138	454	0.399	131	6.15
	980	392	0.400	113	6.16
20	1057	192	0.182	172	5.60
	981	179	0.182	159	5.60

METHOD OF DESIGNING THICKNESS OF COATING FILM AND SEMICONDUCTOR PHOTONIC DEVICE

BACKGROUND OF THE INVENTION

[0001] 1. Field of the Invention

[0002] The present invention relates to a semiconductor photonic device including a semiconductor laser device for use as a light source for optical information processing, a signal source for optical communication and a pumping source for a fiber amplifier, a light emitting diode device, a semiconductor amplifier device, a semiconductor modulator and the like, and to a coating film for use in the semiconductor photonic device.

[0003] 2. Description of the Background Art

[0004] In general, a coating film is formed on an end surface of a semiconductor photonic element in a semiconductor photonic device such as a semiconductor laser device and a light emitting diode device for purposes of protection and reflectivity adjustment. Conventionally, various studies have been done on the power reflectivity of such a coating film.

[0005] A technique for forming an anti-reflection coating film on an end surface of a semiconductor laser element is disclosed, for example, in: K. Shigihara et al., "Antireflection coating for laser diodes," ELECTRONICS LETTERS, 31st Aug. 1995, Vol. 31, No. 18, pp. 1574-1576; and Japanese Patent Application Laid-Open No. 5-243689 (1993). According to this technique, if a single-layer coating film having a refractive index n_1 and a thickness d_1 is formed on an end surface of a semiconductor laser having an effective refractive index n_e, the coating film becomes an anti-reflection film when the following conditions are satisfied: $n_1=n_e^{1/2}$ and $d_1=\lambda_0/(4\cdot n_1)$, where λ_0 is the value of the lasing wavelength of the semiconductor laser. At this time, the magnitude of the reflection amplitude vector of the coating film is zero. The "reflection amplitude vector" used herein refers to the amplitude vector of a reflected wave obtained when the amplitude vector of an incident wave (referred to hereinafter as an "incident amplitude vector") is placed on the positive real axis in a complex plane and is defined to have a magnitude of "1." Thus, the reflection amplitude vector is a vector indicative of the position of an amplitude reflectivity in the complex plane.

[0006] A technique for improving the design flexibility of an anti-reflection coating film is disclosed in Japanese Patent Application Laid-Open No. 2004-88049.

[0007] A coating film having a power reflectivity greater than zero is disclosed in Japanese Patent Application Laid-Open No. 2004-289108. According to Japanese Patent Application Laid-Open No. 2004-289108, if the coating film is a single-layer film, the power reflectivity of the coating film takes on a relative minimum value not equal to zero when the following conditions are satisfied: $n_1\neq n_e^{1/2}$ and $d_1=\lambda_0/(4\cdot n_1)\times m$ (where m is an odd number). Thus, when $n^1\neq n_e^{1/2}$ and the thickness of the coating film is an odd multiple of $\lambda_0/(4\cdot n_1)$, the reflection amplitude vector of the coating film is present on the negative real axis in a complex plane. In this case, there is a phase difference of 180 degrees between the incident amplitude vector and the reflection amplitude vector. Then, the imaginary components of the incident and reflection amplitude vectors are equal to zero, and a difference between the real components of the vectors is equal to a power transmissivity. The value of the power reflectivity is obtained by subtracting the power transmissivity from one.

[0008] For designing the coating film having a power reflectivity greater than zero, the conventional techniques establish the condition that the thickness of the coating film is an odd multiple of $\lambda_0/(4\cdot n_1)$ as described above to result in the reflection amplitude vector positioned on the real axis in the complex plane. It is hence necessary to determine the thickness of the coating film so that the amplitude reflectivity is a real number when designing the thickness of the coating film having the power reflectivity greater than zero. This results in a low degree of design flexibility of the thickness of the coating film, and creates a likelihood that the coating film having a desired characteristic is not designed.

SUMMARY OF THE INVENTION

[0009] It is an object of the present invention to provide a technique capable of improving the design flexibility of the thickness of a coating film provided on an end surface of a semiconductor photonic element.

[0010] A first aspect of the present invention is intended for a method of designing the thickness of a coating film including a plurality of layers and provided on an end surface of a semiconductor photonic element including an active layer through which light propagates. According to the present invention, the method includes the following steps (a) and (b). The step (a) is to select an imaginary number as a value of an amplitude reflectivity of the coating film. The step (b) is to determine the thickness of each of the plurality of layers of the coating film so that the value of the amplitude reflectivity of the coating film is equal to the imaginary number selected in the step (a).

[0011] According to a second aspect of the present invention, a semiconductor photonic device includes a semiconductor photonic element, and a coating film. The semiconductor photonic element, includes an active layer through which light propagates. The coating film includes a plurality of layers and is provided on an end surface of the semiconductor photonic element. The coating film has an amplitude reflectivity taking on a value set at an imaginary value.

[0012] The use of the imaginary value as the value of the amplitude reflectivity of the coating film makes it possible to design the thickness of the coating film having a predetermined power reflectivity in consideration for more complex numbers having the same amplitude as the value of the amplitude reflectivity than real numbers when used. This improves the design flexibility of the thickness of the coating film to make the coating film having a desired characteristic easy to design.

[0013] These and other objects, features, aspects and advantages of the present invention will become more apparent from the following detailed description of the present invention when taken in conjunction with the accompanying drawings.

BRIEF DESCRIPTION OF THE DRAWINGS

[0014] **FIG. 1** shows the amplitude reflectivity of a coating film represented in a complex plane;

[0015] **FIG. 2** is a side view showing a structure of a semiconductor photonic device having a single-layer coating film on an end surface of a semiconductor photonic element;

[0016] **FIG. 3** is a graph showing the wavelength dependence of the power reflectivity of the single-layer coating film;

[0017] **FIG. 4** is a side view showing a structure of a semiconductor photonic device according to the present invention;

[0018] **FIG. 5** is a flowchart showing a method of designing the thickness of a coating film according to the present invention;

[0019] **FIG. 6** is a side view showing a structure of the semiconductor photonic device according to a first preferred embodiment of the present invention;

[0020] **FIG. 7** is a graph showing the wavelength dependence of the power reflectivity of a coating film according to the first preferred embodiment of the present invention;

[0021] **FIG. 8** is a graph showing the wavelength dependence of the power reflectivity of the single-layer coating film;

[0022] **FIG. 9** is a graph showing the wavelength dependence of the power reflectivity of the coating film according to the first preferred embodiment of the present invention;

[0023] **FIG. 10** is a graph showing the wavelength dependence of the power reflectivity of the single-layer coating film;

[0024] **FIG. 11** is a graph showing the wavelength dependence of the power reflectivity of a coating film according to a second preferred embodiment of the present invention;

[0025] **FIG. 12** is a graph showing the wavelength dependence of the power reflectivity of the single-layer coating film;

[0026] **FIG. 13** is a graph showing the wavelength dependence of the power reflectivity of the coating film according to the second preferred embodiment of the present invention;

[0027] **FIG. 14** is a graph showing the wavelength dependence of the power reflectivity of the single-layer coating film;

[0028] **FIG. 15** is a side view showing a structure of the semiconductor photonic device according to a third preferred embodiment of the present invention;

[0029] **FIG. 16** is a graph showing the wavelength dependence of the power reflectivity of a coating film according to the third preferred embodiment of the present invention;

[0030] **FIG. 17** is a graph showing the wavelength dependence of the power reflectivity of the single-layer coating film;

[0031] **FIG. 18** is a graph showing the wavelength dependence of the power reflectivity of the coating film according to the third preferred embodiment of the present invention;

[0032] **FIG. 19** is a graph showing the wavelength dependence of the power reflectivity of the single-layer coating film;

[0033] **FIG. 20** is a side view showing a structure of the semiconductor photonic device according to a fourth preferred embodiment of the present invention;

[0034] **FIG. 21** is a graph showing the wavelength dependence of the power reflectivity of a coating film according to the fourth preferred embodiment of the present invention;

[0035] **FIG. 22** is a graph showing the wavelength dependence of the power reflectivity of the single-layer coating film;

[0036] **FIG. 23** is a graph showing the wavelength dependence of the power reflectivity of the coating film according to the fourth preferred embodiment of the present invention;

[0037] **FIG. 24** is a graph showing the wavelength dependence of the power reflectivity of the single-layer coating film;

[0038] **FIG. 25** is a side view showing a structure of the semiconductor photonic device according to a fifth preferred embodiment of the present invention;

[0039] **FIG. 26** is a graph showing the wavelength dependence of the power reflectivity of a coating film according to the fifth preferred embodiment of the present invention;

[0040] **FIG. 27** is a graph showing the wavelength dependence of the power reflectivity of the single-layer coating film;

[0041] **FIG. 28** is a graph showing the wavelength dependence of the power reflectivity of the coating film according to the fifth preferred embodiment of the present invention;

[0042] **FIG. 29** is a graph showing the wavelength dependence of the power reflectivity of the single-layer coating film;

[0043] **FIG. 30** is a side view showing a structure of the semiconductor photonic device according to a sixth preferred embodiment of the present invention;

[0044] **FIG. 31** is a graph showing the wavelength dependence of the power reflectivity of a coating film according to the sixth preferred embodiment of the present invention;

[0045] **FIG. 32** is a graph showing the wavelength dependence of the power reflectivity of the single-layer coating film;

[0046] **FIG. 33** is a graph showing the wavelength dependence of the power reflectivity of the coating film according to the sixth preferred embodiment of the present invention;

[0047] **FIG. 34** is a graph showing the wavelength dependence of the power reflectivity of the single-layer coating film;

[0048] **FIG. 35** is a side view showing a structure of the semiconductor photonic device according to a seventh preferred embodiment of the present invention;

[0049] **FIG. 36** is a graph showing the wavelength dependence of the power reflectivity of a coating film according to the seventh preferred embodiment of the present invention;

[0050] **FIG. 37** is a graph showing the wavelength dependence of the power reflectivity of the single-layer coating film;

[0051] **FIG. 38** is a graph showing the wavelength dependence of the power reflectivity of the coating film according to the seventh preferred embodiment of the present invention;

[0052] **FIG. 39** is a side view showing a structure of the semiconductor photonic device according to an eighth preferred embodiment of the present invention;

[0053] **FIG. 40** is a graph showing the wavelength dependence of the power reflectivity of a coating film according to the eighth preferred embodiment of the present invention;

[0054] **FIG. 41** is a graph showing the wavelength dependence of the power reflectivity of the single-layer coating film;

[0055] **FIG. 42** is a graph showing the wavelength dependence of the power reflectivity of the coating film according to the eighth preferred embodiment of the present invention;

[0056] **FIG. 43** is a graph showing the wavelength dependence of the power reflectivity of the single-layer coating film;

[0057] **FIG. 44** is a graph showing the wavelength dependence of the power reflectivity of a coating film according to a ninth preferred embodiment of the present invention;

[0058] **FIG. 45** is a graph showing the wavelength dependence of the power reflectivity of the single-layer coating film;

[0059] **FIG. 46** is a graph showing the wavelength dependence of the power reflectivity of the coating film according to the ninth preferred embodiment of the present invention;

[0060] **FIG. 47** is a graph showing the wavelength dependence of the power reflectivity of the single-layer coating film;

[0061] **FIG. 48** is a graph showing the wavelength dependence of the power reflectivity of a coating film according to a tenth preferred embodiment of the present inventions;

[0062] **FIG. 49** is a graph showing the wavelength dependence of the power reflectivity of the single-layer coating film;

[0063] **FIG. 50** is a graph showing the wavelength dependence of the power reflectivity of the coating film according to the tenth preferred embodiment of the present invention;

[0064] **FIG. 51** is a graph showing the wavelength dependence of the power reflectivity of the single-layer coating film;

[0065] **FIG. 52** is a graph showing the wavelength dependence of the power reflectivity of a coating film according to an eleventh preferred embodiment of the present invention;

[0066] **FIG. 53** is a graph showing the wavelength dependence of the power reflectivity of the single-layer coating film;

[0067] **FIG. 54** is a graph showing the wavelength dependence of the power reflectivity of the coating film according to the eleventh preferred embodiment of the present invention;

[0068] **FIG. 55** is a graph showing the wavelength dependence of the power reflectivity of the single-layer coating film;

[0069] **FIG. 56** is a graph showing the wavelength dependence of the power reflectivity of a coating film according to a twelfth preferred embodiment of the present invention;

[0070] **FIG. 57** is a graph showing the wavelength dependence of the power reflectivity of the single-layer coating film;

[0071] **FIG. 58** is a graph showing the wavelength dependence of the power reflectivity of the coating film according to the twelfth preferred embodiment of the present invention;

[0072] **FIG. 59** is a graph showing the wavelength dependence of the power reflectivity of the single-layer coating film;

[0073] **FIG. 60** is a graph showing the wavelength dependence of the power reflectivity of a coating film according to a thirteenth preferred embodiment of the present invention;

[0074] **FIG. 61** is a graph showing the wavelength dependence of the power reflectivity of the single-layer coating film;

[0075] **FIG. 62** is a graph showing the wavelength dependence of the power reflectivity of the coating film according to the thirteenth preferred embodiment of the present invention;

[0076] **FIG. 63** is a graph showing the wavelength dependence of the power reflectivity of the single-layer coating film;

[0077] **FIG. 64** is a graph showing the wavelength dependence of the power reflectivity of a coating film according to a fourteenth preferred embodiment of the present invention;

[0078] **FIG. 65** is a graph showing the wavelength dependence of the power reflectivity of the single-layer coating film;

[0079] **FIG. 66** is a graph showing the wavelength dependence of the power reflectivity of the coating film according to the fourteenth preferred embodiment of the present invention;

[0080] **FIG. 67** is a graph showing the wavelength dependence of the power reflectivity of the single-layer coating film;

[0081] **FIG. 68** is a graph showing the wavelength dependence of the power reflectivity of a coating film according to a fifteenth preferred embodiment of the present invention;

[0082] **FIG. 69** is a graph showing the wavelength dependence of the power reflectivity of the single-layer coating film;

[0083] **FIG. 70** is a graph showing the wavelength dependence of the power reflectivity of the coating film according to the fifteenth preferred embodiment of the present invention;

[0084] **FIG. 71** is a graph showing the wavelength dependence of the power reflectivity of the single-layer coating film;

[0085] **FIG. 72** is a graph showing the wavelength dependence of the power reflectivity of a coating film according to a sixteenth preferred embodiment of the present invention;

[0086] **FIG. 73** is a graph showing the wavelength dependence of the power reflectivity of the single-layer coating film;

[0087] **FIG. 74** is a graph showing the wavelength dependence of the power reflectivity of the coating film according to the sixteenth preferred embodiment of the present invention;

[0088] **FIG. 75** is a graph showing the wavelength dependence of the power reflectivity of the single-layer coating film;

[0089] **FIG. 76** is a graph showing the wavelength dependence of the power reflectivity of a coating film according to a seventeenth preferred embodiment of the present invention;

[0090] **FIG. 77** is a graph showing the wavelength dependence of the power reflectivity of the single-layer coating film;

[0091] **FIG. 78** is a graph showing the wavelength dependence of the power reflectivity of the coating film according to the seventeenth preferred embodiment of the present invention;

[0092] **FIG. 79** is a graph showing the wavelength dependence of the power reflectivity of the single-layer coating film;

[0093] **FIG. 80** is a graph showing the wavelength dependence of the power reflectivity of a coating film according to an eighteenth preferred embodiment of the present invention;

[0094] **FIG. 81** is a graph showing the wavelength dependence of the power reflectivity of the single-layer coating film;

[0095] **FIG. 82** is a graph showing the wavelength dependence of the power reflectivity of the coating film according to the eighteenth preferred embodiment of the present invention;

[0096] **FIG. 83** is a graph showing the wavelength dependence of the power reflectivity of the single-layer coating film;

[0097] **FIG. 84** is a graph showing the wavelength dependence of the power reflectivity of a coating film according to a nineteenth preferred embodiment of the present invention;

[0098] **FIG. 85** is a graph showing the wavelength dependence of the power reflectivity of the single-layer coating film;

[0099] **FIG. 86** is a graph showing the wavelength dependence of the power reflectivity of the coating film according to the nineteenth preferred embodiment of the present invention;

[0100] **FIG. 87** is a graph showing the wavelength dependence of the power reflectivity of the single-layer coating film;

[0101] **FIG. 88** is a graph showing the wavelength dependence of the power reflectivity of a coating film according to a twentieth preferred embodiment of the present invention;

[0102] **FIG. 89** is a graph showing the wavelength dependence of the power reflectivity of the single-layer coating film;

[0103] **FIG. 90** is a graph showing the wavelength dependence of the power reflectivity of the coating film according to the twentieth preferred embodiment of the present invention;

[0104] **FIG. 91** is a graph showing the wavelength dependence of the power reflectivity of the single-layer coating film; and

[0105] **FIGS. 92 and 93** are tables listing conditions and results according to the first to twentieth preferred embodiments of the present invention.

DESCRIPTION OF THE PREFERRED EMBODIMENTS

[0106] **FIG. 1** shows that the amplitude reflectivity r of a coating film provided on an end surface of a semiconductor photonic element having an active layer, such as a semiconductor laser element, is represented in a complex plane. A phase angle θ in **FIG. 1** is an angle formed by a positive real axis and a reflection amplitude vector rv, that is, a vector indicative of the position of the amplitude reflectivity r in the complex plane.

[0107] When the wavelength of light propagating through the active layer is denoted generally by λ, the amplitude reflectivity r for the light is expressed by $r=r_r(\lambda)+ir_i(\lambda)$ where $r_r(\lambda)$ and $r_i(\lambda)$ are the real part and the imaginary part, respectively, of the amplitude reflectivity r, i is an imaginary unit, and $i^2=-1$.

[0108] For $\lambda=\lambda_0$, the amplitude reflectivity r equals zero and a power reflectivity R expressed by $|r|^2$ also equals zero when $r_r(\lambda)$ and $r_i(\lambda)$ satisfy

$$r_r(\lambda_0)=0 \quad (1)$$

$$r_i(\lambda_0)=0 \quad (2)$$

[0109] Thus, an anti-reflection coating film is prepared by designing the coating film so that Equations (1) and (2) are satisfied.

[0110] The above-mentioned method, however, cannot be employed for the preparation of a coating film having a power reflectivity R greater than zero, rather than the anti-reflection coating film. **FIG. 2** is a side view showing a structure of a semiconductor photonic device having a single-layer coating film **2** provided on an end surface **1***b* of a semiconductor photonic element **1** including an active layer **1***a*. The power reflectivity R of the single-layer coating film **2** in contact with free space **3** filled with air or nitrogen as shown in **FIG. 2** takes on a relative minimum value for the wavelength $\lambda=\lambda_0$ when the following equation is satisfied:

$$d_f = \frac{\lambda_0}{4n_f}(2m+1) \quad (3)$$

where d_f is the thickness of the single-layer coating film **2**, n_f is the refractive index of the coating film **2**, and m is a non-negative integer such as 0, 1 and 2. The amplitude reflectivity r at this time is expressed by:

$$r = \frac{n_c - n_f^2}{n_c + n_f^2} \quad (4)$$

where n_c is the effective refractive index of the semiconductor photonic element **1**.

[0111] Setting the thickness d_f of the coating film **2** so that Equation (3) is satisfied causes the power reflectivity R to take on a relative minimum value of 4% for the wavelength $\lambda=\lambda_0$ when the effective refractive index n_c of the semiconductor photonic element **1** is 3.37 and the refractive index n_f of the coating film **2** is 2.248 or 1.499.

[0112] **FIG. 3** is a graph showing the wavelength dependence of the power reflectivity R of the coating film **2** when λ_0=980 nm, n_c=3.37 and n_f=1.499 are set. In **FIG. 3**, a curve **103** is plotted for the thickness $d_f=\lambda_0/(4\ n_f)$=169.08 nm of the coating film **2**, and a curve **104** is plotted for the thickness $d_f=5\ \lambda_0/(4\ n_f)$=845.41 nm.

[0113] As illustrated in **FIG. 3**, the power reflectivity R takes on a relative minimum value of 4% for the wavelength λ of 980 nm, whether the thickness d_f is set at $\lambda_0/(4\ n_f)$ or at $5\ \lambda_0/(4\ n_f)$. For the thickness d_f set at $\lambda_0/(4\ n_f)$, the curve **103** shows that a wavelength band for which the power reflectivity R falls within ±2% from the relative minimum value of 4% is from 848 nm to 1161 nm to provide a wavelength bandwidth of 313 nm. For the thickness d_f set at $5\ \lambda_0/(4\ n_f)$, the curve **104** shows that a wavelength band for which the power reflectivity R falls within ±2% from the relative minimum value of 4% is from 951 nm to 1011 nm to provide a wavelength bandwidth of 60 nm. The value obtained by dividing the wavelength bandwidth of 60 nm by 981 nm that is the median value of the wavelength band is approximately 0.06, which is a measure of the extent of the wavelength band. For the coating film **2** as shown in **FIG. 2**, as the thickness d_f thereof is increased in increments of an odd multiple of $\lambda_0/(4\ n_f)$, the wavelength band for which the power reflectivity R falls within a predetermined range becomes narrower.

[0114] As discussed above, when the thickness d_f of the coating film **2** is set at an odd multiple of $\lambda_0/(4\ n_f)$, the amplitude reflectivity r is a real number as will be understood from Equation (4) described above, and thus the reflection amplitude vector rv for the coating film **2** is present on the real axis. In other words, it is necessary to design the thickness of the coating film so that the reflection amplitude vector rv is positioned on the real axis. Thus, this method is low in the degree of design flexibility of the coating film, and sometimes cannot provide a desired characteristic.

[0115] The present invention employs an imaginary number, i.e. a complex number having a nonzero imaginary part, as the value of the amplitude reflectivity r to make it possible to design the thickness of the coating film having a predetermined power reflectivity R in consideration for various complex numbers having the same amplitude as the value of the amplitude reflectivity, thereby improving the design flexibility of the thickness of the coating film. The basic principle of the present invention will now be described by using the coating film having a two-layer structure as an example.

Basic Principle of Present Invention

[0116] **FIG. 4** is a side view showing a structure of a semiconductor photonic device provided with a coating film **6** having a two-layer structure on the end surface **1***b* of the semiconductor photonic element **1**. The semiconductor photonic device shown in **FIG. 4** may be used as a semiconductor laser device, a light emitting diode device, a semiconductor amplifier device or a semiconductor modulator. As shown in **FIG. 4**, the semiconductor photonic element **1** has the active layer **1***a* which propagates light therethrough. When the semiconductor photonic element **1** is a semiconductor laser element, the light generated in the active layer **1***a* is repeatedly reflected from a pair of cladding layers (not shown) which hold the active layer **1***a* therebetween, whereby laser light is outputted from the semiconductor photonic element **1**.

[0117] The coating film **6** includes a first layer film **4** having a refractive index n_1 and a thickness d_1, and a second layer film **5** having a refractive index n_2 and a thickness d_2. The first layer film **4** and the second layer film **5** are stacked in the order named on the end surface **1***b* of the semiconductor photonic element **1** including an end surface of the active layer **1***a*.

[0118] When the wavelength of light propagating through the active layer **1***a* is denoted generally by λ, the amount of phase change ϕ_1 of light in the first layer film **4** and the amount of phase change ϕ_2 of light in the second layer film **5** are expressed respectively as:

$$\phi_1 = \frac{2\pi}{\lambda} n_1 d_1 \quad (5a)$$

$$\phi_2 = \frac{2\pi}{\lambda} n_2 d_2 \quad (5b)$$

[0119] The amplitude reflectivity r in the complex plane is expressed as:

$$r = \frac{(m_{11} + m_{12})n_c - (m_{21} + m_{22})}{(m_{11} + m_{12})n_c + (m_{21} + m_{22})} \quad (6)$$

where m_{11}, m_{12}, m_{21} and m_{22} are elements of a characteristic matrix for the coating film **6**, and satisfy the following determinant:

$$\begin{bmatrix} m_{11} & m_{12} \\ m_{21} & m_{22} \end{bmatrix} = \begin{bmatrix} \cos\phi_1 & -\frac{i}{n_1}\sin\phi_1 \\ -in_1\sin\phi_1 & \cos\phi_1 \end{bmatrix} \times \begin{bmatrix} \cos\phi_2 & -\frac{i}{n_2}\sin\phi_2 \\ -in_2\sin\phi_2 & \cos\phi_2 \end{bmatrix} \quad (7a)$$

[0120] Using Equation (7a), Equation (6) is rewritten as:

$$r = \frac{(n_c-1)\cos\phi_1\cos\phi_2 + \left(\frac{n_1}{n_2}-\frac{n_2 n_c}{n_1}\right)\sin\phi_1\sin\phi_2 - i\left\{\left(\frac{n_c}{n_2}-n_2\right)\cos\phi_1\sin\phi_2 + \left(\frac{n_c}{n_1}-n_1\right)\sin\phi_1\cos\phi_2\right\}}{(n_c+1)\cos\phi_1\cos\phi_2 - \left(\frac{n_2 n_c}{n_1}+\frac{n_1}{n_2}\right)\sin\phi_1\sin\phi_2 - i\left\{\left(\frac{n_c}{n_2}+n_2\right)\cos\phi_1\sin\phi_2 + \left(\frac{n_c}{n_1}+n_1\right)\sin\phi_1\cos\phi_2\right\}} \quad (6a)$$

[0121] Equation (6a) defines the amplitude reflectivity r by using the refractive indices n_1 and n_2 and the amounts of phase change ϕ_1 and ϕ_2 for the respective layers of the coating film **6**, and the effective refractive index n_c of the semiconductor photonic element **1**. The amount of phase change ϕ_1 is defined by the thickness d_1, the refractive index n_1 and the wavelength λ of the light propagating through the active layer **1***a* according to Equation (5a). The amount of phase change ϕ_2 is defined by the thickness d_2, the refractive index n_2 and the wavelength λ according to Equation (5b). Therefore, it may be said that Equation (6) defines the amplitude reflectivity r based on the refractive indices n_1 and n_2, the effective refractive index n_c, the thicknesses d_1 and d_2, and the wavelength λ.

[0122] Because the magnitude |r| of the amplitude reflectivity r of the coating film **6** having the power reflectivity $R=R_t$ is equal to $R_t^{1/2}$, the amplitude reflectivity r is positioned on a circle with its center at the origin and with a radius equal to $R_t^{1/2}$. Thus, for designing the coating film **6** having the power reflectivity $R=R_t$ where R_t is the design value of the power reflectivity R, it is necessary to set the position of the amplitude reflectivity r in the complex plan at any position lying on the circle with its center at the origin and with the radius equal to $R_t^{1/2}$. In other words, it is necessary to define the reflection amplitude vector rv as any vector with its initial point at the origin and with a magnitude equal to $R_t^{1/2}$. The design value R_t of the power reflectivity R is referred to hereinafter as a "design reflectivity R_t."

[0123] In accordance with the above, the coating film **6** having the power reflectivity $R=R_t$ is designed by determining the amounts of phase change ϕ_1 and ϕ_2 so that the value of the amplitude reflectivity r in Equation (6a) equals a complex number positioned at any point lying on the circle with its center at the origin and with the radius equal to $R_t^{1/2}$ and then determining the thicknesses d_1 and d_2 of the respective layers of the coating film **6** using Equations (5a) and (5b). A method of determining the thicknesses d_1 and d_2 of the respective layers of the coating film **6** having the power reflectivity $R=R_t$ for the wavelength $\lambda=\lambda_t$ will be described below.

[0124] **FIG. 5** is a flowchart showing a method of designing the thickness of a coating film. As shown in **FIG. 5**, any single point lying on a circle with its center at the origin and with a radius equal to $R_t^{1/2}$ is selected in a complex plane in Step s**1**. In Step s**2**, a complex number positioned at the point selected in Step s**1** is substituted as the value of the amplitude reflectivity r into Equation (6a). In Step s**3**, the refractive indices n_1 and n_2 of the respectively layers of the coating film **6** and the effective refractive index n_c are substituted into Equation (6a). This provides Equation (6a) in which the amounts of phase change ϕ_1 and ϕ_2 are unknowns.

[0125] Next, the left-hand and right-hand sides of Equation (6a) obtained in Step s**3** are decomposed into a real part and an imaginary part, and an equation for the real part and an equation for the imaginary part are formulated in Step s**4**. If the values on the left-hand and right-hand sides of Equation (6a) are, for example, a+ib and c+id respectively, the equation a=b and the equation c=d are formulated. This provides a system of two simultaneous equations with two unknowns. In Step s**5**, the values of the amounts of phase change ϕ_1 and ϕ_2 are found from the system of two simultaneous equations obtained in Step s**4**.

[0126] In Step s**6**, the thicknesses d_1 and d_2 are found by substituting the amounts of phase changes ϕ_1 and ϕ_2 found in Step s**5** into Equations (5a) and (5b) respectively, and further substituting the design value λ_t of the wavelength λ into Equations (5a) and (5b). This determines the thicknesses d_1 and d_2 of the respective layers of the coating film **6**. The design value λ_t of the wavelength λ is referred to hereinafter as a "design wavelength λ_t."

[0127] Thus, the coating film **6** which satisfies the power reflectivity $R=R_t$ for the wavelength $\lambda=\lambda_t$ is designed by substituting the complex number having the magnitude of $R^{t1/2}$ as the value of the amplitude reflectivity r into Equation (6a) and then determining the thicknesses d_1 and d_2 using the equations obtained by the substitution.

[0128] If a real number is employed as the value of the amplitude reflectivity r as disclosed in Japanese Patent Application Laid-Open No. 2004-289108 described above, only a point on the positive real axis or a point on the negative real axis is selectable in Step s**1**. As a result, there are only two pairs of thicknesses d_1 and d_2 determined in Step s**6**. It is hence impossible to ensure a sufficient degree of design flexibility of the thickness of the coating film **6**.

[0129] To solve such a problem, the present invention employs an imaginary number as the value of the amplitude reflectivity r for substitution into Equation (6a) to determine the thickness of each of the layers of the coating film **2** so that the value of the amplitude reflectivity r is an imaginary number. This allows the selection of any point on the circle with its center at the origin and with the radius equal to $R_t^{1/2}$ except the points on the real axis in Step s**1**, thereby to achieve the selection of more than two points. Thus, more complex numbers having the same magnitude can be substituted into Equation (6a) in Step s**2**, and more pairs of thicknesses d_1 and d_2 can be determined in Step s**6**. This improves the design flexibility of the thickness of the coating film **6** to make the coating film **6** having a desired characteristic easy to design.

[0130] First to twentieth preferred embodiments to be described below illustrate the characteristics of coating films designed using a film thickness designing method according to the present invention under various conditions established regarding a layer structure of the coating films and the like.

First Preferred Embodiment

[0131] **FIG. 6** is a side view showing a structure of the semiconductor photonic device provided with a coating film **13** having a six-layer structure on the end surface **1***b* of the semiconductor photonic element **1**. As illustrated in **FIG. 6**,

the coating film **13** according to the first preferred embodiment of the present invention includes: a first layer film **7** having the refractive index n_1 and a thickness Ad_1; a second layer film **8** having the refractive index n_2 and a thickness Ad_2; a third layer film **9** having the refractive index n, and a thickness Bd_1; a fourth layer film **10** having the refractive index n_2 and a thickness Bd_2; a fifth layer film **11** having the refractive index n_1 and a thickness Cd_1; and a sixth layer film **12** having the refractive index n_2 and a thickness Cd_2.

[0132] Each of the first layer film **7**, the third layer film **9** and the fifth layer film **11** is a tantalum oxide (Ta_2O_5) layer, and each of the second layer film **8**, the fourth layer film **10** and the sixth layer film **12** is a silicon oxide (SiO_2) layer. Thus, the coating film **13** according to the first preferred embodiment is composed of two material layers: the tantalum oxide layer and the silicon oxide layer.

[0133] In the first preferred embodiment, the first and second layer films **7** and **8**, the third and fourth layer films **9** and **10**, and the fifth and sixth layer films **11** and **12** constitute unit layer pairs each composed of the tantalum oxide layer and the silicon oxide layer arranged in a stacked relation. In other words, the coating film **13** according to the first preferred embodiment includes three unit layer pairs each composed of the tantalum oxide layer and the silicon oxide layer arranged in a stacked relation. The reference characters A, B and C which determine the thicknesses of the respective layers of the coating film **13** designate parameters individually determined for the respective unit layer pairs and each indicating a contribution ratio of the thickness of a corresponding unit layer pair to the thickness of the entire coating film **13**. The reference characters d_1 and d_2 according to the first preferred embodiment designate basic thicknesses individually determined for the respective material layers. Thus, the first preferred embodiment determines the thicknesses of the respective layers of the coating film **13** by multiplying the basic thicknesses by the parameters indicating the contribution ratios.

[0134] The amounts of phase change for the first to sixth layer films **7** to **12** are designated by $A\phi_1$, $A\phi_2$, $B\phi_1$, $B\phi_2$, $C\phi_1$ and $C\phi_2$, respectively, using Equations (5a) and (5b). The reference characters ϕ_1 and ϕ_2 according to the first preferred embodiment designate the basic amounts of phase change individually determined for the respective material layers. Therefore, the elements m_{11}, m_{12}, m_{21} and m_{22} of a characteristic matrix for the coating film **13** according to the first preferred embodiment satisfy the following determinant:

$$\begin{bmatrix} m_{11} & m_{12} \\ m_{21} & m_{22} \end{bmatrix} = \begin{bmatrix} \cos A\phi_1 & -\frac{i}{n_1}\sin A\phi_1 \\ -in_1\sin A\phi_1 & \cos A\phi_1 \end{bmatrix} \begin{bmatrix} \cos A\phi_2 & -\frac{i}{n_2}\sin A\phi_2 \\ -in_2\sin A\phi_2 & \cos A\phi_2 \end{bmatrix} \times \begin{bmatrix} \cos B\phi_1 & -\frac{i}{n_1}\sin B\phi_1 \\ -in_1\sin B\phi_1 & \cos B\phi_1 \end{bmatrix} \begin{bmatrix} \cos B\phi_2 & -\frac{i}{n_2}\sin B\phi_2 \\ -in_2\sin B\phi_2 & \cos B\phi_2 \end{bmatrix} \times \begin{bmatrix} \cos C\phi_1 & -\frac{i}{n_1}\sin C\phi_1 \\ -in_1\sin C\phi_1 & \cos C\phi_1 \end{bmatrix} \begin{bmatrix} \cos C\phi_2 & -\frac{i}{n_2}\sin C\phi_2 \\ -in_2\sin C\phi_2 & \cos C\phi_2 \end{bmatrix} \quad (7b)$$

[0135] For designing the thickness of the coating film **13** so that the value of the amplitude reflectivity r is an imaginary number, the first preferred embodiment previously determines the values of the parameters A to C, and executes Steps s**1** to s**5** using Equations (6) and (7b) described above to determine the values of the basic amounts of phase change ϕ_1 and ϕ_2. Thereafter, Step s**6** is executed to determine the values of the basic thicknesses d_1 and d_2, and the thicknesses of the respective layers of the coating film **13** are determined using the previously determined values of the parameters A to C and the values of the basic thicknesses d_1 and d_2 determined in Step s**6**. If the designed characteristic of the coating film **13** is insufficient, the basic thicknesses d_1 and d_2 are determined again by changing the parameters A to C, and the thicknesses of the respective layers of the coating film **13** are designed again.

[0136] In the first preferred embodiment, the effective refractive index n_e of the semiconductor photonic element **1** is "3.37." The refractive index n_1 is "2.057" which is greater than $n_e^{1/2}$ (=1.84), and the refractive index n_2 is "1.480" which is less than $n_e^{1/2}$. The design wavelength λ_t is 980 nm.

[0137] For designing the thickness of the coating film **13** having the power reflectivity R of 4% (R_t=4%) when the wavelength λ equals the design wavelength of 980 nm under the above-mentioned conditions, a point which provides a phase angle θ of 60 degrees is selected, for example, in Step s**1** so that the reflection amplitude vector rv is located in the first quadrant (or the upper right quadrant) of the complex plane. Then, because the magnitude of the complex number at the selected point is 0.2, the values of the real and imaginary parts r_r and r_i of the complex number inputted as the value of the amplitude reflectivity r are "+0.1" and "+0.17320508," respectively, in Step s**2**.

[0138] When A=1.22, B=1.84 and C=2.19 are set, the basic amounts of phase change ϕ_1 and ϕ_2 determined in Step s**5** are "1.3449" and "0.463002," respectively. Accordingly, the thicknesses of the first to sixth layer films **7** to **12** determined in Step s**6** are 124.41 nm, 59.53 nm, 187.64 nm, 89.78 nm, 223.33 nm and 106.86 nm, respectively.

[0139] **FIG. 7** shows the wavelength dependence of the power reflectivity R of the coating film **13** thus designed, that is, how the power reflectivity R changes as the wavelength λ is hypothetically changed. As illustrated in **FIG. 7**, the power reflectivity R is 4% when the wavelength λ equals the design wavelength of 980 nm. A wavelength band for which the power reflectivity R is approximately equal to the design reflectivity of 4% is wide. The power reflectivity R falls within a range from 3.3% to 6.0% for the wavelength λ ranging from 833 nm to 1078 nm.

[0140] When the allowable range of the power reflectivity R (referred to hereinafter as an "allowable reflectivity

range") is, for example, ±2% from the design reflectivity of 4%, the wavelength band for which the power reflectivity R falls within the allowable reflectivity range is also from 833 nm to 1078 nm, to provide a wavelength bandwidth W of 245 nm. The center wavelength λ_c of the wavelength band is 956 nm. The value obtained by dividing the wavelength bandwidth W by the center wavelength λ_c is approximately 0.256, which is a measure of the extent of the wavelength band. This value is greater than 0.06, and is also sufficiently greater than that obtained when the above-mentioned coating film **2** having the characteristic indicated by the curve **103** of **FIG. 3** is provided on the end surface **1***b* of the semiconductor photonic element **1**. Therefore, it may be said that the wavelength band for which the power reflectivity R falls within the allowable reflectivity range is a wide band.

[0141] If the value of the center wavelength λ_c has a decimal part, the value of the center wavelength λ_c is herein rounded to the nearest whole number. The same is true for a value t_r to be described later which is a quarter of the center wavelength λ_c.

[0142] Because the thicknesses of the first to sixth layer films **7** to **12** take on the above-mentioned values, the optical thickness t of the coating film **13**, i.e. the sum of the products of the refractive indices and thicknesses of the respective layers of the coating film **13**, is 1480.41 nm. This value is approximately 6.19 times the value t_r (239 nm) which is a quarter of the center wavelength λ_c, and is sufficiently greater than 3 $\lambda_c/4$. Thus, the coating film **13** is a very thick film. This improves heat dissipation characteristics at the end surface **1***b* of the semiconductor photonic element **1** to suppress the increase in temperature of the end surface **1***b*.

[0143] The semiconductor photonic device shown in **FIG. 2** will be considered for comparison with the semiconductor photonic device of the first preferred embodiment. For the semiconductor photonic device shown in **FIG. 2**, the power reflectivity R takes on a relative minimum value of 4% for the wavelength λ equal to λ_c (956 nm) when the coating film **2** having a refractive index n_f of "1.4989" and a thickness d_f of five times 159.45 nm, i.e. five times $\lambda_c/(4n_f)$, is provided on the end surface **1***b* of the semiconductor photonic element **1**. **FIG. 8** shows the wavelength dependence of the power reflectivity R in this case. As illustrated in **FIG. 8**, the wavelength band for which the power reflectivity R falls within ±2% from the design reflectivity of 4% is from 928 nm to 986 nm, to provide a wavelength bandwidth W_r of 58 nm.

[0144] The above-mentioned value "1.4989" of the refractive index n_f is obtained by substituting R_t=0.04 and n_c=3.37 into

$$R_t=((n_c-n_f^2)/(n_c+n_f^2))^2 \quad (8)$$

[0145] As described above, the wavelength bandwidth W (245 nm) for the coating film **13** of the first preferred embodiment is greater than the wavelength bandwidth W_r (58 nm) for the coating film **2** shown in **FIG. 2**. It may be said that the wavelength band for the coating film **13** is a wide band.

[0146] In general, the wavelength λ of light propagating through the active layer **1***a* is sometimes varied from the design wavelength λ_t depending on temperature change and the like. To obtain stable characteristics of the semiconductor photonic device even if the wavelength λ is varied, it is desirable that the center wavelength λ_c of the wavelength band for which the power reflectivity R falls within the allowable reflectivity range be equal to or close to the design wavelength λ_t. For example, the center wavelength λ_c takes on a value close to the design wavelength λ_t of 980 nm when the thickness of the coating film **13** is determined using the basic thicknesses d_1 and d_2 obtained by setting the basic amounts of phase change ϕ_1 and ϕ_2 at "1.3449" and "0.463002," respectively, in a similar manner to the above instance and substituting 1006 nm, rather than the design wavelength λ_t, for λ in Equations (5a) and (5b). **FIG. 9** shows the wavelength dependence of the power reflectivity R in this case.

[0147] As illustrated in **FIG. 9**, the power reflectivity R falls within a range from 3.3% to 6.0% for the wavelength λ ranging from 855 nm to 1107 nm. The wavelength band for which the power reflectivity R falls within ±2% from the design reflectivity of 4% is also from 855 nm to 1107 nm, to provide a wavelength bandwidth W of 252 nm. The center wavelength λ_c of the wavelength band is 981 nm, which is very close to the design wavelength of 980 nm. The value obtained by dividing the wavelength bandwidth W (252 nm) by the center wavelength λ_c (981 nm) is approximately 0.257, which is greater than 0.06 and shows that the wavelength band for which the power reflectivity R falls within the allowable reflectivity range is a wide band.

[0148] In this case, the thicknesses of the first to sixth layer films **7** to **12** of the coating film **13** are 127.71 nm, 61.11 nm, 192.63 nm, 92.16 nm, 229.26 nm and 109.69 nm, respectively. The optical thickness t of the coating film **13**, i.e. the sum of the products of the refractive indices and thicknesses of the respective layers of the coating film **13**, is 1519.69 nm. This value is approximately 6.20 times the value t_r (245 nm) which is a quarter of the center wavelength λ_c. Thus, the coating film **13** is a very thick film. This improves heat dissipation characteristics at the end surface **1***b* of the semiconductor photonic element **1** to suppress the increase in temperature of the end surface **1***b*.

[0149] The semiconductor photonic device shown in **FIG. 2** will be considered for comparison with the semiconductor photonic device including the coating film **13** having the characteristics shown in **FIG. 9**. For the semiconductor photonic device shown in **FIG. 2**, the power reflectivity R takes on a relative minimum value of 4% for the wavelength λ equal to ϕ_c (981 nm) when the coating film **2** having the above-mentioned refractive index n_f of "1.4989" and a thickness d_f of five times 163.62 nm, i.e. five times $\lambda_c/(4n_f)$, is provided on the end surface **1***b* of the semiconductor photonic element **1**. **FIG. 10** shows the wavelength dependence of the power reflectivity R in this case. As illustrated in **FIG. 10**, the wavelength band for which the power reflectivity R falls within ±2% from the design reflectivity of 4% is from 951 nm to 1011 nm, to provide a wavelength bandwidth W_r of 60 nm.

[0150] Thus, even when the center wavelength λ_c is made closer to the design wavelength λ_t, the wavelength bandwidth W (252 nm) for the coating film **13** is greater than the wavelength bandwidth W_r (60 nm) for the coating film **2** shown in **FIG. 2**.

[0151] Although the center wavelength λ_c is close to the design wavelength λ_t in the above instance, the center wavelength λ_c may be made exactly equal to the design

wavelength λ_t by adjusting the values of the parameters A to C or the value substituted for λ in Equations (5a) and (5b).

[0152] If the coating film **13** is absent on the end surface **1***b* of the semiconductor photonic element **1**, the value of the power reflectivity R on the end surface **1***b* is approximately 29.4%. This value is defined by the effective refractive index n_c (3.37) of the semiconductor photonic element **1** and a refractive index in the free space **3**, and is calculated as $((3.37-1)/(3.37+1))^2$ assuming that the refractive index in the free space **3** is "1."

[0153] As illustrated in **FIG. 7**, the power reflectivity R is 4% when the wavelength λ is equal to the design wavelength λ_t. Therefore, when the wavelength λ takes on the same value as the design wavelength λ_t, the power reflectivity R for the semiconductor photonic device of the first preferred embodiment is lower than the power reflectivity R on the end surface **1***b* obtained when the coating film **13** is absent on the end surface **1***b* of the semiconductor photonic element **1**.

Second Preferred Embodiment

[0154] **FIG. 11** shows the wavelength dependence of the power reflectivity R of the coating film **13** in the semiconductor photonic device according to the second preferred embodiment of the present invention. The semiconductor photonic device according to the second preferred embodiment is similar to the semiconductor photonic device according to the first preferred embodiment except that an alumina (Al_2O_3) layer is employed in place of the silicon oxide layer as the material layer for the second, fourth and sixth layer films **8**, **10** and **12** of the coating film **13**. Thus, the coating film **13** according to the second preferred embodiment is composed of two material layers: the tantalum oxide layer and the alumina layer.

[0155] Because the alumina layer is employed in place of the silicon oxide layer, the refractive index n_2 according to the second preferred embodiment is "1.620." The design wavelength λ_1 is set at 808 nm according to the second preferred embodiment.

[0156] For designing the thickness of the coating film **13** having the power reflectivity R of 4% (R_t=4%) when the wavelength λ equals the design wavelength of 808 nm in the semiconductor photonic device as mentioned above, a point which provides a phase angle θ of 150 degrees is selected, for example, in Step s**1** so that the reflection amplitude vector rv is located in the second quadrant (or the upper left quadrant) of the complex plane. Then, the values of the real and imaginary parts r_r and r_i of the complex number inputted as the value of the amplitude reflectivity r are "−0.17320508" and "+0.1," respectively, in Step s**2**.

[0157] When A=2.15, B=2.00 and C=2.00 are set, the basic amounts of phase change ϕ_1 and ϕ_2 determined in Step s**5** are "0.587068" and "1.04832," respectively. Accordingly, the thicknesses of the first to sixth layer films **7** to **12** determined in Step s**6** are 78.91 nm, 178.92 nm, 73.40 nm, 166.43 nm, 73.40 nm and 166.43 nm, respectively.

[0158] **FIG. 11** shows the wavelength dependence of the power reflectivity R of the coating film **13** thus designed. As illustrated in **FIG. 11**, the power reflectivity R is 4% when the wavelength λ equals the design wavelength of 808 nm. The wavelength band for which the power reflectivity R is approximately equal to the design reflectivity of 4% is wide. The power reflectivity R falls within a range from 3.6% to 6.0% for the wavelength λ ranging from 779 nm to 962 nm.

[0159] When the allowable reflectivity range is, for example, ±2% from the design reflectivity of 4%, the wavelength band for which the power reflectivity R falls within the allowable reflectivity range is also from 779 nm to 962 nm, to provide a wavelength bandwidth W of 183 nm. The center wavelength λ_c of the wavelength band is 871 nm. The value obtained by dividing the wavelength bandwidth W by the center wavelength λ_c is approximately 0.210, which is greater than 0.06. It may be said that the wavelength band for which the power reflectivity R falls within the allowable reflectivity range is a wide band.

[0160] Because the thicknesses of the first to sixth layer films **7** to **12** take on the above-mentioned values, the optical thickness t of the coating film **13**, i.e. the sum of the products of the refractive indices and thicknesses of the respective layers of the coating film **13**, is 1293.37 nm. This value is approximately 5.93 times the value t_r (218 nm) which is a quarter of the center wavelength λ_c, and is sufficiently greater than 3 $\lambda_c/4$. Thus, the coating film **13** is a very thick film. This improves heat dissipation characteristics at the end surface **1***b* of the semiconductor photonic element **1** to suppress the increase in temperature of the end surface **1***b*.

[0161] The semiconductor photonic device shown in **FIG. 2** will be considered for comparison. For the semiconductor photonic device shown in **FIG. 2**, the power reflectivity R takes on a relative minimum value of 4% for the wavelength λ equal to λ_c (871 nm) when the coating film **2** having the refractive index n_f of "1.4989" as in the first preferred embodiment and a thickness d_f of five times 145.27 nm, i.e. five times $\lambda_c/(4n_f)$, is provided on the end surface **1***b* of the semiconductor photonic element **1**. **FIG. 12** shows the wavelength dependence of the power reflectivity R in this case. As illustrated in **FIG. 12**, the wavelength band for which the power reflectivity R falls within ±2% from the design reflectivity of 4% is from 845 nm to 899 nm, to provide a wavelength bandwidth W_r of 54 nm.

[0162] Thus, the wavelength bandwidth W (183 nm) for the coating film **13** of the second preferred embodiment is greater than the wavelength bandwidth W_r (54 nm) for the coating film **2** shown in **FIG. 2**.

[0163] As mentioned above, because the wavelength λ of light propagating through the active layer **1***a* is sometimes varied, it is desirable that the center wavelength λ_c of the wavelength band for which the power reflectivity R falls within the allowable reflectivity range be equal to or close to the design wavelength λ_t. For example, the center wavelength λ_c takes on a value close to the design wavelength λ_t of 808 nm when the thickness of the coating film **13** is determined using the basic thicknesses d_1 and d_2 obtained by setting the basic amounts of phase change ϕ_1 and ϕ_2 at "0.587068" and "1.04832," respectively, in a similar manner to the above instance and substituting 751 nm, rather than the design wavelength λ_t, for λ in Equations (5a) and (5b). **FIG. 13** shows the wavelength dependence of the power reflectivity R in this case.

[0164] As illustrated in **FIG. 13**, the power reflectivity R falls within a range from 3.3% to 6.0% for the wavelength λ ranging from 724 nm to 894 nm. The wavelength band for

which the power reflectivity R falls within ±2% from the design reflectivity of 4% is also from 724 nm to 894 nm, to provide a wavelength bandwidth W of 170 nm. The center wavelength λ_c of the wavelength band is 809 nm, which is very close to the design wavelength of 808 nm. The value obtained by dividing the wavelength bandwidth W (170 nm) by the center wavelength λ_c (809 nm) is approximately 0.210, which is greater than 0.06 and shows that the wavelength band for which the power reflectivity R falls within the allowable reflectivity range is a wide band.

[0165] In this case, the thicknesses of the first to sixth layer films **7** to **12** of the coating film **13** are 73.34 nm, 166.29 nm, 68.23 nm, 154.69 nm, 68.23 nm and 154.69 nm, respectively. The optical thickness t of the coating film **13**, i.e. the sum of the products of the refractive indices and thicknesses of the respective layers of the coating film **13**, is 1202.14 nm. This value is approximately 5.95 times the value t_r (202 nm) which is a quarter of the center wavelength λ_c. Thus, the coating film **13** is a very thick film.

[0166] The semiconductor photonic device shown in **FIG. 2** will be considered for comparison. For the semiconductor photonic device shown in **FIG. 2**, the power reflectivity R is 4% for the wavelength λ equal to λ_c (809 nm) when the coating film **2** having the above-mentioned refractive index n_f of "1.4989" and a thickness d_f of five times 134.93 nm, i.e. five times $\lambda_c/(4n_f)$, is provided on the end surface **1***b* of the semiconductor photonic element **1**. **FIG. 14** shows the wavelength dependence of the power reflectivity R in this case. As illustrated in **FIG. 14**, the wavelength band for which the power reflectivity R falls within ±2% from the design reflectivity of 4% is from 784 nm to 834 nm, to provide a wavelength bandwidth W_r of 50 nm.

[0167] Thus, even when the center wavelength λ_c is made closer to the design wavelength λ_t, the wavelength bandwidth W (170 nm) for the coating film **13** is greater than the wavelength bandwidth W_r (50 nm) for the coating film **2** shown in **FIG. 2**.

[0168] Although the center wavelength λ_c is close to the design wavelength λ_t in the above instance, the center wavelength λ_c may be made exactly equal to the design wavelength λ_t by adjusting the values of the parameters A to C or the value substituted for λ in Equations (5a) and (5b), as in the first preferred embodiment.

Third Preferred Embodiment

[0169] **FIG. 15** is a side view showing a structure of the semiconductor photonic device according to the third preferred embodiment of the present invention. A coating film **21** having a seven-layer structure is provided on the end surface **1***b* of the semiconductor photonic element **1** in the third preferred embodiment.

[0170] As illustrated in **FIG. 15**, the coating film **21** according to the third preferred embodiment of the present invention includes: a first layer film **14** having the refractive index n_2 and a thickness Od_2; a second layer film **15** having the refractive index n_1 and the thickness Ad_1; a third layer film **16** having the refractive index n_2 and the thickness Ad_2; a fourth layer film **17** having the refractive index n_1 and the thickness Bd_1; a fifth layer film **18** having the refractive index n_2 and the thickness Bd_2; a sixth layer film **19** having the refractive index n_1 and the thickness Cd_1; and a seventh layer film **20** having the refractive index n_2 and the thickness Cd_2.

[0171] Each of the first layer film **14**, the third layer film **16**, the fifth layer film **18** and the seventh layer film **20** is an alumina layer, and each of the second layer film **15**, the fourth layer film **17** and the sixth layer film **19** is a tantalum oxide layer. Thus, the coating film **21** according to the third preferred embodiment is composed of two material layers: the alumina layer and the tantalum oxide layer.

[0172] In the third preferred embodiment, the second and third layer films **15** and **16**, the fourth and fifth layer films **17** and **18**, and the sixth and seventh layer films **19** and **20** constitute unit layer pairs each composed of the alumina layer and the tantalum oxide layer arranged in a stacked relation. The reference characters A, B and C which determine the thicknesses of the second to seventh layer films **15** to **20** of the coating film **21** designate parameters individually determined for the respective unit layer pairs and each indicating a contribution ratio of the thickness of a corresponding unit layer pair to the thickness of the entire coating film **21**. The reference character O which determines the thickness of the first layer film **14** designates a parameter indicating a contribution ratio of the thickness of the first layer film **14** to the thickness of the entire coating film **21**. The reference characters d_1 and d_2 according to the third preferred embodiment also designate basic thicknesses individually determined for the respective material layers.

[0173] The amounts of phase change for the first to seventh layer films **14** to **20** are designated by $O\phi_2$, $A\phi_1$, $A\phi_2$, $B\phi_1$, $B\phi_2$, $C\phi_1$ and $C\phi_2$, respectively, using Equations (5a) and (5b). Therefore, the elements m_{11}, m_{12}, m_{21} and m_{22} of a characteristic matrix for the coating film **21** according to the third preferred embodiment satisfy the following determinant:

$$\begin{bmatrix} m_{11} & m_{12} \\ m_{21} & m_{22} \end{bmatrix} = \begin{bmatrix} \cos O\phi_2 & -\frac{i}{n_2}\sin O\phi_2 \\ -in_2\sin O\phi_2 & \cos O\phi_2 \end{bmatrix} \times \tag{7c}$$

$$\begin{bmatrix} \cos A\phi_1 & -\frac{i}{n_1}\sin A\phi_1 \\ -in_1\sin A\phi_1 & \cos A\phi_1 \end{bmatrix} \begin{bmatrix} \cos A\phi_2 & -\frac{i}{n_2}\sin A\phi_2 \\ -in_2\sin A\phi_2 & \cos A\phi_2 \end{bmatrix} \times$$

$$\begin{bmatrix} \cos B\phi_1 & -\frac{i}{n_1}\sin B\phi_1 \\ -in_1\sin B\phi_1 & \cos B\phi_1 \end{bmatrix} \begin{bmatrix} \cos B\phi_2 & -\frac{i}{n_2}\sin B\phi_2 \\ -in_2\sin B\phi_2 & \cos B\phi_2 \end{bmatrix} \times$$

-continued

$$\begin{bmatrix} \cos C\phi_1 & -\frac{i}{n_1}\sin C\phi_1 \\ -in_1\sin C\phi_1 & \cos C\phi_1 \end{bmatrix}\begin{bmatrix} \cos C\phi_2 & -\frac{i}{n_2}\sin C\phi_2 \\ -in_2\sin C\phi_2 & \cos C\phi_2 \end{bmatrix}$$

[0174] For designing the thickness of the coating film **21** so that the value of the amplitude reflectivity r is an imaginary number, the third preferred embodiment previously determines the values of the parameters A, B, C and O, and executes Steps s**1** to s**5** using Equations (6) and (7c) described above to determine the values of the basic amounts of phase change ϕ_1 and ϕ_2. Thereafter, Step s**6** is executed to determine the values of the basic thicknesses d_1 and d_2, and the thicknesses of the respective layers of the coating film **21** are determined using the previously determined values of the parameters A, B, C and O and the values of the basic thicknesses d_1 and d_2 determined in Step s**6**. If the designed characteristic of the coating film **21** is insufficient, the basic thicknesses d_1 and d_2 are determined again by changing the parameters A, B, C and O, and the thickness of the coating film **21** is designed again.

[0175] In the third preferred embodiment, the effective refractive index n_c of the semiconductor photonic element **1** is "3.37." The refractive indices n_1 and n_2 are "2.057" and "1.620," respectively. The design wavelength λ_t is 1310 nm.

[0176] For designing the thickness of the coating film **21** having the power reflectivity R of 4% (R_t=4%) when the wavelength λ equals the design wavelength of 1310 nm under the above-mentioned conditions, a point which provides a phase angle θ of 225 degrees is selected, for example, in Step s**1** so that the reflection amplitude vector rv is located in the third quadrant (or the lower left quadrant) of the complex plane. Then, the values of the real and imaginary parts r_r and r_i of the complex number inputted as the value of the amplitude reflectivity r are "−0.141421356" and "−0.141421356," respectively, in Step s**2**.

[0177] When O=0.10, A=1.80, B=2.00 and C=2.00 are set, the basic amounts of phase change ϕ_1 and ϕ_2 determined in Step s**5** are "0.992102" and "0.536659," respectively. Accordingly, the thicknesses of the first to seventh layer films **14** to **20** determined in Step s**6** are 6.91 nm, 181.00 nm, 124.32 nm, 201.12 nm, 138.14 nm, 201.12 nm and 138.14 nm, respectively.

[0178] **FIG. 16** shows the wavelength dependence of the power reflectivity R of the coating film **21** thus designed. As illustrated in **FIG. 16**, the power reflectivity R is 4% when the wavelength λ equals the design wavelength of 1310 nm. A wavelength band for which the power reflectivity R is approximately equal to the design reflectivity of 4% is wide. The power reflectivity R falls within a range from 4.0% to 6.0% for the wavelength λ ranging from 1116 nm to 1383 nm.

[0179] When the allowable reflectivity range is, for example, ±2% from the design reflectivity of 4%, the wavelength band for which the power reflectivity R falls within the allowable reflectivity range is also from 1116 nm to 1383 nm, to provide a wavelength bandwidth W of 267 nm. The center wavelength λ_c of the wavelength band is 1250 nm. The value obtained by dividing the wavelength bandwidth W by the center wavelength λ_c is approximately 0.216, which is greater than 0.06. It may be said that the wavelength band for which the power reflectivity R falls within the allowable reflectivity range is a wide band.

[0180] Because the thicknesses of the first to seventh layer films **14** to **20** take on the above-mentioned values, the optical thickness t of the coating film **21**, i.e. the sum of the products of the refractive indices and thicknesses of the respective layers of the coating film **21**, is 1859.89 nm. This value is approximately 5.94 times the value t_r (313 nm) which is a quarter of the center wavelength λ_c. Thus, the coating film **21** is a very thick film. This improves heat dissipation characteristics at the end surface **1***b* of the semiconductor photonic element **1** to suppress the increase in temperature of the end surface **1***b*.

[0181] The semiconductor photonic device shown in **FIG. 2** will be considered for comparison. For the semiconductor photonic device shown in **FIG. 2**, the power reflectivity R is 4% for the wavelength λ equal to λ_c (1250 nm) when the coating film **2** having the refractive index n_f of "1.4989" as in the first preferred embodiment and a thickness d_f of five times 208.49 nm, i.e. five times $\lambda_c/(4n_f)$, is provided on the end surface **1***b* of the semiconductor photonic element **1**. **FIG. 17** shows the wavelength dependence of the power reflectivity R in this case. As illustrated in **FIG. 17**, the wavelength band for which the power reflectivity R falls within ±2% from the design reflectivity of 4% is from 1213 nm to 1290 nm, to provide a wavelength bandwidth W_r of 77 nm.

[0182] Thus, the wavelength bandwidth W (267 nm) for the coating film **21** of the third preferred embodiment is greater than the wavelength bandwidth W_r (77 nm) for the coating film **2** shown in **FIG. 2**.

[0183] Because the wavelength λ of light propagating through the active layer **1***a* is sometimes varied, it is desirable that the center wavelength λ_c of the wavelength band for which the power reflectivity R falls within the allowable reflectivity range be equal to or close to the design wavelength λ_t. For example, the center wavelength λ_c takes on a value close to the design wavelength λ_t of 1310 nm when the thickness of the coating film **21** is determined using the basic thicknesses d_1 and d_2 obtained by setting the basic amounts of phase change ϕ_1 and ϕ_2 at "0.992102" and "0.536659," respectively, in a similar manner to the above instance and substituting 1374 nm, rather than the design wavelength λ_t, for λ in Equations (5a) and (5b). **FIG. 18** shows the wavelength dependence of the power reflectivity R in this case.

[0184] As illustrated in **FIG. 18**, the power reflectivity R falls within a range from 4.0% to 6.0% for the wavelength λ ranging from 1170 nm to 1451 nm. The wavelength band for which the power reflectivity R falls within ±2% from the design reflectivity of 4% is also from 1170 nm to 1451 nm, to provide a wavelength bandwidth W of 281 nm. The center

wavelength λ_c of the wavelength band is 1311 nm, which is very close to the design wavelength of 1310 nm. The value obtained by dividing the wavelength bandwidth W (281 nm) by the center wavelength λ_c (1311 nm) is approximately 0.214, which is greater than 0.06 and shows that the wavelength band for which the power reflectivity R falls within the allowable reflectivity range is a wide band.

[0185] In this case, the thicknesses of the first to seventh layer films **14** to **20** of the coating film **21** are 7.24 nm, 189.85 nm, 130.40 nm, 210.94 nm, 144.88 nm, 210.94 nm and 144.88 nm, respectively. The optical thickness t of the coating film **21** is 1950.72 nm. This value is approximately 5.95 times the value t_r (328 nm) which is a quarter of the center wavelength λ_c. Thus, the coating film **21** is a very thick film.

[0186] The semiconductor photonic device shown in **FIG. 2** will be considered for comparison. For the semiconductor photonic device shown in **FIG. 2**, the power reflectivity R is 4% for the wavelength λ equal to λ_c (1311 nm) when the coating film **2** having the above-mentioned refractive index n_f of "1.4989" and a thickness d_f of five times 218.66 nm, i.e. five times $\lambda_c/(4n_f)$, is provided on the end surface **1***b* of the semiconductor photonic element **1**. **FIG. 19** shows the wavelength dependence of the power reflectivity R in this case. As illustrated in **FIG. 19**, the wavelength band for which the power reflectivity R falls within ±2% from the design reflectivity of 4% is from 1271 nm to 1352 nm, to provide a wavelength bandwidth W_r of 81 nm.

[0187] Thus, even when the center wavelength λ_c is made closer to the design wavelength λ_t, the wavelength bandwidth W (281 nm) for the coating film **21** is greater than the wavelength bandwidth W_r (81 nm) for the coating film **2** shown in **FIG. 2**.

[0188] Although the center wavelength λ_c is close to the design wavelength λ_t in the above instance, the center wavelength λ_c may be made exactly equal to the design wavelength λ_t by adjusting the values of the parameters A, B, C and O or the value substituted for λ in Equations (5a) and (5b), as in the first and second preferred embodiments.

Fourth Preferred Embodiment

[0189] **FIG. 20** is a side view showing a structure of the semiconductor photonic device according to the fourth preferred embodiment of the present invention. A coating film **29** having a seven-layer structure is provided on the end surface **1***b* of the semiconductor photonic element **1** in the fourth preferred embodiment.

[0190] As illustrated in **FIG. 20**, the coating film **29** according to the fourth preferred embodiment of the present invention includes: a first layer film **22** having a refractive index n_3 and a thickness d_3; a second layer film **23** having the refractive index n_1 and the thickness Ad_1; a third layer film **24** having the refractive index n_2 and the thickness Ad_2; a fourth layer film **25** having the refractive index n_1 and the thickness Bd_1; a fifth layer film **26** having the refractive index n_2 and the thickness Bd_2; a sixth layer film **27** having the refractive index n_1 and the thickness Cd_1; and a seventh layer film **28** having the refractive index n_2 and the thickness Cd_2.

[0191] The first layer film **22** is an aluminum nitride layer. Each of the second layer film **23**, the fourth layer film **25** and the sixth layer film **27** is a tantalum oxide layer. Each of the third layer film **24**, the fifth layer film **26** and the seventh layer film **28** is an alumina layer. Thus, the coating film **29** according to the fourth preferred embodiment is composed of three material layers: the aluminum nitride layer, the tantalum oxide layer, and the alumina layer.

[0192] In the fourth preferred embodiment, the second and third layer films **23** and **24**, the fourth and fifth layer films **25** and **26**, and the sixth and seventh layer films **27** and **28** constitute unit layer pairs each composed of the tantalum oxide layer and the alumina layer arranged in a stacked relation. The reference characters A, B and C which determine the thicknesses of the second to seventh layer films **23** to **28** of the coating film **29** designate parameters individually determined for the respective unit layer pairs and each indicating a contribution ratio of the thickness of a corresponding unit layer pair to the thickness of the entire coating film **29**. The reference characters d_1 and d_2 according to the fourth preferred embodiment also designate basic thicknesses individually determined for the respective material layers.

[0193] The amounts of phase change for the second to seventh layer films **23** to **28** are designated by $A\phi_1$, $A\phi_2$, $B\phi_1$, $B\phi_2$, $C\phi_1$ and $C\phi_2$, respectively, using Equations (5a) and (5b). The amount of phase change ϕ_3 for the first layer film **22** is expressed by:

$$\phi_3 = \frac{2\pi}{\lambda} n_3 d_3 \tag{9}$$

[0194] Therefore, the elements m_{11}, m_{12}, m_{21} and m_{22} of a characteristic matrix for the coating film **29** according to the fourth preferred embodiment satisfy the following determinant:

$$\begin{bmatrix} m_{11} & m_{12} \\ m_{21} & m_{22} \end{bmatrix} = \begin{bmatrix} \cos\phi_3 & -\frac{i}{n_3}\sin\phi_3 \\ -in_3\sin\phi_3 & \cos\phi_3 \end{bmatrix} \times \begin{bmatrix} \cos A\phi_1 & -\frac{i}{n_1}\sin A\phi_1 \\ -in_1\sin A\phi_1 & \cos A\phi_1 \end{bmatrix} \begin{bmatrix} \cos A\phi_2 & -\frac{i}{n_2}\sin A\phi_2 \\ -in_2\sin A\phi_2 & \cos A\phi_2 \end{bmatrix} \times \tag{7d}$$

-continued

$$\begin{bmatrix} \cos B\phi_1 & -\frac{i}{n_1}\sin B\phi_1 \\ -in_1\sin B\phi_1 & \cos B\phi_1 \end{bmatrix}\begin{bmatrix} \cos B\phi_2 & -\frac{i}{n_2}\sin B\phi_2 \\ -in_2\sin B\phi_2 & \cos B\phi_2 \end{bmatrix}\times$$

$$\begin{bmatrix} \cos C\phi_1 & -\frac{i}{n_1}\sin C\phi_1 \\ -in_1\sin C\phi_1 & \cos C\phi_1 \end{bmatrix}\begin{bmatrix} \cos C\phi_2 & -\frac{i}{n_2}\sin C\phi_2 \\ -in_2\sin C\phi_2 & \cos C\phi_2 \end{bmatrix}$$

[0195] For designing the thickness of the coating film **29** so that the value of the amplitude reflectivity r is an imaginary number, the fourth preferred embodiment previously determines the values of the parameters A, B and C, and previously determines the thickness d_3 of the first layer film **22**, thereby to handle the value of the amount of phase change ϕ_3 as a known value. Steps s**1** to s**5** are executed using Equations (6) and (7d) described above to determine the values of the basic amounts of phase change ϕ_1 and ϕ_2. Thereafter, Step s**6** is executed to determine the values of the basic thicknesses d_1 and d_2, and the thicknesses of the second to seventh layer films **23** to **28** of the coating film **29** are determined using the previously determined values of the parameters A, B and C and the values of the basic thicknesses d_1 and d_2 determined in Step s**6**. If the designed characteristic of the coating film **29** is insufficient, the basic thicknesses d_1 and d_2 are determined again by changing the parameters A, B and C or the thickness d_3, and the thickness of the coating film **29** is designed again.

[0196] The method of determining the thickness when the coating film is composed of the three material layers is described above. However, if the coating film is composed of four or more material layers, this method is capable of determining the thicknesses of the respective layers of the coating film in a similar manner to the fourth preferred embodiment by handling the thicknesses of some of the plurality of layers of the coating film which are included in the first and second material layers as unknown values while handling the thicknesses of the remaining layers which are included in the third and its subsequent material layers as known values.

[0197] In the fourth preferred embodiment, the effective refractive index n_c of the semiconductor photonic element **1** is "3.37." The refractive indices n_1 to n_3 are "2.057,""1.620" and "2.072," respectively. The design wavelength λ_t is 1550 nm.

[0198] For designing the thicknesses of the respective layers of the coating film **29** having the power reflectivity R of 4% when the wavelength λ equals the design wavelength of 1550 nm under the above-mentioned conditions, a point which provides a phase angle θ of 330 degrees is selected, for example, in Step s**1** so that the reflection amplitude vector rv is located in the fourth quadrant (or the lower right quadrant) of the complex plane. Then, the values of the real and imaginary parts r_r and r_i of the complex number inputted as the value of the amplitude reflectivity r are "+0.17320508" and "−0.1," respectively, in Step s**2**.

[0199] When A=1.69, B=1.65, C=2.08 and d_3=7.5 nm are set, the basic amounts of phase change ϕ_1 and ϕ_2 determined in Step s**5** are "1.33612" and "0.478116," respectively. Accordingly, the thicknesses of the second to seventh layer films **23** to **28** determined in Step s**6** are 270.80 nm, 123.04 nm, 264.39 nm, 120.13 nm, 333.29 nm and 151.44 nm, respectively.

[0200] **FIG. 21** shows the wavelength dependence of the power reflectivity R of the coating film **29** thus designed. As illustrated in **FIG. 21**, the power reflectivity R is 4% when the wavelength λ equals the design wavelength of 1550 nm. A wavelength band for which the power reflectivity R is approximately equal to the design reflectivity of 4% is wide. The power reflectivity R falls within a range from 2.1% to 6.0% for the wavelength λ ranging from 1420 nm to 1898 nm.

[0201] When the allowable reflectivity range is, for example, ±2% from the design reflectivity of 4%, the wavelength band for which the power reflectivity R falls within the allowable reflectivity range is also from 1420 nm to 1898 nm, to provide a wavelength bandwidth W of 478 nm. The center wavelength λ_c of the wavelength band is 1659 nm. The value obtained by dividing the wavelength bandwidth W by the center wavelength λ_c is approximately 0.288, which is greater than 0.06. It may be said that the wavelength band for which the power reflectivity R falls within the allowable reflectivity range is a wide band.

[0202] Because the thicknesses of the first to seventh layer films **22** to **28** take on the above-mentioned values, the optical thickness t of the coating film **29**, i.e. the sum of the products of the refractive indices and thicknesses of the respective layers of the coating film **29**, is 2441.27 nm. This value is approximately 5.88 times the value t_r (415 nm) which is a quarter of the center wavelength λ_c. Thus, the coating film **29** is a very thick film. This improves heat dissipation characteristics at the end surface **1***b* of the semiconductor photonic element **1** to suppress the increase in temperature of the end surface **1***b*.

[0203] The semiconductor photonic device shown in **FIG. 2** will be considered for comparison. For the semiconductor photonic device shown in **FIG. 2**, the power reflectivity R is 4% for the wavelength λ equal to λ_c (1659 nm) when the coating film **2** having the refractive index n_f of "1.4989" as in the first preferred embodiment and a thickness d_f of five times 276.70 nm, i.e. five times $\lambda_c/(4n_f)$, is provided on the end surface **1***b* of the semiconductor photonic element **1**. **FIG. 22** shows the wavelength dependence of the power reflectivity R in this case. As illustrated in **FIG. 22**, the wavelength band for which the power reflectivity R falls within ±2% from the design reflectivity of 4% is from 1609 nm to 1712 nm, to provide a wavelength bandwidth W_r of 103 nm.

[0204] Thus, the wavelength bandwidth W (478 nm) for the coating film **29** of the fourth preferred embodiment is greater than the wavelength bandwidth W_r (103 nm) for the coating film **2** shown in **FIG. 2**.

[0205] Because the wavelength λ of light propagating through the active layer **1***a* is sometimes varied, it is desirable that the center wavelength λ_c of the wavelength band for which the power reflectivity R falls within the allowable reflectivity range be equal to or close to the design wavelength λ_t. For example, when d_3=7.02 nm in the above instance, the basic amounts of phase change ϕ_1 and ϕ_2 are "1.33612" and "0.478115," respectively. The center wavelength λ_c takes on a value equal to the design wavelength of 1550 nm when the thickness of the coating film **29** is determined using the basic thicknesses d_1 and d_2 obtained by substituting the above-mentioned values of the basic amounts of phase change ϕ_1 and ϕ_2 into Equations (5a) and (5b) and substituting 1451 nm, rather than the design wavelength λ_t, for λ in Equations (5a) and (5b). **FIG. 23** shows the wavelength dependence of the power reflectivity R in this case.

[0206] As illustrated in **FIG. 23**, the power reflectivity R falls within a range from 2.0% to 6.0% for the wavelength λ ranging from 1322 nm to 1777 nm. The wavelength band for which the power reflectivity R falls within ±2% from the design reflectivity of 4% is also from 1322 nm to 1777 nm, to provide a wavelength bandwidth W of 455 nm. The center wavelength λ_c of the wavelength band is 1550 nm, which is equal to the design wavelength of 1550 nm. The value obtained by dividing the wavelength bandwidth W (455 nm) by the center wavelength λ_c (1550 nm) is approximately 0.294, which is greater than 0.06 and shows that the wavelength band for which the power reflectivity R falls within the allowable reflectivity range is a wide band.

[0207] In this case, the thicknesses of the first to seventh layer films **22** to **28** of the coating film **29** are 7.02 nm, 253.50 nm, 115.18 nm, 247.50 nm, 112.46 nm, 312.01 nm and 141.77 nm, respectively. The optical thickness t of the coating film **29** is 2285.35 nm. This value is approximately 5.89 times the value t_r (388 nm) which is a quarter of the center wavelength λ_c. Thus, the coating film **29** is a very thick film.

[0208] The semiconductor photonic device shown in **FIG. 2** will be considered for comparison. For the semiconductor photonic device shown in **FIG. 2**, the power reflectivity R is 4% for the wavelength λ equal to λ_c (1550 nm) when the coating film **2** having the above-mentioned refractive index n_f of "1.4989" and a thickness d_f of five times 258.52 nm, i.e. five times $\lambda_c/(4n_f)$, is provided on the end surface **1***b* of the semiconductor photonic element **1**. **FIG. 24** shows the wavelength dependence of the power reflectivity R in this case. As illustrated in **FIG. 24**, the wavelength band for which the power reflectivity R falls within ±2% from the design reflectivity of 4% is from 1503 nm to 1600 nm, to provide a wavelength bandwidth W_r of 97 nm.

[0209] Thus, even when the center wavelength λ_c is made equal to the design wavelength λ_t, the wavelength bandwidth W (455 nm) for the coating film **29** is greater than the wavelength bandwidth W_r (97 nm) for the coating film **2** shown in **FIG. 2**.

Fifth Preferred Embodiment

[0210] **FIG. 25** is a side view showing a structure of the semiconductor photonic device according to the fifth preferred embodiment of the present invention. A coating film **38** having an eight-layer structure is provided on the end surface **1***b* of the semiconductor photonic element **1** in the fifth preferred embodiment.

[0211] As illustrated in **FIG. 25**, the coating film **38** according to the fifth preferred embodiment of the present invention includes: a first layer film **30** having the refractive index n_1 and the thickness Ad_1; a second layer film **31** having the refractive index n_2 and the thickness Ad_2; a third layer film **32** having the refractive index n_1 and the thickness Bd_1; a fourth layer film **33** having the refractive index n_2 and the thickness Bd_2; a fifth layer film **34** having the refractive index n_1 and the thickness Cd_1; a sixth layer film **35** having the refractive index n_2 and the thickness Cd_2; a seventh layer film **36** having the refractive index n_1 and a thickness Dd_1; and an eighth layer film **37** having the refractive index n_2 and a thickness Dd_2.

[0212] Each of the first layer film **30**, the third layer film **32**, the fifth layer film **34** and the seventh layer film **36** is a tantalum oxide layer, and each of the second layer film **31**, the fourth layer film **33**, the sixth layer film **35** and the eighth layer film **37** is a silicon oxide layer. Thus, the coating film **38** according to the fifth preferred embodiment is composed of two material layers: the tantalum oxide layer and the silicon oxide layer.

[0213] In the fifth preferred embodiment, the first and second layer films **30** and **31**, the third and fourth layer films **32** and **33**, the fifth and sixth layer films **34** and **35**, and the seventh and eighth layer films **36** and **37** constitute unit layer pairs each composed of the tantalum oxide layer and the silicon oxide layer arranged in a stacked relation. In other words, the coating film **38** includes four unit layer pairs each composed of the tantalum oxide layer and the silicon oxide layer arranged in a stacked relation. The reference characters A, B, C and D which determine the thicknesses of the respective layers of the coating film **38** designate parameters individually determined for the respective unit layer pairs and each indicating a contribution ratio of the thickness of a corresponding unit layer pair to the thickness of the entire coating film **38**. The reference characters d_1 and d_2 according to the fifth preferred embodiment also designate basic thicknesses individually determined for the respective material layers in a similar manner to the first preferred embodiment.

[0214] The amounts of phase change for the first to eighth layer films **30** to **37** are designated by $A\phi_1$, $A\phi_2$, $B\phi_1$, $B\phi_2$, $C\phi_1$, $C\phi_2$, $D\phi_1$ and $D\phi_2$, respectively, using Equations (5a) and (5b). Therefore, the elements m_{11}, m_{12}, m_{21} and m_{22} of a characteristic matrix for the coating film **38** according to the fifth preferred embodiment satisfy the following determinant:

$$\begin{bmatrix} m_{11} & m_{12} \\ m_{21} & m_{22} \end{bmatrix} \tag{7e}$$

$$= \begin{bmatrix} \cos A\phi_1 & -\frac{i}{n_1}\sin A\phi_1 \\ -in_1\sin A\phi_1 & \cos A\phi_1 \end{bmatrix} \begin{bmatrix} \cos A\phi_2 & -\frac{i}{n_2}\sin A\phi_2 \\ -in_2\sin A\phi_2 & \cos A\phi_2 \end{bmatrix} \times$$

$$\begin{bmatrix} \cos B\phi_1 & -\frac{i}{n_1}\sin B\phi_1 \\ -in_1\sin B\phi_1 & \cos B\phi_1 \end{bmatrix} \begin{bmatrix} \cos B\phi_2 & -\frac{i}{n_2}\sin B\phi_2 \\ -in_2\sin B\phi_2 & \cos B\phi_2 \end{bmatrix} \times$$

-continued

$$\begin{bmatrix} \cos C\phi_1 & -\frac{i}{n_1}\sin C\phi_1 \\ -in_1\sin C\phi_1 & \cos C\phi_1 \end{bmatrix}$$

$$\begin{bmatrix} \cos C\phi_2 & -\frac{i}{n_2}\sin C\phi_2 \\ -in_2\sin C\phi_2 & \cos C\phi_2 \end{bmatrix} \times$$

$$\begin{bmatrix} \cos D\phi_1 & -\frac{i}{n_1}\sin D\phi_1 \\ -in_1\sin D\phi_1 & \cos D\phi_1 \end{bmatrix}$$

$$\begin{bmatrix} \cos D\phi_2 & -\frac{i}{n_2}\sin D\phi_2 \\ -in_2\sin D\phi_2 & \cos D\phi_2 \end{bmatrix}$$

[0215] For designing the thickness of the coating film **38** so that the value of the amplitude reflectivity r is an imaginary number the fifth preferred embodiment previously determines the values of the parameters A to D, and executes Steps s**1** to s**5** using Equations (6) and (7d) described above to determine the values of the basic amounts of phase change ϕ_1 and ϕ_2. Thereafter, Step s**6** is executed to determine the values of the basic thicknesses d_1 and d_2, and the thicknesses of the respective layers of the coating film **38** are determined using the previously determined values of the parameters A to D and the values of the basic thicknesses d_1 and d_2 determined in Step s**6**. If the designed characteristic of the coating film **38** is insufficient, the basic thicknesses d_1 and d_2 are determined again by changing the parameters A to D, and the thickness of the coating film **38** is designed again.

[0216] Because GaN (gallium nitride) based semiconductor is employed in the semiconductor photonic element **1** of the fifth preferred embodiment, the effective refractive index n_c of the semiconductor photonic element **1** is "2.50." The design wavelength λ_1 is 410 nm. The refractive index n_1 of the tantalum oxide layer is greater than $n_c^{1/2}$ (=1.581), and is set at "2.128" in consideration for wavelength dispersion because the design wavelength λ_t is as short as 410 nm. The refractive index n_2 of the silicon oxide layer is "1.480" which is less than $n_c^{1/2}$.

[0217] For designing the thickness of the coating film **38** having the power reflectivity R of 4% when the wavelength λ equals the design wavelength of 410 nm under the above-mentioned conditions, a point which provides a phase angle θ of 45 degrees is selected, for example, in Step s**1** so that the reflection amplitude vector rv is located in the first quadrant (or the upper right quadrant) of the complex plane. Then, the values of the real and imaginary parts r_r and r_i of the complex number inputted as the value of the amplitude reflectivity r are "+0.141421356" and "+0.141421356," respectively, in Step s**2**.

[0218] When A=1.38, B=2.30, C=2.00 and D=2.00 are set, the basic amounts of phase change ϕ_1 and ϕ_2 determined in Step s**5** are "1.56840" and "0.526521," respectively. Accordingly, the thicknesses of the first to eighth layer films **30** to **37** determined in Step s**6** are 66.37 nm, 32.04 nm, 110.62 nm, 53.39 nm, 96.19 nm, 46.43 nm, 96.19 nm and 46.43 nm, respectively.

[0219] **FIG. 26** shows the wavelength dependence of the power reflectivity R of the coating film **38** thus designed. As illustrated in **FIG. 26**, the power reflectivity R is 4% when the wavelength λ equals the design wavelength of 410 nm. A wavelength band for which the power reflectivity R is approximately equal to the design reflectivity of 4% is wide. The power reflectivity R falls within a range from 3.9% to 6.0% for the wavelength λ ranging from 386 nm to 488 nm.

[0220] When the allowable reflectivity range is, for example, ±2% from the design reflectivity of 4%, the wavelength band for which the power reflectivity R falls within the allowable reflectivity range is also from 386 nm to 488 nm, to provide a wavelength bandwidth W of 102 nm. The center wavelength λ_c of the wavelength band is 437 nm. The value obtained by dividing the wavelength bandwidth W by the center wavelength λ_c is approximately 0.233, which is greater than 0.06. It may be said that the wavelength band for which the power reflectivity R falls within the allowable reflectivity range is a wide band.

[0221] Because the thicknesses of the first to eighth layer films **30** to **37** take on the above-mentioned values, the optical thickness t of the coating film **38**, i.e. the sum of the products of the refractive indices and thicknesses of the respective layers of the coating film **38**, is 1049.89 nm. This value is approximately 9.63 times the value t_r (109 nm) which is a quarter of the center wavelength λ_c. Thus, the coating film **38** is a very thick film. This improves heat dissipation characteristics at the end surface **1***b* of the semiconductor photonic element **1** to suppress the increase in temperature of the end surface **1***b*.

[0222] The semiconductor photonic device shown in **FIG. 2** will be considered for comparison. For the semiconductor photonic device shown in **FIG. 2**, the power reflectivity R takes on a relative minimum value of 4% for the wavelength λ equal to λ_c (437 nm) when the coating film **2** having a refractive index n_f of "1.291" and a thickness d_f of five times 84.62 nm, i.e. five times $\lambda_c/(4n_f)$, is provided on the end surface **1***b* of the semiconductor photonic element **1**. **FIG. 27** shows the wavelength dependence of the power reflectivity R in this case. As illustrated in **FIG. 27**, the wavelength band for which the power reflectivity R falls within ±2% from the design reflectivity of 4% is from 419 nm to 457 nm, to provide a wavelength bandwidth W_r of 38 nm.

[0223] The above-mentioned value "1.291" of the refractive index n_f is obtained by substituting R_t=0.04 and n_c=2.50 into Equation (8).

[0224] Thus, the wavelength bandwidth W (102 nm) for the coating film **38** of the fifth preferred embodiment is greater than the wavelength bandwidth W_r (38 nm) for the coating film **2** shown in **FIG. 2**.

[0225] Because the wavelength λ of light propagating through the active layer **1***a* is sometimes varied, it is desirable that the center wavelength λ_c of the wavelength band for which the power reflectivity R falls within the allowable reflectivity range be equal to or close to the design wavelength λ_t. For example, the center wavelength λ_c takes on a value equal to the design wavelength λ_t of 410 nm when the thickness of the coating film **38** is determined using the basic thicknesses d_1 and d_2 obtained by setting the basic amounts of phase change ϕ_1 and ϕ_2 at "1.56840" and "0.526521," respectively, in a similar manner to the above

instance and substituting 384 nm, rather than the design wavelength λ_t, for λ in Equations (5a) and (5b). **FIG. 28** shows the wavelength dependence of the power reflectivity R in this case.

[0226] As illustrated in **FIG. 28**, the power reflectivity R falls within a range from 3.9% to 6.0% for the wavelength λ ranging from 362 nm to 457 nm. The wavelength band for which the power reflectivity R falls within ±2% from the design reflectivity of 4% is also from 362 nm to 457 nm, to provide a wavelength bandwidth W of 95 nm. The center wavelength λ_c of the wavelength band is 410 nm, which is equal to the design wavelength of 410 nm. The value obtained by dividing the wavelength bandwidth W (95 nm) by the center wavelength λ_c (410 nm) is approximately 0.224, which is greater than 0.06 and shows that the wavelength band for which the power reflectivity R falls within the allowable reflectivity range is a wide band.

[0227] In this case, the thicknesses of the first to eighth layer films **30** to **37** of the coating film **38** are 62.16 nm, 30.00 nm, 103.60 nm, 50.00 nm, 90.09 nm, 43.48 nm, 90.09 nm and 43.48 nm, respectively. The optical thickness t of the coating film **38** is 983.26 nm. This value is approximately 9.55 times the value t_r (103 nm) which is a quarter of the center wavelength λ_c. Thus, the coating film **38** is a very thick film.

[0228] The semiconductor photonic device shown in **FIG. 2** will be considered for comparison. For the semiconductor photonic device shown in **FIG. 2**, the power reflectivity R is 4% for the wavelength λ equal to λ_c (410 nm) when the coating film **2** having the above-mentioned refractive index n_f of "1.291" and a thickness d_f of five times 79.40 nm, i.e. five times $\lambda_c/(4n_f)$, is provided on the end surface **1***b* of the semiconductor photonic element **1**. **FIG. 29** shows the wavelength dependence of the power reflectivity R in this case. As illustrated in **FIG. 29**, the wavelength band for which the power reflectivity R falls within ±2% from the design reflectivity of 4% is from 393 nm to 429 nm, to provide a wavelength bandwidth W_r of 36 nm.

[0229] Thus, even when the center wavelength λ_c is made equal to the design wavelength λ_t, the wavelength bandwidth W (95 nm) for the coating film **38** is greater than the wavelength bandwidth W_r (36 nm) for the coating film **2** shown in **FIG. 2**.

Sixth Preferred Embodiment

[0230] **FIG. 30** is a side view showing a structure of the semiconductor photonic device according to the sixth preferred embodiment of the present invention. A coating film **47** having an eight-layer structure is provided on the end surface **1***b* of the semiconductor photonic element **1** in the sixth preferred embodiment.

[0231] As illustrated in **FIG. 30**, the coating film **47** according to the sixth preferred embodiment of the present invention includes: a first layer film **39** having the refractive index n_3 and the thickness d_3; a second layer film **40** having the refractive index n_2 and the thickness Ad_2; a third layer film **41** having the refractive index n_1 and the thickness Bd_1; a fourth layer film **42** having the refractive index n_2 and the thickness Bd_2; a fifth layer film **43** having the refractive index n_1 and the thickness Cd_1; a sixth layer film **44** having the refractive index n_2 and the thickness Cd_2; a seventh layer film **45** having the refractive index n_1 and the thickness Dd_1; and an eighth layer film **46** having the refractive index n_2 and the thickness Dd_2.

[0232] The first layer film **39** is an aluminum nitride layer. Each of the second layer film **40**, the fourth layer film **42**, the sixth layer film **44** and the eighth layer film **46** is a silicon oxide layer. Each of the third layer film **41**, the fifth layer film **43** and the seventh layer film **45** is a tantalum oxide layer. Thus, the coating film **47** according to the sixth preferred embodiment is composed of three material layers: the aluminum nitride layer, the silicon oxide layer, and the tantalum oxide layer.

[0233] In the sixth preferred embodiment, the third and fourth layer films **41** and **42**, the fifth and sixth layer films **43** and **44**, and the seventh and eighth layer films **45** and **46** constitute unit layer pairs each composed of the tantalum oxide layer and the silicon oxide layer arranged in a stacked relation. The reference characters B, C and D which determine the thicknesses of the third to eighth layer films **41** to **46** of the coating film **47** designate parameters individually determined for the respective unit layer pairs and each indicating a contribution ratio of the thickness of a corresponding unit layer pair to the thickness of the entire coating film **47**. The reference character A which determines the thickness of the second layer film **40** designates a parameter indicating a contribution ratio of the thickness of the second layer film **40** to the thickness of the entire coating film **47**. The reference characters d_1 and d_2 according to the sixth preferred embodiment also designate basic thicknesses individually determined for the respective material layers.

[0234] The amounts of phase change for the second to eighth layer films **40** to **46** are designated by $A\phi_2$, $B\phi_1$, $B\phi_2$, $C\phi_1$, $C\phi_2$, $D\phi_1$ and $D\phi_2$, respectively, using Equations (5a) and (5b). The amount of phase change ϕ_3 for the first layer film **39** is expressed by Equation (9) described above. Therefore, the elements m_{11}, m_{12}, m_{21} and m_{22} of a characteristic matrix for the coating film **47** according to the sixth preferred embodiment satisfy the following determinant:

$$\begin{bmatrix} m_{11} & m_{12} \\ m_{21} & m_{22} \end{bmatrix} = \tag{7f}$$

$$\begin{bmatrix} \cos\phi_3 & -\frac{i}{n_3}\sin\phi_3 \\ -in_3\sin\phi_3 & \cos\phi_3 \end{bmatrix} \begin{bmatrix} \cos A\phi_2 & -\frac{i}{n_2}\sin A\phi_2 \\ -in_2\sin A\phi_2 & \cos A\phi_2 \end{bmatrix} \times \begin{bmatrix} \cos B\phi_1 & -\frac{i}{n_1}\sin B\phi_1 \\ -in_1\sin B\phi_1 & \cos B\phi_1 \end{bmatrix} \begin{bmatrix} \cos B\phi_2 & -\frac{i}{n_2}\sin B\phi_2 \\ -in_2\sin B\phi_2 & \cos B\phi_2 \end{bmatrix} \times \begin{bmatrix} \cos C\phi_1 & -\frac{i}{n_1}\sin C\phi_1 \\ -in_1\sin C\phi_1 & \cos C\phi_1 \end{bmatrix} \begin{bmatrix} \cos C\phi_2 & -\frac{i}{n_2}\sin C\phi_2 \\ -in_2\sin C\phi_2 & \cos C\phi_2 \end{bmatrix} \times \begin{bmatrix} \cos D\phi_1 & -\frac{i}{n_1}\sin D\phi_1 \\ -in_1\sin D\phi_1 & \cos D\phi_1 \end{bmatrix} \begin{bmatrix} \cos D\phi_2 & -\frac{i}{n_2}\sin D\phi_2 \\ -in_2\sin D\phi_2 & \cos D\phi_2 \end{bmatrix}$$

[0235] For designing the thickness of the coating film **47** so that the value of the amplitude reflectivity r is an imaginary number, the sixth preferred embodiment previously determines the values of the parameters A to D, and previously determines the thickness d_3 of the first layer film **39**, thereby to handle the value of the amount of phase change ϕ_3 as a known value. Steps s**1** to s**5** are executed using Equations (6) and (7f) described above to determine the values of the basic amounts of phase change ϕ_1 and ϕ_2. Thereafter, Step s**6** is executed to determine the values of the basic thicknesses d_1 and d_2, and the thicknesses of the second to eighth layer films **40** to **46** of the coating film **47** are determined using the previously determined values of the parameters A to D and the values of the basic thicknesses d_1 and d_2 determined in Step s**6**. If the designed characteristic of the coating film **47** is insufficient, the basic thicknesses d_1 and d_2 are determined again by changing the parameters A to D or the thickness d_3, and the thickness of the coating film **47** is designed again.

[0236] In the sixth preferred embodiment, the effective refractive index n_c of the semiconductor photonic element **1** is "3.37." The refractive indices n_1 to n_3 are "2.057,""1.480" and "2.072," respectively. The design wavelength λ_t is 650 nm.

[0237] For designing the thickness of the coating film **47** having the power reflectivity R of 4% when the wavelength λ equals the design wavelength of 650 nm under the above-mentioned conditions, a point which provides a phase angle θ of 135 degrees is selected, for example, in Step s**1** so that the reflection amplitude vector rv is located in the second quadrant (or the upper left quadrant) of the complex plane. Then, the values of the real and imaginary parts r_r and r_i of the complex number inputted as the value of the amplitude reflectivity r are "−0.141421356" and "+0.141421356," respectively, in Step s**2**.

[0238] When A=2.50, B=1.90, C=1.00, D=2.05 and d_3=40.0 nm are set, the basic amounts of phase change ϕ_1 and ϕ_2 determined in Step s**5** are "0.674374" and "1.15311," respectively. Accordingly, the thicknesses of the second to eighth layer films **40** to **46** determined in Step s**6** are 201.50 nm, 64.44 nm, 153.14 nm, 33.92 nm, 80.60 nm, 69.53 nm and 165.23 nm, respectively.

[0239] **FIG. 31** shows the wavelength dependence of the power reflectivity R of the coating film **47** thus designed. As illustrated in **FIG. 31**, the power reflectivity R is 4% when the wavelength λ equals the design wavelength of 650 nm. A wavelength band for which the power reflectivity R is approximately equal to the design reflectivity of 4% is wide. The power reflectivity R falls within a range from 4.0% to 6.0% for the wavelength λ ranging from 630 nm to 736 nm.

[0240] When the allowable reflectivity range is, for example, ±2% from the design reflectivity of 4%, the wavelength band for which the power reflectivity R falls within the allowable reflectivity range is also from 630 nm to 736 nm, to provide a wavelength bandwidth W of 106 nm. The center wavelength λ_c of the wavelength band is 683 nm. The value obtained by dividing the wavelength bandwidth W by the center wavelength λ_c is approximately 0.155, which is greater than 0.06. It may be said that the wavelength band for which the power reflectivity R falls within the allowable reflectivity range is a wide band.

[0241] Because the thicknesses of the first to eighth layer films **39** to **46** take on the above-mentioned values, the optical thickness t of the coating film **47**, i.e. the sum of the products of the refractive indices and thicknesses of the respective layers of the coating film **47**, is 1316.93 nm. This value is approximately 7.70 times the value t_r (171 nm) which is a quarter of the center wavelength λ_c. Thus, the coating film **47** is a very thick film. This improves heat dissipation characteristics at the end surface **1***b* of the semiconductor photonic element **1** to suppress the increase in temperature of the end surface **1***b*.

[0242] The semiconductor photonic device shown in **FIG. 2** will be considered for comparison. For the semiconductor photonic device shown in **FIG. 2**, the power reflectivity R is 4% for the wavelength λ equal to λ_c (683 nm) when the coating film **2** having the refractive index n_f of "1.4989" as in the first preferred embodiment and a thickness d_f of five times 113.92 nm, i.e. five times $\lambda_c/(4n_f)$, is provided on the end surface **1***b* of the semiconductor photonic element **1**. **FIG. 32** shows the wavelength dependence of the power reflectivity R in this case. As illustrated in **FIG. 32**, the wavelength band for which the power reflectivity R falls within ±2% from the design reflectivity of 4% is from 663 nm to 705 nm, to provide a wavelength bandwidth W_r of 42 nm.

[0243] Thus, the wavelength bandwidth W (106 nm) for the coating film **47** of the sixth preferred embodiment is greater than the wavelength bandwidth W_r (42 nm) for the coating film **2** shown in **FIG. 2**.

[0244] Because the wavelength λ of light propagating through the active layer **1***a* is sometimes varied, it is desirable that the center wavelength λ_c of the wavelength band for which the power reflectivity R falls within the allowable reflectivity range be equal to or close to the design wavelength λ_t. For example, when d_3=38.03 nm in the above instance, the basic amounts of phase change ϕ_1 and ϕ_2 are "0.674368" and "1.15312," respectively. The center wavelength λ_c takes on a value equal to the design wavelength λ_t of 650 nm when the thickness of the coating film **47** is determined using the basic thicknesses d_1 and d_2 obtained by substituting the above-mentioned values of the basic amounts of phase change ϕ_1 and ϕ_2 into Equations (5a) and (5b) and substituting 618 nm, rather than the design wavelength λ_t, for λ in Equations (5a) and (5b). **FIG. 33** shows the wavelength dependence of the power reflectivity R in this case.

[0245] As illustrated in **FIG. 33**, the power reflectivity R falls within a range from 4.0% to 6.0% for the wavelength λ ranging from 599 nm to 700 nm. The wavelength band for which the power reflectivity R falls within ±2% from the design reflectivity of 4% is also from 599 nm to 700 nm, to provide a wavelength bandwidth W of 101 nm. The center wavelength λ_c of the wavelength band is 650 nm, which is equal to the design wavelength of 650 nm. The value obtained by dividing the wavelength bandwidth W (101 nm) by the center wavelength λ_c (650 nm) is approximately 0.155, which is greater than 0.06 and shows that the wavelength band for which the power reflectivity R falls within the allowable reflectivity range is a wide band.

[0246] In this case, the thicknesses of the first to eighth layer films **39** to **46** of the coating film **47** are 38.03 nm, 191.59 nm, 61.27 nm, 145.61 nm, 32.25 nm, 76.63 nm, 66.10 nm and 157.10 nm, respectively. The optical thickness t of the coating film **47** is 1252.11 nm. This value is

approximately 7.68 times the value t_r (163 nm) which is a quarter of the center wavelength λ_c. Thus, the coating film **47** is a very thick film.

[**0247**] The semiconductor photonic device shown in **FIG. 2** will be considered for comparison. For the semiconductor photonic device shown in **FIG. 2**, the power reflectivity R is 4% for the wavelength λ equal to λ_c (650 nm) when the coating film **2** having the above-mentioned refractive index n_f of "1.4989" and a thickness d_f of five times 108.41 nm, i.e. five times $\lambda_c/(4n_f)$, is provided on the end surface **1***b* of the semiconductor photonic element **1**. **FIG. 34** shows the wavelength dependence of the power reflectivity R in this case. As illustrated in **FIG. 34**, the wavelength band for which the power reflectivity R falls within ±2% from the design reflectivity of 4% is from 631 nm to 670 nm, to provide a wavelength bandwidth W_r of 39 nm.

[**0248**] Thus, even when the center wavelength λ_c is made equal to the design wavelength λ_t, the wavelength bandwidth W (101 nm) for the coating film **47** is greater than the wavelength bandwidth W_r (39 nm) for the coating film **2** shown in **FIG. 2**.

Seventh Preferred Embodiment

[**0249**] **FIG. 35** is a side view showing a structure of the semiconductor photonic device according to the seventh preferred embodiment of the present invention. A coating film **57** having a nine-layer structure is provided on the end surface **1***b* of the semiconductor photonic element **1** in the seventh preferred embodiment.

[**0250**] As illustrated in **FIG. 35**, the coating film **57** according to the seventh preferred embodiment of the present invention includes: a first layer film **48** having the refractive index n_2 and the thickness Od_2; a second layer film **49** having the refractive index n_1 and the thickness Ad_1; a third layer film **50** having the refractive index n_2 and the thickness Ad_2; a fourth layer film **51** having the refractive index n_1 and the thickness Bd_1; a fifth layer film **52** having the refractive index n_2 and the thickness Bd_2; a sixth layer film **53** having the refractive index n_1 and the thickness Cd_1; a seventh layer film **54** having the refractive index n_2 and the thickness Cd_2, an eighth layer film **55** having the refractive index n_1 and the thickness Dd_1; and a ninth layer film **56** having the refractive index n_2 and the thickness Dd_2.

[**0251**] Each of the first layer film **48**, the third layer film **50**, the fifth layer film **52**, the seventh layer film **54** and the ninth layer film **56** is an alumina layer, and each of the second layer film **49**, the fourth layer film **51**, the sixth layer film **53** and the eighth layer film **55** is a tantalum oxide layer. Thus, the coating film **57** according to the seventh preferred embodiment is composed of two material layers: the alumina layer and the tantalum oxide layer.

[**0252**] In the seventh preferred embodiment, the second and third layer films **49** and **50**, the fourth and fifth layer films **51** and **52**, the sixth and seventh layer films **53** and **54**, and the eighth and ninth layer films **55** and **56** constitute unit layer pairs each composed of the alumina layer and the tantalum oxide layer arranged in a stacked relation. The reference characters A, B, C and D which determine the thicknesses of the second to ninth layer films **49** to **56** of the coating film **57** designate parameters individually determined for the respective unit layer pairs and each indicating a contribution ratio of the thickness of a corresponding unit layer pair to the thickness of the entire coating film **57**. The reference character O which determines the thickness of the first layer film **48** designates a parameter indicating a contribution ratio of the thickness of the first layer film **48** to the thickness of the entire coating film **57**. The reference characters d_1 and d_2 according to the seventh preferred embodiment also designate basic thicknesses individually determined for the respective material layers.

[**0253**] The amounts of phase change for the first to ninth layer films **48** to **56** are designated by $O\phi_2$, $A\phi_1$, $A\phi_2$, $B\phi_1$, $B\phi_2$, $C\phi_1$, $C\phi_2$, $D\phi_1$ and $D\phi_2$, respectively, using Equations (5a) and (5b). Therefore, the elements m_{11}, m_{12}, m_{21} and m_{22} of a characteristic matrix for the coating film **57** according to the seventh preferred embodiment satisfy the following determinant:

$$\begin{bmatrix} m_{11} & m_{12} \\ m_{21} & m_{22} \end{bmatrix} = \begin{bmatrix} \cos O\phi_2 & -\frac{i}{n_2}\sin O\phi_2 \\ -in_2\sin O\phi_2 & \cos O\phi_2 \end{bmatrix} \times \tag{7g}$$

$$\begin{bmatrix} \cos A\phi_1 & -\frac{i}{n_1}\sin A\phi_1 \\ -in_1\sin A\phi_1 & \cos A\phi_1 \end{bmatrix} \begin{bmatrix} \cos A\phi_2 & -\frac{i}{n_2}\sin A\phi_2 \\ -in_2\sin A\phi_2 & \cos A\phi_2 \end{bmatrix} \times$$

$$\begin{bmatrix} \cos B\phi_1 & -\frac{i}{n_1}\sin B\phi_1 \\ -in_1\sin B\phi_1 & \cos B\phi_1 \end{bmatrix} \begin{bmatrix} \cos B\phi_2 & -\frac{i}{n_2}\sin B\phi_2 \\ -in_2\sin B\phi_2 & \cos B\phi_2 \end{bmatrix} \times$$

$$\begin{bmatrix} \cos C\phi_1 & -\frac{i}{n_1}\sin C\phi_1 \\ -in_1\sin C\phi_1 & \cos C\phi_1 \end{bmatrix}$$

$$\begin{bmatrix} \cos C\phi_2 & -\frac{i}{n_2}\sin C\phi_2 \\ -in_2\sin C\phi_2 & \cos C\phi_2 \end{bmatrix} \times$$

$$\begin{bmatrix} \cos D\phi_1 & -\frac{i}{n_1}\sin D\phi_1 \\ -in_1\sin D\phi_1 & \cos D\phi_1 \end{bmatrix}$$

$$\begin{bmatrix} \cos D\phi_2 & -\frac{i}{n_2}\sin D\phi_2 \\ -in_2\sin D\phi_2 & \cos D\phi_2 \end{bmatrix}$$

[**0254**] For designing the thickness of the coating film **57** so that the value of the amplitude reflectivity r is an imaginary number, the seventh preferred embodiment previously determines the values of the parameters A, B, C, D and O, and executes Steps s**1** to s**5** using Equations (6) and (7g) described above to determine the values of the basic amounts of phase change ϕ_1 and ϕ_2. Thereafter, Step s**6** is executed to determine the values of the basic thicknesses d_1 and d_2, and the thicknesses of the respective layers of the coating film **57** are determined using the previously determined values of the parameters A, B, C, D and O and the values of the basic thicknesses d_1 and d_2 determined in Step s**6**. If the designed characteristic of the coating film **57** is insufficient, the basic thicknesses d_1 and d_2 are determined again by changing the parameters A, B, C, D and O, and the thickness of the coating film **57** is designed again.

[**0255**] In the seventh preferred embodiment, the effective refractive index n_e of the semiconductor photonic element **1**

is "3.37." The refractive indices n_1 and n_2 are "2.057" and "1.620," respectively. The design wavelength λ_t is 980 nm.

[0256] For designing the thickness of the coating film **57** having the power reflectivity R of 4% (R_t=4%) when the wavelength λ equals the design wavelength of 980 nm under the above-mentioned conditions, a point which provides a phase angle θ of 240 degrees is selected, for example, in Step s**1** so that the reflection amplitude vector rv is located in the third quadrant (or the lower left quadrant) of the complex plane. Then, the values of the real and imaginary parts r_r and r_i of the complex number inputted as the value of the amplitude reflectivity r are "−0.1" and "−0.17320508," respectively, in Step s**2**.

[0257] When O=0.46, A=1.44, B=2.00, C=2.00 and D=2.00 are set, the basic amounts of phase change ϕ_1 and ϕ_2 determined in Step s**5** are "1.15080" and "0.506897," respectively. Accordingly, the thicknesses of the first to ninth layer films **48** to **56** determined in Step s**6** are 22.45 nm, 125.65 nm, 70.28 nm, 174.52 nm, 97.61 nm, 174.52 nm, 97.61 nm, 174.52 nm and 97.61 nm, respectively.

[0258] **FIG. 36** shows the wavelength dependence of the power reflectivity R of the coating film **57** thus designed. As illustrated in **FIG. 36**, the power reflectivity R is 4% when the wavelength λ equals the design wavelength of 980 nm. A wavelength band for which the power reflectivity R is approximately equal to the design reflectivity of 4% is wide. The power reflectivity R falls within a range from 4.0% to 6.0% for the wavelength λ ranging from 913 nm to 1031 nm.

[0259] When the allowable reflectivity range is, for example, ±2% from the design reflectivity of 4%, the wavelength band for which the power reflectivity R falls within the allowable reflectivity range is also from 913 nm to 1031 nm, to provide a wavelength bandwidth W of 118 nm. The center wavelength λ_c of the wavelength band is 972 nm. The value obtained by dividing the wavelength bandwidth W by the center wavelength λ_c is approximately 0.121, which is greater than 0.06. It may be said that the wavelength band for which the power reflectivity R falls within the allowable reflectivity range is a wide band.

[0260] Because the thicknesses of the first to ninth layer films **48** to **56** take on the above-mentioned values, the optical thickness t of the coating film **57**, i.e. the sum of the products of the refractive indices and thicknesses of the respective layers of the coating film **57**, is 1960.03 nm. This value is approximately 8.07 times the value t_r (243 nm) which is a quarter of the center wavelength λ_c. Thus, the coating film **57** is a very thick film. This improves heat dissipation characteristics at the end surface **1***b* of the semiconductor photonic element **1** to suppress the increase in temperature of the end surface **1***b*.

[0261] The semiconductor photonic device shown in **FIG. 2** will be considered for comparison. For the semiconductor photonic device shown in **FIG. 2**, the power reflectivity R is 4% for the wavelength λ equal to λ_c (972 nm) when the coating film **2** having the refractive index n_f of "1.4989" as in the first preferred embodiment and a thickness d_f of five times 162.12 nm, i.e. five times $\lambda_c/(4n_f)$, is provided on the end surface **1***b* of the semiconductor photonic element **1**. **FIG. 37** shows the wavelength dependence of the power reflectivity R in this case. As illustrated in **FIG. 37**, the wavelength band for which the power reflectivity R falls within ±2% from the design reflectivity of 4% is from 943 nm to 1003 nm, to provide a wavelength bandwidth W_r of 60 nm.

[0262] Thus, the wavelength bandwidth W (118 nm) for the coating film **57** of the seventh preferred embodiment is greater than the wavelength bandwidth W_r (60 nm) for the coating film **2** shown in **FIG. 2**.

[0263] Because the wavelength λ of light propagating through the active layer **1***a* is sometimes varied, it is desirable that the center wavelength λ_c of the wavelength band for which the power reflectivity R falls within the allowable reflectivity range be equal to or close to the design wavelength λ_t. For example, the center wavelength λ_c takes on a value equal to the design wavelength λ_t of 980 nm when the thickness of the coating film **57** is determined using the basic thicknesses d_1 and d_2 obtained by setting the basic amounts of phase change ϕ_1 and ϕ_2 at "1.15080" and "0.506897," respectively, in a similar manner to the above instance and substituting 988 nm, rather than the design wavelength λ_t, for λ in Equations (5a) and (5b). **FIG. 38** shows the wavelength dependence of the power reflectivity R in this case.

[0264] As illustrated in **FIG. 38**, the power reflectivity R falls within a range from 4.0% to 6.0% for the wavelength λ ranging from 921 nm to 1039 nm. The wavelength band for which the power reflectivity R falls within ±2% from the design reflectivity of 4% is also from 921 nm to 1039 nm, to provide a wavelength bandwidth W of 118 nm. The center wavelength λ_c of the wavelength band is 980 nm, which is equal to the design wavelength of 980 nm. The value obtained by dividing the wavelength bandwidth W (118 nm) by the center wavelength λ_c (980 nm) is approximately 0.120, which is greater than 0.06 and shows that the wavelength band for which the power reflectivity R falls within the allowable reflectivity range is a wide band.

[0265] In this case, the thicknesses of the first to ninth layer films **48** to **56** of the coating film **57** are 22.63 nm, 126.68 nm, 70.85 nm, 175.94 nm, 98.40 nm, 175.94 nm, 98.40 nm, 175.94 nm and 98.40 nm, respectively. The optical thickness t of the coating film **57** is 1975.97 nm. This value is approximately 8.07 times the value t_r (245 nm) which is a quarter of the center wavelength λ_c. Thus, the coating film **57** is a very thick film.

[0266] The semiconductor photonic device shown in **FIG. 2** will be considered for comparison. For the semiconductor photonic device shown in **FIG. 2**, the power reflectivity R is 4% for the wavelength λ equal to λ_c (980 nm) when the coating film **2** having the above-mentioned refractive index n_f of "1.4989" and a thickness d_f of five times 163.45 nm, i.e. five times $\lambda_c/(4n_f)$, is provided on the end surface **1***b* of the semiconductor photonic element **1**. The wavelength dependence of the power reflectivity R in this case is substantially similar to that shown in **FIG. 10** described above. As illustrated in **FIG. 10**, the wavelength band for which the power reflectivity R falls within ±2% from the design reflectivity of 4% is from 951 nm to 1011 nm, to provide a wavelength bandwidth W_r of 60 nm.

[0267] Thus, even when the center wavelength λ_c is made equal to the design wavelength λ_t, the wavelength bandwidth W (118 nm) for the coating film **57** is greater than the wavelength bandwidth W_r (60 nm) for the coating film **2** shown in **FIG. 2**.

Eighth Preferred Embodiment

[0268] **FIG. 39** is a side view showing a structure of the semiconductor photonic device according to the eighth preferred embodiment of the present invention. A coating film **68** having a ten-layer structure is provided on the end surface **1***b* of the semiconductor photonic element **1** in the eighth preferred embodiment.

[0269] As illustrated in **FIG. 39**, the coating film **68** according to the eighth preferred embodiment of the present invention includes: a first layer film **58** having the refractive index n_3 and the thickness d_3; a second layer film **59** having the refractive index n_2 and the thickness Ad_2; a third layer film **60** having the refractive index n_1 and the thickness Bd_1; a fourth layer film **61** having the refractive index n_2 and the thickness Bd_2; a fifth layer film **62** having the refractive index n_1 and the thickness Cd_1; a sixth layer film **63** having the refractive index n_2 and the thickness Cd_2; a seventh layer film **64** having the refractive index n_1 and the thickness Dd_1; an eighth layer film **65** having the refractive index n_2 and the thickness Dd_2; a ninth layer film **66** having the refractive index n_1 and a thickness Ed_1; and a tenth layer film **67** having the refractive index n_2 and a thickness Ed_2.

[0270] The first layer film **58** is an alumina layer. Each of the second layer film **59**, the fourth layer film **61**, the sixth layer film **63**, the eighth layer film **65** and the tenth layer film **67** is a silicon oxide layer. Each of the third layer film **60**, the fifth layer film **62**, the seventh layer film **64** and the ninth layer film **66** is an aluminum nitride layer. Thus, the coating film **68** according to the eighth preferred embodiment is composed of three material layers: the alumina layer, the silicon oxide layer, and the aluminum nitride layer.

[0271] In the eighth preferred embodiment, the third and fourth layer films **60** and **61**, the fifth and sixth layer films **62** and **63**, the seventh and eighth layer films **64** and **65**, and the ninth and tenth layer films **66** and **67** constitute unit layer pairs each composed of the silicon oxide layer and the aluminum nitride layer arranged in a stacked relation. The reference characters B, C, D and E which determine the thicknesses of the third to tenth layer films **60** to **67** of the coating film **68** designate parameters individually determined for the respective unit layer pairs and each indicating a contribution ratio of the thickness of a corresponding unit layer pair to the thickness of the entire coating film **68**. The reference character A which determines the thickness of the second layer film **59** designates a parameter indicating a contribution ratio of the thickness of the second layer film **59** to the thickness of the entire coating film **68**. The reference characters d_1 and d_2 according to the eighth preferred embodiment also designate basic thicknesses individually determined for the respective material layers.

[0272] The amounts of phase change for the second to tenth layer films **59** to **67** are designated by $A\phi_2$, $B\phi_1$, $B\phi_2$, $C\phi_1$, $C\phi_2$, $D\phi_1$, $D\phi_2$, $E\phi_1$ and $E\phi_2$, respectively, using Equations (5a) and (5b). The amount of phase change ϕ_3 for the first layer film **58** is expressed by Equation (9) described above. Therefore, the elements m_{11}, m_{12}, m_{21} and m_{22} of a characteristic matrix for the coating film **68** according to the eighth preferred embodiment satisfy the following determinant:

$$\begin{bmatrix} m_{11} & m_{12} \\ m_{21} & m_{22} \end{bmatrix} = \begin{bmatrix} \cos\phi_3 & -\frac{i}{n_3}\sin\phi_3 \\ -in_3\sin\phi_3 & \cos\phi_3 \end{bmatrix} \tag{7h}$$

$$\begin{bmatrix} \cos A\phi_2 & -\frac{i}{n_2}\sin A\phi_2 \\ -in_2\sin A\phi_2 & \cos A\phi_2 \end{bmatrix} \times \begin{bmatrix} \cos B\phi_1 & -\frac{i}{n_1}\sin B\phi_1 \\ -in_1\sin B\phi_1 & \cos B\phi_1 \end{bmatrix}$$

$$\begin{bmatrix} \cos B\phi_2 & -\frac{i}{n_2}\sin B\phi_2 \\ -in_2\sin B\phi_2 & \cos B\phi_2 \end{bmatrix} \times \begin{bmatrix} \cos C\phi_1 & -\frac{i}{n_1}\sin C\phi_1 \\ -in_1\sin C\phi_1 & \cos C\phi_1 \end{bmatrix}$$

$$\begin{bmatrix} \cos C\phi_2 & -\frac{i}{n_2}\sin C\phi_2 \\ -in_2\sin C\phi_2 & \cos C\phi_2 \end{bmatrix} \times$$

$$\begin{bmatrix} \cos D\phi_1 & -\frac{i}{n_1}\sin D\phi_1 \\ -in_1\sin D\phi_1 & \cos D\phi_1 \end{bmatrix}$$

$$\begin{bmatrix} \cos D\phi_2 & -\frac{i}{n_2}\sin D\phi_2 \\ -in_2\sin D\phi_2 & \cos D\phi_2 \end{bmatrix} \times$$

$$\begin{bmatrix} \cos E\phi_1 & -\frac{i}{n_1}\sin E\phi_1 \\ -in_1\sin E\phi_1 & \cos E\phi_1 \end{bmatrix}$$

$$\begin{bmatrix} \cos E\phi_2 & -\frac{i}{n_2}\sin E\phi_2 \\ -in_2\sin E\phi_2 & \cos E\phi_2 \end{bmatrix}$$

[0273] For designing the thickness of the coating film **68** so that the value of the amplitude reflectivity r is an imaginary number, the eighth preferred embodiment previously determines the values of the parameters A, B, C, D and E, and previously determines the thickness d_3 of the first layer film **58**, thereby to handle the value of the amount of phase change ϕ_3 as a known value. Steps s**1** to s**5** are executed using Equations (6) and (7h) described above to determine the values of the basic amounts of phase change ϕ_1 and ϕ_2. Thereafter, Step s**6** is executed to determine the values of the basic thicknesses d_1 and d_2, and the thicknesses of the second to tenth layer films **59** to **67** of the coating film **68** are determined using the previously determined values of the parameters A, B, C, D and E and the values of the basic thicknesses d_1 and d_2 determined in Step s**6**. If the designed characteristic of the coating film **68** is insufficient, the basic thicknesses d_1 and d_2 are determined again by changing the parameters A, B, C, D and E or the thickness d_3, and the thickness of the coating film **68** is designed again.

[0274] In the eighth preferred embodiment, the effective refractive index n_e of the semiconductor photonic element **1** is "3.37." The refractive indices n_1 to n_3 are "2.072,""1.480" and "1.620," respectively. The design wavelength λ_t is 808 nm.

[0275] For designing the thickness of the coating film **68** having the power reflectivity R of 4% when the wavelength λ equals the design wavelength of 808 nm under the above-mentioned conditions, a point which provides a phase angle θ of 315 degrees is selected, for example, in Step s**1** so that the reflection amplitude vector rv is located in the fourth quadrant (or the lower right quadrant) of the complex

plane. Then, the values of the real and imaginary parts r_r and r_i of the complex number inputted as the value of the amplitude reflectivity r are "+0.141421356" and "−0.141421356,", respectively, in Step s**2**.

[**0276**] When A=0.63, B=1.87, C=2.01, D=2.00, E=2.00 and d_3=40.0 nm are set, the basic amounts of phase change ϕ_1 and ϕ_2 determined in Step s**5** are "0.219827" and "1.23802," respectively. Accordingly, the thicknesses of the second to tenth layer films **59** to **67** determined in Step s**6** are 67.77 nm, 25.51 nm, 201.16 nm, 27.42 nm, 216.22 nm, 27.29 nm, 215.14 nm, 27.29 nm and 215.14 nm, respectively.

[**0277**] **FIG. 40** shows the wavelength dependence of the power reflectivity R of the coating film **68** thus designed. As illustrated in **FIG. 40**, the power reflectivity R is 4% when the wavelength λ equals the design wavelength of 808 nm. A wavelength band for which the power reflectivity R is approximately equal to the design reflectivity of 4% is wide. The power reflectivity R falls within a range from 4.0% to 6.0% for the wavelength λ ranging from 793 nm to 893 nm.

[**0278**] When the allowable reflectivity range is, for example, ±2% from the design reflectivity of 4%, the wavelength band for which the power reflectivity R falls within the allowable reflectivity range is also from 793 nm to 893 nm, to provide a the wavelength bandwidth W of 100 nm. The center wavelength λ_c of the wavelength band is 843 nm. The value obtained by dividing the wavelength bandwidth W by the center wavelength λ_c is approximately 0.119, which is greater than 0.06. It may be said that the wavelength band for which the power reflectivity R falls within the allowable reflectivity range is a wide band.

[**0279**] Because the thicknesses of the first to tenth layer films **58** to **67** take on the above-mentioned values, the optical thickness t of the coating film **68**, i.e. the sum of the products of the refractive indices and thicknesses of the respective layers of the coating film **68**, is 1642.40 nm. This value is approximately 7.78 times the value t_r (211 nm) which is a quarter of the center wavelength λ_c. Thus, the coating film **68** is a very thick film. This improves heat dissipation characteristics at the end surface **1***b* of the semiconductor photonic element **1** to suppress the increase in temperature of the end surface **1***b*.

[**0280**] The semiconductor photonic device shown in **FIG. 2** will be considered for comparison. For the semiconductor photonic device shown in **FIG. 2**, the power reflectivity R is 4% for the wavelength λ equal to λ_c (843 nm) when the coating film **2** having the refractive index n_f of "1.4989" as in the first preferred embodiment and a thickness d_f of five times 140.60 nm, i.e. five times $\lambda_c/(4n_f)$, is provided on the end surface **1***b* of the semiconductor photonic element **1**. **FIG. 41** shows the wavelength dependence of the power reflectivity R in this case. As illustrated in **FIG. 41**, the wavelength band for which the power reflectivity R falls within ±2% from the design reflectivity of 4% is from 818 nm to 870 nm, to provide a wavelength bandwidth W_r of 52 nm.

[**0281**] Thus, the wavelength bandwidth W (100 nm) for the coating film **68** of the eighth preferred embodiment is greater than the wavelength bandwidth W_r (52 nm) for the coating film **2** shown in **FIG. 2**.

[**0282**] Because the wavelength λ of light propagating through the active layer **1***a* is sometimes varied, it is desirable that the center wavelength λ_c of the wavelength band for which the power reflectivity R falls within the allowable reflectivity range be equal to or close to the design wavelength λ_t. For example, when d_3=40.47 nm, A=0.63, B=1.87, C=1.96, D=2.00 and E=2.00 are set, the basic amounts of phase change ϕ_1 and ϕ_2 are "0.235529" and "1.21623," respectively. The center wavelength λ_c takes on a value equal to the design wavelength of 808 nm when the thickness of the coating film **68** is determined using the basic thicknesses d_1 and d_2 obtained by substituting the above-mentioned values of the basic amounts of phase change ϕ_1 and ϕ_2 into Equations (5a) and (5b) and substituting 779 nm, rather than the design wavelength λ_t, for λ in Equations (5a) and (5b). **FIG. 42** shows the wavelength dependence of the power reflectivity R in this case.

[**0283**] As illustrated in **FIG. 42**, the power reflectivity R falls within a range from 2.0% to 6.0% for the wavelength λ ranging from 763 nm to 853 nm. The wavelength band for which the power reflectivity R falls within ±2% from the design reflectivity of 4% is also from 763 nm to 853 nm, to provide a wavelength bandwidth W of 90 nm. The center wavelength λ_c of the wavelength band is 808 nm, which is equal to the design wavelength of 808 nm. The value obtained by dividing the wavelength bandwidth W (90 nm) by the center wavelength λ_c (808 nm) is approximately 0.111, which is greater than 0.06 and shows that the wavelength band for which the power reflectivity R falls within the allowable reflectivity range is a wide band.

[**0284**] In this case, the thicknesses of the first to tenth layer films **58** to **67** of the coating film **68** are 40.47 nm, 64.19 nm, 26.35 nm, 190.53 nm, 27.62 nm, 199.70 nm, 28.19 nm, 203.77 nm, 28.19 nm and 203.77 nm, respectively. The optical thickness t of the coating film **68** is 1569.91 nm. This value is approximately 7.77 times the value t_r (202 nm) which is a quarter of the center wavelength λ_c. Thus, the coating film **68** is a very thick film.

[**0285**] The semiconductor photonic device shown in **FIG. 2** will be considered for comparison. For the semiconductor photonic device shown in **FIG. 2**, the power reflectivity R is 4% for the wavelength λ equal to λ_c (808 nm) when the coating film **2** having the above-mentioned refractive index n_f of "1.4989" and a thickness d_f of five times 134.77 nm, i.e. five times $\lambda_c/(4n_f)$, is provided on the end surface **1***b* of the semiconductor photonic element **1**. **FIG. 43** shows the wavelength dependence of the power reflectivity R in this case. As illustrated in **FIG. 43**, the wavelength band for which the power reflectivity R falls within ±2% from the design reflectivity of 4% is from 774 nm to 834 nm, to provide a wavelength bandwidth W_r of 60 nm.

[**0286**] Thus, even when the center wavelength λ_c is made equal to the design wavelength λ_t, the wavelength bandwidth W (90 nm) for the coating film **68** is greater than the wavelength bandwidth W_r (60 nm) for the coating film **2** shown in **FIG. 2**.

Ninth Preferred Embodiment

[**0287**] **FIG. 44** shows the wavelength dependence of the power reflectivity R of the coating film **13** in the semiconductor photonic device according to the ninth preferred embodiment of the present invention. The semiconductor photonic device according to the ninth preferred embodiment is similar to the semiconductor photonic device

according to the first preferred embodiment except that the design wavelength λ_t is changed from 980 nm to 1310 nm.

[0288] For designing the thickness of the coating film **13** having a power reflectivity R of 8% (R_t=8%) when the wavelength λ equals the design wavelength of 1310 nm, a point which provides a phase angle θ of 30 degrees is selected, for example, in Step s**1** so that the reflection amplitude vector rv is located in the first quadrant (or the upper right quadrant) of the complex plane according to the ninth preferred embodiment. Then, because the magnitude of the complex number at the selected point is 0.282842712, the values of the real and imaginary parts r_r and r_i of the complex number inputted as the value of the amplitude reflectivity r are "+0.244948974" and "+0.141421356," respectively, in Step s**2**.

[0289] When A=3.15, B=2.54 and C=2.05 are set, the basic amounts of phase change ϕ_1 and ϕ_2 determined in Step s**5** are "1.23348" and "0.560095," respectively. Accordingly, the thicknesses of the first to sixth layer films **7** to **12** determined in Step s**6** are 393.82 nm, 248.54 nm, 317.56 nm, 200.41 nm, 256.30 nm and 161.75 nm, respectively.

[0290] **FIG. 44** described above shows the wavelength dependence of the power reflectivity R of the coating film **13** thus designed. As illustrated in **FIG. 44**, the power reflectivity R is 8% when the wavelength λ equals the design wavelength of 1310 nm. A wavelength band for which the power reflectivity R is approximately equal to the design reflectivity of 8% is wide. The power reflectivity R falls within a range from 6.5% to 10.0% for the wavelength λ ranging from 1059 nm to 1509 nm.

[0291] When the allowable reflectivity range is, for example, ±2% from the design reflectivity of 8%, the wavelength band for which the power reflectivity R falls within the allowable reflectivity range is also from 1059 nm to 1509 nm, to provide a wavelength bandwidth W of 450 nm. The center wavelength λ_c of the wavelength band is 1284 nm. The value obtained by dividing the wavelength bandwidth W by the center wavelength λ_c is approximately 0.356, which is greater than 0.06. It may be said that the wavelength band for which the power reflectivity R falls within the allowable reflectivity range is a wide band.

[0292] Because the thicknesses of the first to sixth layer films **7** to **12** take on the above-mentioned values, the optical thickness t of the coating film **13**, i.e. the sum of the products of the refractive indices and thicknesses of the respective layers of the coating film **13**, is 2894.35 nm. This value is approximately 9.02 times the value t_r (321 nm) which is a quarter of the center wavelength λ_c. Thus, the coating film **13** is a very thick film. This improves heat dissipation characteristics at the end surface **1***b* of the semiconductor photonic element **1** to suppress the increase in temperature of the end surface **1***b*.

[0293] The semiconductor photonic device shown in **FIG. 2** will be considered for comparison. For the semiconductor photonic device shown in **FIG. 2**, the power reflectivity R is 8% for the wavelength λ equal to λ_c (1284 nm) when the coating film **2** having a refractive index n_f of "1.3726" and a thickness d_f of five times 223.86 nm, i.e. five times $\lambda_c/(4n_f)$, is provided on the end surface **1***b* of the semiconductor photonic element **1**. **FIG. 45** shows the wavelength dependence of the power reflectivity R in this case. As illustrated in **FIG. 45**, the wavelength band for which the power reflectivity R falls within ±2% from the design reflectivity of 8% is from 1241 nm to 1330 nm, to provide a wavelength bandwidth W_r of 89 nm.

[0294] The above-mentioned value "1.3726" of the refractive index n_f is obtained by substituting R_t=0.08 and n_c=3.37 into Equation (8).

[0295] Thus, the wavelength bandwidth W (450 nm) for the coating film **13** of the ninth preferred embodiment is greater than the wavelength bandwidth W_r (89 nm) for the coating film **2** shown in **FIG. 2**.

[0296] As mentioned above, because the wavelength λ of light propagating through the active layer **1***a* is sometimes varied, it is desirable that the center wavelength λ_c of the wavelength band for which the power reflectivity R falls within the allowable reflectivity range be equal to or close to the design wavelength λ_t. For example, the center wavelength λ_c takes on a value equal to the design wavelength λ_t of 1310 nm when the thickness of the coating film **13** is determined using the basic thicknesses d_1 and d_2 obtained by setting the basic amounts of phase change ϕ_1 and ϕ_2 at "1.23348" and "0.560095," respectively, in a similar manner to the above instance and substituting 1336 nm, rather than the design wavelength λ_t, for λ in Equations (5a) and (5b). **FIG. 46** shows the wavelength dependence of the power reflectivity R in this case.

[0297] As illustrated in **FIG. 46**, the power reflectivity R falls within a range from 6.5% to 10.0% for the wavelength λ ranging from 1080 nm to 1539 nm. The wavelength band for which the power reflectivity R falls within ±2% from the design reflectivity of 8% is also from 1080 nm to 1539 nm, to provide a wavelength bandwidth W of 459 nm. The center wavelength λ_c of the wavelength band is 1310 nm, which is equal to the design wavelength of 1310 nm. The value obtained by dividing the wavelength bandwidth W (459 nm) by the center wavelength λ_c (1310 nm) is approximately 0.350, which is greater than 0.06 and shows that the wavelength band for which the power reflectivity R falls within the allowable reflectivity range is a wide band.

[0298] In this case, the thicknesses of the first to sixth layer films **7** to **12** of the coating film **13** are 401.64 nm, 253.48 nm, 323.86 nm, 204.39 nm, 261.38 nm and 164.96 nm, respectively. The optical thickness t of the coating film **13** is 2951.80 nm. This value is approximately 9.00 times the value t_r (328 nm) which is a quarter of the center wavelength λ_c. Thus, the coating film **13** is a very thick film.

[0299] The semiconductor photonic device shown in **FIG. 2** will be considered for comparison. For the semiconductor photonic device shown in **FIG. 2**, the power reflectivity R is 8% for the wavelength λ equal to λ_c (1310 nm) when the coating film **2** having the above-mentioned refractive index n_f of "1.3726" and a thickness d_f of five times 238.60 nm, i.e. five times $\lambda_c/(4n_f)$, is provided on the end surface **1***b* of the semiconductor photonic element **1**. **FIG. 47** shows the wavelength dependence of the power reflectivity R in this case. As illustrated in **FIG. 47**, the wavelength band for which the power reflectivity R falls within ±2% from the design reflectivity of 8% is from 1266 nm to 1357 nm, to provide a wavelength bandwidth W_r of 91 nm.

[0300] Thus, even when the center wavelength λ_c is made equal to the design wavelength λ_t, the wavelength band-

width W (459 nm) for the coating film **13** is greater than the wavelength bandwidth W_r (91 nm) for the coating film **2** shown in **FIG. 2**.

Tenth Preferred Embodiment

[0301] **FIG. 48** shows the wavelength dependence of the power reflectivity R of the coating film **13** in the semiconductor photonic device according to the tenth preferred embodiment of the present invention. The semiconductor photonic device according to the tenth preferred embodiment is similar to the semiconductor photonic device according to the second preferred embodiment except that the design wavelength λ_t is changed from 808 nm to 1550 nm.

[0302] For designing the thickness of the coating film **13** having the power reflectivity R of 8% (R_t=8%) when the wavelength λ equals the design wavelength of 1550 nm, a point which provides a phase angle θ of 120 degrees is selected, for example, in Step s**1** so that the reflection amplitude vector rv is located in the second quadrant (or the upper left quadrant) of the complex plane according to the tenth preferred embodiment. Then, the values of the real and imaginary parts r_r and r_i of the complex number inputted as the value of the amplitude reflectivity r are "−0.141421356" and "+0.244948974," respectively, in Step s**2**.

[0303] When A=2.00, B=2.00 and C=2.00 are set, the basic amounts of phase change ϕ_1 and ϕ_2 determined in Step s**5** are "0.591234" and "1.06568," respectively. Accordingly, the thicknesses of the first to sixth layer films **7** to **12** determined in Step s**6** are 141.81 nm, 324.56 nm, 141.81 nm, 324.56 nm, 141.81 nm and 324.56 nm, respectively.

[0304] **FIG. 48** described above shows the wavelength dependence of the power reflectivity R of the coating film **13** thus designed. As illustrated in **FIG. 48**, the power reflectivity R is 8% when the wavelength λ equals the design wavelength of 1550 nm. A wavelength band for which the power reflectivity R is approximately equal to the design reflectivity of 8% is wide. The power reflectivity R falls within a range from 7.2% to 10.0% for the wavelength λ ranging from 1441 nm to 1868 nm.

[0305] When the allowable reflectivity range is, for example, ±2% from the design reflectivity of 8%, the wavelength band for which the power reflectivity R falls within the allowable reflectivity range is also from 1441 nm to 1868 nm, to provide a wavelength bandwidth W of 427 nm. The center wavelength λ_c of the wavelength band is 1655 nm. The value obtained by dividing the wavelength bandwidth W by the center wavelength λ_c is approximately 0.258, which is greater than 0.06. It may be said that the wavelength band for which the power reflectivity R falls within the allowable reflectivity range is a wide band.

[0306] Because the thicknesses of the first to sixth layer films **7** to **12** take on the above-mentioned values, the optical thickness t of the coating film **13** is 2452.47 nm. This value is approximately 5.92 times the value t_r (414 nm) which is a quarter of the center wavelength λ_c. Thus, the coating film **13** is a very thick film. This improves heat dissipation characteristics at the end surface **1***b* of the semiconductor photonic element **1** to suppress the increase in temperature of the end surface **1***b*.

[0307] The semiconductor photonic device shown in **FIG. 2** will be considered for comparison. For the semiconductor photonic device shown in **FIG. 2**, the power reflectivity R is 8% for the wavelength λ equal to λ_c (1655 nm) when the coating film **2** having the refractive index n_f of "1.3726" as in the ninth preferred embodiment and a thickness d_f of five times 301.44 nm, i.e. five times $\lambda_c/(4n_f)$, is provided on the end surface **1***b* of the semiconductor photonic element **1**. **FIG. 49** shows the wavelength dependence of the power reflectivity R in this case. As illustrated in **FIG. 49**, the wavelength band for which the power reflectivity R falls within ±2% from the design reflectivity of 8% is from 1600 nm to 1714 nm, to provide a wavelength bandwidth W_r of 114 nm.

[0308] Thus, the wavelength bandwidth W (427 nm) for the coating film **13** of the tenth preferred embodiment is wider than the wavelength bandwidth W_r (114 nm) for the coating film **2** shown in **FIG. 2**.

[0309] As mentioned above, because the wavelength λ of light propagating through the active layer **1***a* is sometimes varied, it is desirable that the center wavelength λ_c of the wavelength band for which the power reflectivity R falls within the allowable reflectivity range be equal to or close to the design wavelength λ_t. For example, the center wavelength λ_c takes on a value equal to the design wavelength λ_t of 1510 nm when the thickness of the coating film **13** is determined using the basic thicknesses d_1 and d_2 obtained by setting the basic amounts of phase change ϕ_1 and ϕ_2 at "0.591234" and "1.06568," respectively, in a similar manner to the above instance and substituting 1452 nm, rather than the design wavelength λ_t, for λ in Equations (5a) and (5b). **FIG. 50** shows the wavelength dependence of the power reflectivity R in this case.

[0310] As illustrated in **FIG. 50**, the power reflectivity R falls within a range from 7.2% to 10.0% for the wavelength λ ranging from 1350 nm to 1750 nm. The wavelength band for which the power reflectivity R falls within ±2% from the design reflectivity of 8% is also from 1350 nm to 1750 nm, to provide a wavelength bandwidth W of 400 nm. The center wavelength λ_c of the wavelength band is 1550 nm, which is equal to the design wavelength of 1550 nm. The value obtained by dividing the wavelength bandwidth W (400 nm) by the center wavelength λ_c (1550 nm) is approximately 0.258, which is greater than 0.06 and shows that the wavelength band for which the power reflectivity R falls within the allowable reflectivity range is a wide band.

[0311] In this case, the thicknesses of the first to sixth layer films **7** to **12** of the coating film **13** are 132.84 nm, 304.04 nm, 132.84 nm, 304.04 nm, 132.84 nm and 304.04 nm, respectively. The optical thickness t of the coating film **13** is 2297.39 nm. This value is approximately 5.92 times the value t_r (388 nm) which is a quarter of the center wavelength λ_c. Thus, the coating film **13** is a very thick film.

[0312] The semiconductor photonic device shown in **FIG. 2** will be considered for comparison. For the semiconductor photonic device shown in **FIG. 2**, the power reflectivity R is 8% for the wavelength λ equal to λ_c (1550 nm) when the coating film **2** having the above-mentioned refractive index n_f of "1.3726" and a thickness d_f of five times 282.31 nm, i.e. five times $\lambda_c/(4n_f)$, is provided on the end surface **1***b* of the semiconductor photonic element **1**. **FIG. 51** shows the wavelength dependence of the power reflectivity R in this case. As illustrated in **FIG. 51**, the wavelength band for which the power reflectivity R falls within ±2% from the

design reflectivity of 8% is from 1498 nm to 1606 nm, to provide a wavelength bandwidth W_r of 108 nm.

[0313] Thus, even when the center wavelength λ_c is made equal to the design wavelength λ_t, the wavelength bandwidth W (400 nm) for the coating film **13** is greater than the wavelength bandwidth W_r (108 nm) for the coating film **2** shown in **FIG. 2**.

Eleventh Preferred Embodiment

[0314] **FIG. 52** shows the wavelength dependence of the power reflectivity R of the coating film **21** in the semiconductor photonic device according to the eleventh preferred embodiment of the present invention. The semiconductor photonic device according to the eleventh preferred embodiment is similar to the semiconductor photonic device shown in **FIG. 15** according to the third preferred embodiment except that the material layer for the first layer film **14**, the third layer film **16**, the fifth layer film **18** and the seventh layer film **20** is changed from the alumina layer to a silicon oxide layer, that the effective refractive index n_c of the semiconductor photonic element **1** is changed from "3.37" to "2.50," and that the design wavelength λ_t is changed from 1310 nm to 410 nm.

[0315] Thus, because the silicon oxide layer is employed in place of the alumina layer, the refractive index n_2 of the first layer film **14**, the third layer film **16**, the fifth layer film **18** and the seventh layer film **20** is 1.480 according to the eleventh preferred embodiment. Because the design wavelength λ_t is 410 nm, the refractive index n_1 of the second layer film **15**, the fourth layer film **17** and the sixth layer film **19** which are the tantalum oxide layers is set at "2.128" in consideration for wavelength dispersion.

[0316] Because GaN based semiconductor is employed in the semiconductor photonic element **1** of the eleventh preferred embodiment, the effective refractive index n_c of the semiconductor photonic element **1** is "2.50," as described above.

[0317] For designing the thickness of the coating film **21** having the power reflectivity R of 8% (R_t=8%) when the wavelength λ equals the design wavelength of 410 nm, a point which provides a phase angle θ of 210 degrees is selected, for example, in Step s**1** so that the reflection amplitude vector rv is located in the third quadrant (or the lower left quadrant) of the complex plane according to the eleventh preferred embodiment. Then, the values of the real and imaginary parts r_r and r_i of the complex number inputted as the value of the amplitude reflectivity r are "−0.244948974" and "−0.141421356," respectively, in Step s**2**.

[0318] When O=0.25, A=2.35, B=2.00 and C=2.00 are set, the basic amounts of phase change ϕ_1 and ϕ_2 determined in Step s**5** are "1.98646" and "0.294825," respectively. Accordingly, the thicknesses of the first to seventh layer films **14** to **20** determined in Step s**6** are 3.25 nm, 143.15 nm, 30.55 nm, 121.83 nm, 26.00 nm, 121.83 nm and 26.00 nm, respectively.

[0319] **FIG. 52** described above shows the wavelength dependence of the power reflectivity R of the coating film **21** thus designed. As illustrated in **FIG. 52**, the power reflectivity R is 8% when the wavelength λ equals the design wavelength of 410 nm. A wavelength band for which the power reflectivity R is approximately equal to the design reflectivity of 8% is wide. The power reflectivity R falls within a range from 7.7% to 10.0% for the wavelength λ ranging from 362 nm to 424 nm.

[0320] When the allowable reflectivity range is, for example, ±2% from the design reflectivity of 8%, the wavelength band for which the power reflectivity R falls within the allowable reflectivity range is also from 362 nm to 424 nm, to provide a wavelength bandwidth W of 62 nm. The center wavelength λ_c of the wavelength band is 393 nm. The value obtained by dividing the wavelength bandwidth W by the center wavelength λ_c is approximately 0.158, which is greater than 0.06. It may be said that the wavelength band for which the power reflectivity R falls within the allowable reflectivity range is a wide band.

[0321] Because the thicknesses of the first to seventh layer films **14** to **20** take on the above-mentioned values, the optical thickness t of the coating film **21** is 950.12 nm. This value is approximately 9.70 times the value t_r (98 nm) which is a quarter of the center wavelength λ_c. Thus, the coating film **21** is a very thick film. This improves heat dissipation characteristics at the end surface **1***b* of the semiconductor photonic element **1** to suppress the increase in temperature of the end surface **1***b*.

[0322] The semiconductor photonic device shown in **FIG. 2** will be considered for comparison. For the semiconductor photonic device shown in **FIG. 2**, the power reflectivity R is 8% for the wavelength λ equal to λ_c (393 nm) when the coating film **2** having a refractive index n_f of "1.1822" and a thickness d_f of five times 83.11 nm, i.e. five times $\lambda_c/(4n_f)$, is provided on the end surface **1***b* of the semiconductor photonic element **1**. **FIG. 53** shows the wavelength dependence of the power reflectivity R in this case. As illustrated in **FIG. 53**, the wavelength band for which the power reflectivity R falls within ±2% from the design reflectivity of 8% is from 373 nm to 415 nm, to provide a wavelength bandwidth W_r of 42 nm.

[0323] The above-mentioned value "1.1822" of the refractive index n_f is obtained by substituting R_t=0.08 and n_c=2.50 into Equation (8).

[0324] Thus, the wavelength bandwidth W (62 nm) for the coating film **21** of the eleventh preferred embodiment is greater than the wavelength bandwidth W_r (42 nm) for the coating film **2** shown in **FIG. 2**.

[0325] As mentioned above, because the wavelength λ of light propagating through the active layer **1***a* is sometimes varied, it is desirable that the center wavelength λ_c of the wavelength band for which the power reflectivity R falls within the allowable reflectivity range be equal to or close to the design wavelength λ_t. For example, the center wavelength λ_c takes on a value equal to the design wavelength λ_t of 410 nm when the thickness of the coating film **21** is determined using the basic thicknesses d_1 and d_2 obtained by setting the basic amounts of phase change ϕ_1 and ϕ_2 at "1.98646" and "0.294825," respectively, in a similar manner to the above instance and substituting 427 nm, rather than the design wavelength λ_t, for λ in Equations (5a) and (5b). **FIG. 54** shows the wavelength dependence of the power reflectivity R in this case.

[0326] As illustrated in **FIG. 54**, the power reflectivity R falls within a range from 7.7% to 10.0% for the wavelength

λ ranging from 377 nm to 442 nm. The wavelength band for which the power reflectivity R falls within ±2% from the design reflectivity of 8% is also from 377 nm to 442 nm, to provide a wavelength bandwidth W of 65 nm. The center wavelength λ_c of the wavelength band is 410 nm, which is equal to the design wavelength of 410 nm. The value obtained by dividing the wavelength bandwidth W (65 nm) by the center wavelength λ_c (410 nm) is approximately 0.159, which is greater than 0.06 and shows that the wavelength band for which the power reflectivity R falls within the allowable reflectivity range is a wide band.

[0327] In this case, the thicknesses of the first to seventh layer films **14** to **20** of the coating film **21** are 3.38 nm, 149.08 nm, 31.81 nm, 126.88 nm, 27.08 nm, 126.88 nm and 27.08 nm, respectively. The optical thickness t of the coating film **21** is 989.48 nm. This value is approximately 9.61 times the value t_r (103 nm) which is a quarter of the center wavelength λ_c. Thus, the coating film **21** is a very thick film.

[0328] The semiconductor photonic device shown in **FIG. 2** will be considered for comparison. For the semiconductor photonic device shown in **FIG. 2**, the power reflectivity R is 8% for the wavelength λ equal to λ_c (410 nm) when the coating film **2** having the above-mentioned refractive index n_f of "1.1822" and a thickness d_f of five times 86.70 nm, i.e. five times $\lambda_c/(4n_f)$, is provided on the end surface **1***b* of the semiconductor photonic element **1**. **FIG. 55** shows the wavelength dependence of the power reflectivity R in this case. As illustrated in **FIG. 55**, the wavelength band for which the power reflectivity R falls within ±2% from the design reflectivity of 8% is from 389 nm to 433 nm, to provide a wavelength bandwidth W_r of 44 nm.

[0329] Thus, even when the center wavelength λ_c is made equal to the design wavelength λ_t, the wavelength bandwidth W (65 nm) for the coating film **21** is greater than the wavelength bandwidth W_r (44 nm) for the coating film **2** shown in **FIG. 2**.

Twelfth Preferred Embodiment

[0330] **FIG. 56** shows the wavelength dependence of the power reflectivity R of the coating film **29** in the semiconductor photonic device according to the twelfth preferred embodiment of the present invention. The semiconductor photonic device according to the twelfth preferred embodiment is similar to the semiconductor photonic device shown in **FIG. 20** according to the fourth preferred embodiment except that the design wavelength λ_t is changed from 1550 nm to 650 nm.

[0331] For designing the thickness of the coating film **29** having the power reflectivity R of 8% (R_t=8%) when the wavelength λ equals the design wavelength of 650 nm, a point which provides a phase angle θ of 300 degrees is selected, for example, in Step s**1** so that the reflection amplitude vector rv is located in the fourth quadrant (or the lower right quadrant) of the complex plane according to the twelfth preferred embodiment. Then, the values of the real and imaginary parts r_r and r_i of the complex number inputted as the value of the amplitude reflectivity r are "+0.141421356" and "−0.244948974," respectively, in Step s**2**.

[0332] When A=1.23, B=2.00, C=2.00 and d_3=10.0 nm are set, the basic amounts of phase change ϕ_1 and ϕ_2 determined in Step s**5** are "0.707793" and "2.25201," respectively. Accordingly, the thicknesses of the second to seventh layer films **23** to **28** determined in Step s**6** are 43.78 nm, 176.89 nm, 71.19 nm, 287.62 nm, 71.19 nm and 287.62 nm, respectively.

[0333] **FIG. 56** described above shows the wavelength dependence of the power reflectivity R of the coating film **29** thus designed. As illustrated in **FIG. 56**, the power reflectivity R is 8% when the wavelength λ equals the design wavelength of 650 nm. A wavelength band for which the power reflectivity R is approximately equal to the design reflectivity of 8% is wide. The power reflectivity R falls within a range from 6.0% to 10.0% for the wavelength λ ranging from 594 nm to 709 nm.

[0334] When the allowable reflectivity range is, for example, ±2% from the design reflectivity of 8%, the wavelength band for which the power reflectivity R falls within the allowable reflectivity range is also from 594 nm to 709 nm, to provide a wavelength bandwidth W of 115 nm. The center wavelength λ_c of the wavelength band is 652 nm. The value obtained by dividing the wavelength bandwidth W by the center wavelength λ_c is approximately 0.176, which is greater than 0.06. It may be said that the wavelength band for which the power reflectivity R falls within the allowable reflectivity range is a wide band.

[0335] Because the thicknesses of the first to seventh layer films **22** to **28** take on the above-mentioned values, the optical thickness t of the coating film **29** is 1622.10 nm. This value is approximately 9.95 times the value t_r (163 nm) which is a quarter of the center wavelength λ_c. Thus, the coating film **29** is a very thick film. This improves heat dissipation characteristics at the end surface **1***b* of the semiconductor photonic element **1** to suppress the increase in temperature of the end surface **1***b*.

[0336] The semiconductor photonic device shown in **FIG. 2** will be considered for comparison. For the semiconductor photonic device shown in **FIG. 2**, the power reflectivity R is 8% for the wavelength λ equal to λ_c (652 nm) when the coating film **2** having the refractive index n_f of "1.3726" as in the ninth preferred embodiment and a thickness d_f of five times 118.75 nm, i.e. five times $\lambda_c/(4n_f)$, is provided on the end surface **1***b* of the semiconductor photonic element **1**. **FIG. 57** shows the wavelength dependence of the power reflectivity R in this case. As illustrated in **FIG. 57**, the wavelength band for which the power reflectivity R falls within ±2% from the design reflectivity of 8% is from 630 nm to 675 nm, to provide a wavelength bandwidth W_r of 45 nm.

[0337] Thus, the wavelength bandwidth W (115 nm) for the coating film **29** of the twelfth preferred embodiment is greater than the wavelength bandwidth W_r (45 nm) for the coating film **2** shown in **FIG. 2**.

[0338] As mentioned above, because the wavelength λ of light propagating through the active layer **1***a* is sometimes varied, it is desirable that the center wavelength λ_c of the wavelength band for which the power reflectivity R falls within the allowable reflectivity range be equal to or close to the design wavelength λ_t. For example, the thickness d_3=10.0 nm is set, and the basic amounts of phase change ϕ_1 and ϕ_2 are set at "0.70747" and "2.25219," respectively, by adjusting the parameters A to C. The center wavelength λ_c

takes on a value equal to the design wavelength of 650 nm when the thickness of the coating film **29** is determined using the basic thicknesses d_1 and d_2 obtained by substituting the design wavelength of 650 nm for λ in Equations (5a) and (5b). **FIG. 58** shows the wavelength dependence of the power reflectivity R in this case.

[**0339**] As illustrated in **FIG. 58**, the power reflectivity R falls within a range from 6.0% to 10.0% for the wavelength λ ranging from 592 nm to 707 nm. The wavelength band for which the power reflectivity R falls within ±2% from the design reflectivity of 8% is also from 592 nm to 707 nm, to provide a wavelength bandwidth W of 115 nm. The center wavelength λ_c of the wavelength band is 650 nm, which is equal to the design wavelength of 650 nm. The value obtained by dividing the wavelength bandwidth W (115 nm) by the center wavelength λ_c (650 nm) is approximately 0.177, which is greater than 0.06 and shows that the wavelength band for which the power reflectivity R falls within the allowable reflectivity range is a wide band.

[**0340**] In this case, the thicknesses of the first to seventh layer films **22** to **28** of the coating film **29** are 10.00 nm, 43.63 nm, 176.36 nm, 70.94 nm, 286.76 nm, 70.94 nm and 286.76 nm, respectively. The optical thickness t of the coating film **29** is 1617.12 nm. This value is approximately 9.92 times the value t_r (163 nm) which is a quarter of the center wavelength λ_c. Thus, the coating film **29** is a very thick film.

[**0341**] The semiconductor photonic device shown in **FIG. 2** will be considered for comparison. For the semiconductor photonic device shown in **FIG. 2**, the power reflectivity R is 8% for the wavelength λ equal to λ_c (650 nm) when the coating film **2** having the above-mentioned refractive index n_f of "1.3726" and a thickness d_f of five times 118.39 nm, i.e. five times $\lambda_c/(4n_f)$, is provided on the end surface **1***b* of the semiconductor photonic element **1**. **FIG. 59** shows the wavelength dependence of the power reflectivity R in this case. As illustrated in **FIG. 59**, the wavelength band for which the power reflectivity R falls within ±2% from the design reflectivity of 8% is from 629 nm to 673 nm, to provide a wavelength bandwidth W_r of 44 nm.

[**0342**] Thus, even when the center wavelength λ_c is made equal to the design wavelength λ_t, the wavelength bandwidth W (115 nm) for the coating film **29** is greater than the wavelength bandwidth W_r (44 nm) for the coating film **2** shown in **FIG. 2**.

Thirteenth Preferred Embodiment

[**0343**] **FIG. 60** shows the wavelength dependence of the power reflectivity R of the coating film **38** in the semiconductor photonic device according to the thirteenth preferred embodiment of the present invention. The semiconductor photonic device according to the thirteenth preferred embodiment is similar to the semiconductor photonic device shown in **FIG. 25** according to the fifth preferred embodiment except that the design wavelength λ_t is changed from 410 nm to 980 nm.

[**0344**] For designing the thickness of the coating film **38** having the power reflectivity R of 8% (R_t=8%) when the wavelength λ equals the design wavelength of 980 nm, a point which provides a phase angle θ of 15 degrees is selected, for example, in Step s**1** so that the reflection amplitude vector rv is located in the first quadrant (or the upper right quadrant), of the complex plane according to the thirteenth preferred embodiment. Then, the values of the real and imaginary parts r_r and r_i of the complex number inputted as the value of the amplitude reflectivity r are "+0.27320508" and "+0.07320508," respectively, in Step s**2**.

[**0345**] When A=1.96, B=1.31, C=2.02 and D=2.00 are set, the basic amounts of phase change ϕ_1 and ϕ_2 determined in Step s**5** are "0.30917" and "1.12523," respectively. Accordingly, the thicknesses of the first to eighth layer films **30** to **37** determined in Step s**6** are 45.95 nm, 232.49 nm, 26.49 nm, 134.00 nm, 47.35 nm, 239.54 nm, 46.89 nm and 237.17 nm, respectively.

[**0346**] **FIG. 60** described above shows the wavelength dependence of the power reflectivity R of the coating film **38** thus designed. As illustrated in **FIG. 60**, the power reflectivity R is 8% when the wavelength λ equals the design wavelength of 980 nm. A wavelength band for which the power reflectivity R is approximately equal to the design reflectivity of 8% is wide. The power reflectivity R falls within a range from 6.0% to 10.0% for the wavelength λ ranging from 934 nm to 1129 nm.

[**0347**] When the allowable reflectivity range is, for example, ±2% from the design reflectivity of 8%, the wavelength band for which the power reflectivity R falls within the allowable reflectivity range is also from 934 nm to 1129 nm, to provide a wavelength bandwidth W of 195 nm. The center wavelength λ_c of the wavelength band is 1032 nm. The value obtained by dividing the wavelength bandwidth W by the center wavelength λ_c is approximately 0.189, which is greater than 0.06. It may be said that the wavelength band for which the power reflectivity R falls within the allowable reflectivity range is a wide band.

[**0348**] Because the thicknesses of the first to eighth layer films **30** to **37** take on the above-mentioned values, the optical thickness t of the coating film **38** is 1590.80 nm. This value is approximately 6.17 times the value t_r (258 nm) which is a quarter of the center wavelength λ_c. Thus, the coating film **38** is a very thick film. This improves heat dissipation characteristics at the end surface **1***b* of the semiconductor photonic element **1** to suppress the increase in temperature of the end surface **1***b*.

[**0349**] The semiconductor photonic device shown in **FIG. 2** will be considered for comparison. For the semiconductor photonic device shown in **FIG. 2**, the power reflectivity R is 8% for the wavelength λ equal to λ_c (1032 nm) when the coating film **2** having the refractive index n_f of "1.3726" as in the ninth preferred embodiment and a thickness d_f of five times 187.96 nm, i.e. five times $\lambda_c/(4n_f)$, is provided on the end surface **1***b* of the semiconductor photonic element **1**. **FIG. 61** shows the wavelength dependence of the power reflectivity R in this case. As illustrated in **FIG. 61**, the wavelength band for which the power reflectivity R falls within ±2% from the design reflectivity of 8% is from 998 nm to 1069 nm, to provide a wavelength bandwidth W_r of 71 nm.

[**0350**] Thus, the wavelength bandwidth W (195 nm) for the coating film **38** of the thirteenth preferred embodiment is greater than the wavelength bandwidth W_r (71 nm) for the coating film **2** shown in **FIG. 2**.

[**0351**] As mentioned above, because the wavelength λ of light propagating through the active layer **1***a* is sometimes

varied, it is desirable that the center wavelength λ_c of the wavelength band for which the power reflectivity R falls within the allowable reflectivity range be equal to or close to the design wavelength λ_t. For example, the center wavelength λ_c takes on a value equal to the design wavelength λ_t of 980 nm when the thickness of the coating film **38** is determined using the basic thicknesses d_1 and d_2 obtained by setting the basic amounts of phase change ϕ_1 and ϕ_2 at "0.30917" and "1.12523," respectively, in a similar manner to the above instance and substituting 931 nm, rather than the design wavelength λ_t, for λ in Equations (5a) and (5b). **FIG. 62** shows the wavelength dependence of the power reflectivity R in this case.

[**0352**] As illustrated in **FIG. 62**, the power reflectivity R falls within a range from 6.0% to 10.0% for the wavelength λ ranging from 887 nm to 1073 nm. The wavelength band for which the power reflectivity R falls within ±2% from the design reflectivity of 8% is also from 887 nm to 1073 nm, to provide a wavelength bandwidth W of 186 nm. The center wavelength λ_c of the wavelength band is 980 nm, which is equal to the design wavelength of 980 nm. The value obtained by dividing the wavelength bandwidth W (186 nm) by the center wavelength λ_c (980 nm) is approximately 0.190, which is greater than 0.06 and shows that the wavelength band for which the power reflectivity R falls within the allowable reflectivity range is a wide band.

[**0353**] In this case, the thicknesses of the first to eighth layer films **30** to **37** of the coating film **38** are 43.65 nm, 220.80 nm, 25.17 nm, 127.30 nm, 44.99 nm, 227.56 nm, 44.54 nm and 225.31 nm, respectively. The optical thickness t of the coating film **38** is 1511.16 nm. This value is approximately 6.17 times the value t_r (245 nm) which is a quarter of the center wavelength λ_c. Thus, the coating film **38** is a very thick film.

[**0354**] The semiconductor photonic device shown in **FIG. 2** will be considered for comparison. For the semiconductor photonic device shown in **FIG. 2**, the power reflectivity R is 8% for the wavelength λ equal to λ_c (980 nm) when the coating film **2** having the above-mentioned refractive index n_f of "1.3726" and a thickness d_f of five times 178.49 nm, i.e. five times $\lambda_c/(4n_f)$, is provided on the end surface **1***b* of the semiconductor photonic element **1**. **FIG. 63** shows the wavelength dependence of the power reflectivity R in this case. As illustrated in **FIG. 63**, the wavelength band for which the power reflectivity R falls within ±2% from the design reflectivity of 8% is from 947 nm to 1015 nm, to provide a wavelength bandwidth W_r of 68 nm.

[**0355**] Thus, even when the center wavelength λ_c is made equal to the design wavelength λ_t, the wavelength bandwidth W (186 nm) for the coating film **38** is greater than the wavelength bandwidth W_r (68 nm) for the coating film **2** shown in **FIG. 2**.

Fourteenth Preferred Embodiment

[**0356**] **FIG. 64** shows the wavelength dependence of the power reflectivity R of the coating film **47** in the semiconductor photonic device according to the fourteenth preferred embodiment of the present invention. The semiconductor photonic device according to the fourteenth preferred embodiment is similar to the semiconductor photonic device shown in **FIG. 30** according to the sixth preferred embodiment except that the material layer for the second layer film **40**, the fourth layer film **42**, the sixth layer film **44** and the eighth layer film **46** is changed from the silicon oxide layer to a tantalum oxide layer, that the material layer for the third layer film **41**, the fifth layer film **43** and the seventh layer film **45** is changed from the tantalum oxide layer to a silicon oxide layer, and that the design wavelength λ_t is changed from 650 nm to 808 nm. Accordingly, the values of the refractive indices n_1 and n_2 are "1.480" and "2.057," respectively, according to the fourteenth preferred embodiment.

[**0357**] For designing the thickness of the coating film **47** having the power reflectivity R of 8% (R_t=8%) when the wavelength λ equals the design wavelength of 808 nm, a point which provides a phase angle θ of 105 degrees is selected, for example, in Step s**1** so that the reflection amplitude vector rv is located in the second quadrant (or the upper left quadrant) of the complex plane according to the fourteenth preferred embodiment. Then, the values of the real and imaginary parts r_r and r_i of the complex number inputted as the value of the amplitude reflectivity r are "−0.07320508" and "+0.27320508," respectively, in Step s**2**.

[**0358**] When A=2.13, B=2.33, C=2.00, D=2.00 and the thickness d_3=20.0 nm are set, the basic amounts of phase change ϕ_1 and ϕ_2 determined in Step s**5** are "1.94893" and "0.761851," respectively. Accordingly, the thicknesses of the second to eighth layer films **40** to **46** determined in Step s**6** are 101.45 nm, 394.57 nm, 110.98 nm, 338.69 nm, 95.26 nm, 338.69 nm and 95.26 nm, respectively.

[**0359**] **FIG. 64** described above shows the wavelength dependence of the power reflectivity R of the coating film **47** thus designed. As illustrated in **FIG. 64**, the power reflectivity R is 8% when the wavelength λ equals the design wavelength of 808 nm. A wavelength band for which the power reflectivity R is approximately equal to the design reflectivity of 8% is wide. The power reflectivity R falls within a range from 6.3% to 10.0% for the wavelength λ ranging from 804 nm to 893 nm.

[**0360**] When the allowable reflectivity range is, for example, ±2% from the design reflectivity of 8%, the wavelength band for which the power reflectivity R falls within the allowable reflectivity range is also from 804 nm to 893 nm, to provide a wavelength bandwidth W of 89 nm. The center wavelength λ_c of the wavelength band is 849 nm. The value obtained by dividing the wavelength bandwidth W by the center wavelength λ_c is approximately 0.105, which is greater than 0.06. It may be said that the wavelength band for which the power reflectivity R falls within the allowable reflectivity range is a wide band.

[**0361**] Because the thicknesses of the first to eighth layer films **39** to **46** take on the above-mentioned values, the optical thickness t of the coating film **47** is 2456.79 nm. This value is approximately 11.59 times the value t_r (212 nm) which is a quarter of the center wavelength λ_c. Thus, the coating film **47** is a very thick film. This improves heat dissipation characteristics at the end surface **1***b* of the semiconductor photonic element **1** to suppress the increase in temperature of the end surface **1***b*.

[**0362**] The semiconductor photonic device shown in **FIG. 2** will be considered for comparison. For the semiconductor photonic device shown in **FIG. 2**, the power reflectivity R is 8% for the wavelength λ equal to λ_c (849 nm) when the coating film **2** having the refractive index n_f of "1.3726" as

in the ninth preferred embodiment and a thickness d_f of five times 154.63 nm, i.e. five times $\lambda_c/(4n_f)$, is provided on the end surface **1***b* of the semiconductor photonic element **1**. **FIG. 65** shows the wavelength dependence of the power reflectivity R in this case. As illustrated in **FIG. 65**, the wavelength band for which the power reflectivity R falls within ±2% from the design reflectivity of 8% is from 821 nm to 879 nm, to provide a wavelength bandwidth W_r of 58 nm.

[**0363**] Thus, the wavelength bandwidth W (89 nm) for the coating film **47** of the fourteenth preferred embodiment is greater than the wavelength bandwidth W_r (58 nm) for the coating film **2** shown in **FIG. 2**.

[**0364**] As mentioned above, because the wavelength λ of light propagating through the active layer **1***a* is sometimes varied, it is desirable that the center wavelength λ_c of the wavelength band for which the power reflectivity R falls within the allowable reflectivity range be equal to or close to the design wavelength λ_t. For example, the thickness d_3=20.0 nm is set in the above-mentioned instance, and the basic amounts of phase change ϕ_1 and ϕ_2 are set at "1.96555" and "0.745004," respectively, by adjusting the parameters A to D. The center wavelength λ_c takes on a value equal to the design wavelength λ_t of 808 nm when the thickness of the coating film **47** is determined using the basic thicknesses d_1 and d_2 obtained by substituting 770 nm, rather than the design wavelength λ_t, for λ in Equations (5a) and (5b). **FIG. 66** shows the wavelength dependence of the power reflectivity R in this case.

[**0365**] As illustrated in **FIG. 66**, the power reflectivity R falls within a range from 6.1% to 10.0% for the wavelength λ ranging from 766 nm to 850 nm. The wavelength band for which the power reflectivity R falls within ±2% from the design reflectivity of 8% is also from 766 nm to 850 nm, to provide a wavelength bandwidth W of 84 nm. The center wavelength λ_c of the wavelength band is 808 nm, which is equal to the design wavelength of 808 nm. The value obtained by dividing the wavelength bandwidth W (84 nm) by the center wavelength λ_c (808 nm) is approximately 0.104, which is greater than 0.06 and shows that the wavelength band for which the power reflectivity R falls within the allowable reflectivity range is a wide band.

[**0366**] In this case, the thicknesses of the first to eighth layer films **39** to **46** of the coating film **47** are 20.00 nm, 94.54 nm, 379.22 nm, 103.42 nm, 325.51 nm, 88.77 nm, 325.51 nm and 88.77 nm, respectively. The optical thickness t of the coating film **47** is 2338.60 nm. This value is approximately 11.58 times the value t_r (202 nm) which is a quarter of the center wavelength λ_c. Thus, the coating film **47** is a very thick film.

[**0367**] The semiconductor photonic device shown in **FIG. 2** will be considered for comparison. For the semiconductor photonic device shown in **FIG. 2**, the power reflectivity R is 8% for the wavelength λ equal to λ_c (808 nm) when the coating film **2** having the above-mentioned refractive index n_f of "1.3726" and a thickness d_f of five times 147.17 nm, i.e. five times $\lambda_c/(4n_f)$, is provided on the end surface **1***b* of the semiconductor photonic element **1**. **FIG. 67** shows the wavelength dependence of the power reflectivity R in this case. As illustrated in **FIG. 67**, the wavelength band for which the power reflectivity R falls within ±2% from the design reflectivity of 8% is from 781 nm to 837 nm, to provide a wavelength bandwidth W_r of 56 nm.

[**0368**] Thus, even when the center wavelength λ_c is made equal to the design wavelength λ_t, the wavelength bandwidth W (84 nm) for the coating film **47** is greater than the wavelength bandwidth W_r (56 nm) for the coating film **2** shown in **FIG. 2**.

Fifteenth Preferred Embodiment

[**0369**] **FIG. 68** shows the wavelength dependence of the power reflectivity R of the coating film **57** in the semiconductor photonic device according to the fifteenth preferred embodiment of the present invention. The semiconductor photonic device according to the fifteenth preferred embodiment is similar to the semiconductor photonic device shown in **FIG. 35** according to the seventh preferred embodiment except that the material layer for the first layer film **48**, the third layer film **50**, the fifth layer film **52**, the seventh layer film **54** and the ninth layer film **56** is changed from the alumina layer to a tantalum oxide layer, that the material layer for the second layer film **49**, the fourth layer film **51**, the sixth layer film **53** and the eighth layer film **55** is changed from the tantalum oxide layer to an alumina layer, and that the design wavelength λ_t is changed from 980 nm to 1310 nm. Accordingly, the values of the refractive indices n_1 and n_2 are "1.620" and "2.057," respectively.

[**0370**] For designing the thickness of the coating film **57** having the power reflectivity R of 8% (R_t=8%) when the wavelength λ equals the design wavelength of 1310 nm, a point which provides a phase angle θ of 195 degrees is selected, for example, in Step s**1** so that the reflection amplitude vector rv is located in the third quadrant (or the lower left quadrant) of the complex plane according to the fifteenth preferred embodiment. Then, the values of the real and imaginary parts r_r and r_i of the complex number inputted as the value of the amplitude reflectivity r are "−0.27320508" and "−0.07320508," respectively, in Step s**2**.

[**0371**] When O=2.05, A=4.20, B=2.00, C=2.00 and D=2.00 are set, the basic amounts of phase change ϕ_1 and ϕ_2 determined in Step s**5** are "0.410749" and "0.777027," respectively. Accordingly, the thicknesses of the first to ninth layer films **48** to **56** determined in Step s**6** are 161.45 nm, 222.03 nm, 330.78 nm, 105.73 nm, 157.52 nm, 105.73 nm, 157.52 nm, 105.73 nm and 157.52 nm, respectively.

[**0372**] **FIG. 68** described above shows the wavelength dependence of the power reflectivity R of the coating film **57** thus designed. As illustrated in **FIG. 68**, the power reflectivity R is 8% when the wavelength λ equals the design wavelength of 1310 nm. A wavelength band for which the power reflectivity R is approximately equal to the design reflectivity of 8% is wide. The power reflectivity R falls within a range from 6.0% to 10.0% for the wavelength λ ranging from 1358 nm to 1626 nm.

[**0373**] When the allowable reflectivity range is, for example, ±2% from the design reflectivity of 8%, the wavelength band for which the power reflectivity R falls within the allowable reflectivity range is also from 1358 nm to 1626 nm, to provide a wavelength bandwidth W of 268 nm. The center wavelength λ_c of the wavelength band is 1492 nm. The value obtained by dividing the wavelength bandwidth W by the center wavelength λ_c is approximately 0.180, which is greater than 0.06. It may be said that the wavelength band for which the power reflectivity R falls within the allowable reflectivity range is a wide band.

[0374] Because the thicknesses of the first to ninth layer films **48** to **56** take on the above-mentioned values, the optical thickness t of the coating film **57** is 2858.11 nm. This value is approximately 7.66 times the value t_r (373 nm) which is a quarter of the center wavelength λ_c. Thus, the coating film **57** is a very thick film. This improves heat dissipation characteristics at the end surface **1***b* of the semiconductor photonic element **1** to suppress the increase in temperature of the end surface **1***b*.

[0375] The semiconductor photonic device shown in **FIG. 2** will be considered for comparison. For the semiconductor photonic device shown in **FIG. 2**, the power reflectivity R is 8% for the wavelength λ equal to λ_c (1492 nm) when the coating film **2** having the refractive index n_f of "1.3726" as in the ninth preferred embodiment and a thickness d_f of five times 271.75 nm, i.e. five times $\lambda_c/(4n_f)$, is provided on the end surface **1***b* of the semiconductor photonic element **1**. **FIG. 69** shows the wavelength dependence of the power reflectivity R in this case. As illustrated in **FIG. 69**, the wavelength band for which the power reflectivity R falls within ±2% from the design reflectivity of 8% is from 1442 nm to 1545 nm, to provide a wavelength bandwidth W_r of 103 nm.

[0376] Thus, the wavelength bandwidth W (268 nm) for the coating film **57** of the fifteenth preferred embodiment is greater than the wavelength bandwidth W_r (103 nm) for the coating film **2** shown in **FIG. 2**.

[0377] As mentioned above, because the wavelength λ of light propagating through the active layer **1***a* is sometimes varied, it is desirable that the center wavelength λ_c of the wavelength band for which the power reflectivity R falls within the allowable reflectivity range be equal to or close to the design wavelength λ_t. For example, the center wavelength λ_c takes on a value equal to the design wavelength λ_t of 1310 nm when the thickness of the coating film **57** is determined using the basic thicknesses d_1 and d_2 obtained by setting the basic amounts of phase change ϕ_1 and ϕ_2 at "0.410749" and "0.777027," respectively, in a similar manner to the above instance and substituting 1150 nm, rather than the design wavelength λ_t, for λ in Equations (5a) and (5b). **FIG. 70** shows the wavelength dependence of the power reflectivity R in this case.

[0378] As illustrated in **FIG. 70**, the power reflectivity R falls within a range from 6.0% to 10.0% for the wavelength λ ranging from 1192 nm to 1427 nm. The wavelength band for which the power reflectivity R falls within ±2% from the design reflectivity of 8% is also from 1192 nm to 1427 nm, to provide a wavelength bandwidth W of 235 nm. The center wavelength λ_c of the wavelength band is 1310 nm, which is equal to the design wavelength of 1310 nm. The value obtained by dividing the wavelength bandwidth W (235 nm) by the center wavelength λ_c (1310 nm) is approximately 0.179, which is greater than 0.06 and shows that the wavelength band for which the power reflectivity R falls within the allowable reflectivity range is a wide band.

[0379] In this case, the thicknesses of the first to ninth layer films **48** to **56** of the coating film **57** are 141.73 nm, 194.91 nm, 290.38 nm, 92.81 nm, 138.28 nm, 92.81 nm, 138.28 nm, 92.81 nm and 138.28 nm, respectively. The optical thickness t of the coating film **57** is 2508.99 nm. This value is approximately 7.65 times the value t_r (328 nm) which is a quarter of the center wavelength λ_c. Thus, the coating film **57** is a very thick film.

[0380] For the semiconductor photonic device shown in **FIG. 2**, the power reflectivity R is 8% for the wavelength λ equal to λ_c (1310 nm) when the coating film **2** having the above-mentioned refractive index n_f of "1.3726" and a thickness d_f of five times 238.60 nm, i.e. five times $\lambda_c/(4n_f)$, is provided on the end surface **1***b* of the semiconductor photonic element **1**. **FIG. 71** shows the wavelength dependence of the power reflectivity R in this case. As illustrated in **FIG. 71**, the wavelength band for which the power reflectivity R falls within ±2% from the design reflectivity of 8% is from 1266 nm to 1357 nm, to provide a wavelength bandwidth W_r of 91 nm.

[0381] Thus, even when the center wavelength λ_c is made equal to the design wavelength λ_t, the wavelength bandwidth W (235 nm) for the coating film **57** is greater than the wavelength bandwidth W_r (91 nm) for the coating film **2** shown in **FIG. 2**.

Sixteenth Preferred Embodiment

[0382] **FIG. 72** shows the wavelength dependence of the power reflectivity R of the coating film **68** in the semiconductor photonic device according to the sixteenth preferred embodiment of the present invention. The semiconductor photonic device according to the sixteenth preferred embodiment is similar to the semiconductor photonic device shown in **FIG. 39** according to the eighth preferred embodiment except that the material layer for the first layer film **58** is changed from the alumina layer to an aluminum nitride layer, that the material layer for the third layer film **60**, the fifth layer film **62**, the seventh layer film **64** and the ninth layer film **66** is changed from the aluminum nitride layer to a tantalum oxide layer, and that the design wavelength λ_t is changed from 808 nm to 1550 nm. Accordingly, the values of the refractive indices n_1 and n_2 are "2.057" and "2.072," respectively, according to the sixteenth preferred embodiment.

[0383] For designing the thickness of the coating film **68** having the power reflectivity R of 8% (R_t=8%) when the wavelength λ equals the design wavelength of 1550 nm, a point which provides a phase angle θ of 285 degrees is selected, for example, in Step s**1** so that the reflection amplitude vector rv is located in the fourth quadrant (or the lower right quadrant) of the complex plane according to the sixteenth preferred embodiment. Then, the values of the real and imaginary parts r_r and r_i of the complex number inputted as the value of the amplitude reflectivity r are "+0.07320508" and "−0.27320508," respectively, in Step s**2**.

[0384] When A=2.10, B=1.30, C=2.00, D=2.00, E=1.65 and the thickness d_3=20.0 nm are set, the basic amounts of phase change ϕ_1 and ϕ_2 determined in Step s**5** are "0.722395" and "1.59546," respectively. Accordingly, the thicknesses of the second to tenth layer films **59** to **67** determined in Step s**6** are 558.47 nm, 112.63 nm, 345.72 nm, 173.27 nm, 531.87 nm, 173.27 nm, 531.87 nm, 142.95 nm and 438.79 nm, respectively.

[0385] **FIG. 72** described above shows the wavelength dependence of the power reflectivity R of the coating film **68** thus designed. As illustrated in **FIG. 72**, the power reflectivity R is 8% when the wavelength λ equals the design wavelength of 1550 nm. A wavelength band for which the power reflectivity R is approximately equal to the design reflectivity of 8% is wide. The power reflectivity R falls

within a range from 7.6% to 10.0% for the wavelength λ ranging from 1534 nm to 1659 nm.

[0386] When the allowable reflectivity range is, for example, ±2% from the design reflectivity of 8%, the wavelength band for which the power reflectivity R falls within the allowable reflectivity range is also from 1534 nm to 1659 nm, to provide a wavelength bandwidth W of 125 nm. The center wavelength λ_c of the wavelength band is 1597 nm. The value obtained by dividing the wavelength bandwidth W by the center wavelength λ_c is approximately 0.078, which is greater than 0.06. It may be said that the wavelength band for which the power reflectivity R falls within the allowable reflectivity range is a wide band.

[0387] Because the thicknesses of the first to tenth layer films **58** to **67** take on the above-mentioned values, the optical thickness t of the coating film **68** is 4841.95 nm. This value is approximately 12.14 times the value t_r (399 nm) which is a quarter of the center wavelength λ_c. Thus, the coating film **68** is a very thick film. This improves heat dissipation characteristics at the end surface **1***b* of the semiconductor photonic element **1** to suppress the increase in temperature of the end surface **1***b*.

[0388] The semiconductor photonic device shown in **FIG. 2** will be considered for comparison. For the semiconductor photonic device shown in **FIG. 2**, the power reflectivity R is 8% for the wavelength λ equal to λ_c (1597 nm) when the coating film **2** having the refractive index n_f of "1.3726" as in the ninth preferred embodiment and a thickness d_f of five times 290.87 nm, i.e. five times $\lambda_c/(4n_f)$, is provided on the end surface **1***b* of the semiconductor photonic element **1**. **FIG. 73** shows the wavelength dependence of the power reflectivity R in this case. As illustrated in **FIG. 73**, the wavelength band for which the power reflectivity R falls within ±2% from the design reflectivity of 8% is from 1544 nm to 1654 nm, to provide a wavelength bandwidth W_r of 110 nm.

[0389] Thus, the wavelength bandwidth W (125 nm) for the coating film **68** of the sixteenth preferred embodiment is greater than the wavelength bandwidth W_r (110 nm) for the coating film **2** shown in **FIG. 2**.

[0390] As mentioned above, because the wavelength λ of light propagating through the active layer **1***a* is sometimes varied, it is desirable that the center wavelength λ_c of the wavelength band for which the power reflectivity R falls within the allowable reflectivity range be equal to or close to the design wavelength λ_t. For example, when the thickness d_3=20.0 nm, A=2.10, B=1.30, C=2.00, D=2.00 and E=1.65 are set, the basic amounts of phase change ϕ_1 and ϕ_2 are "0.723268" and "1.59370," respectively. The center wavelength λ_c takes on a value equal to the design wavelength of 1550 nm when the thickness of the coating film **68** is determined using the basic thicknesses d_1 and d_2 obtained by substituting the above-mentioned values of the basic amounts of phase change ϕ_1 and ϕ_2 into Equations (5a) and (5b) and substituting 1505 nm, rather than the design wavelength λ_t, for λ in Equations (5a) and (5b). **FIG. 74** shows the wavelength dependence of the power reflectivity R in this case.

[0391] As illustrated in **FIG. 74**, the power reflectivity R falls within a range from 7.6% to 10.0% for the wavelength λ ranging from 1489 nm to 1610 nm. The wavelength band for which the power reflectivity R falls within ±2% from the design reflectivity of 8% is also from 1489 nm to 1610 nm, to provide a wavelength bandwidth W of 121 nm. The center wavelength λ_c of the wavelength band is 1550 nm, which is equal to the design wavelength of 1550 nm. The value obtained by dividing the wavelength bandwidth W (121 nm) by the center wavelength λ_c (1550 nm) is approximately 0.078, which is greater than 0.06 and shows that the wavelength band for which the power reflectivity R falls within the allowable reflectivity range is a wide band.

[0392] In this case, the thicknesses of the first to tenth layer films **58** to **67** of the coating film **68** are 20.00 nm, 541.65 nm, 109.49 nm, 335.31 nm, 168.44 nm, 515.86 nm, 168.44 nm, 515.86 nm, 138.97 nm and 425.59 nm, respectively. The optical thickness t of the coating film **68** is 4700.20 nm. This value is approximately 12.11 times the value t_r (388 nm) which is a quarter of the center wavelength λ_c. Thus, the coating film **68** is a very thick film.

[0393] The semiconductor photonic device shown in **FIG. 2** will be considered for comparison. For the semiconductor photonic device shown in **FIG. 2**, the power reflectivity R is 8% for the wavelength λ equal to λ_c (1550 nm) when the coating film **2** having the above-mentioned refractive index n_f of "1.3726" and a thickness d_f of five times 282.31 nm, i.e. five times $\lambda_c/(4n_f)$, is provided on the end surface **1***b* of the semiconductor photonic element **1**. **FIG. 75** shows the wavelength dependence of the power reflectivity R in this case. As illustrated in **FIG. 75**, the wavelength band for which the power reflectivity R falls within ±2% from the design reflectivity of 8% is from 1498 nm to 1606 nm, to provide a wavelength bandwidth W_r of 108 nm.

[0394] Thus, even when the center wavelength λ_c is made equal to the design wavelength λ_1, the wavelength bandwidth W (121 nm) for the coating film **68** is greater than the wavelength bandwidth W_r (108 nm) for the coating film **2** shown in **FIG. 2**.

Seventeenth Preferred Embodiment

[0395] **FIG. 76** shows the wavelength dependence of the power reflectivity R of the coating film **21** in the semiconductor photonic device according to the seventeenth preferred embodiment of the present invention. The semiconductor photonic device according to the seventeenth preferred embodiment is similar to the semiconductor photonic device shown in **FIG. 15** according to the third preferred embodiment except that the material layer for the first layer film **14**, the third layer film **16**, the fifth layer film **18** and the seventh layer film **20** is changed from the alumina layer to a tantalum oxide layer, that the material layer for the second layer film **15**, the fourth layer film **17** and the sixth layer film **19** is changed from the tantalum oxide layer to a silicon oxide layer, and that the design wavelength λ_t is changed from 1310 nm to 980 nm. Accordingly, the values of the refractive indices n_1 and n_2 are "1.480" and "2.057," respectively.

[0396] For designing the thickness of the coating film **21** having a power reflectivity R of 12% (R_t=12%) when the wavelength λ equals the design wavelength of 980 nm, a point which provides a phase angle θ of 75 degrees is selected, for example, in Step s**1** so that the reflection amplitude vector rv is located in the first quadrant (or the upper right quadrant) of the complex plane according to the

seventeenth preferred embodiment. Then, because the magnitude of the complex number at the selected point is 0.346410161, the values of the real and imaginary parts r_r and r_i of the complex number inputted as the value of the amplitude reflectivity r are "+0.089657547" and "+0.334606521," respectively, in Step s**2**.

[**0397**] When O=2.56, A=2.95, B=2.00 and C=2.00 are set, the basic amounts of phase change ϕ_1 and ϕ_2 determined in Step s**5** are "1.43423" and "0.68016," respectively. Accordingly, the thicknesses of the first to seventh layer films **14** to **20** determined in Step s**6** are 132.03 nm, 445.89 nm, 152.14 nm, 302.30 nm, 103.15 nm, 302.30 nm and 103.15 nm, respectively.

[**0398**] **FIG. 76** described above shows the wavelength dependence of the power reflectivity R of the coating film **21** thus designed. As illustrated in **FIG. 76**, the power reflectivity R is 12% when the wavelength λ equals the design wavelength of 980 nm. A wavelength band for which the power reflectivity R is approximately equal to the design reflectivity of 12% is wide. The power reflectivity R falls within a range from 11.3% to 14.0% for the wavelength λ ranging from 938 nm to 1087 nm.

[**0399**] When the allowable reflectivity range is, for example, ±2% from the design reflectivity of 12%, the wavelength band for which the power reflectivity R falls within the allowable reflectivity range is also from 938 nm to 1087 nm, to provide a wavelength bandwidth W of 149 nm. The center wavelength λ_c of the wavelength band is 1013 nm. The value obtained by dividing the wavelength bandwidth W by the center wavelength λ_c is approximately 0.147, which is greater than 0.06. It may be said that the wavelength band for which the power reflectivity R falls within the allowable reflectivity range is a wide band.

[**0400**] Because the thicknesses of the first to seventh layer films **14** to **20** take on the above-mentioned values, the optical thickness t of the coating film **21** is 2563.62 nm. This value is approximately 10.13 times the value t_r (253 nm) which is a quarter of the center wavelength λ_c. Thus, the coating film **21** is a very thick film. This improves heat dissipation characteristics at the end surface **1***b* of the semiconductor photonic element **1** to suppress the increase in temperature of the end surface **1***b*.

[**0401**] The semiconductor photonic device shown in **FIG. 2** will be considered for comparison. For the semiconductor photonic device shown in **FIG. 2**, the power reflectivity R is 12% for the wavelength λ equal to λ_c (1013 nm) when the coating film **2** having a refractive index n_f of "1.27902" and a thickness d_f of five times 199.00 nm, i.e. five times $\lambda_c/(4n_f)$, is provided on the end surface **1***b* of the semiconductor photonic element **1**. **FIG. 77** shows the wavelength dependence of the power reflectivity R in this case. As illustrated in **FIG. 77**, the wavelength band for which the power reflectivity R falls within ±2% from the design reflectivity of 12% is from 975 nm to 1054 nm, to provide a wavelength bandwidth W_r of 79 nm.

[**0402**] The above-mentioned value "1.27902" of the refractive index n_f is obtained by substituting R_t=0.12 and n_c=3.37 into Equation (8).

[**0403**] Thus, the wavelength bandwidth W (149 nm) for the coating film **21** of the seventeenth preferred embodiment is greater than the wavelength bandwidth W_r (79 nm) for the coating film **2** shown in **FIG. 2**.

[**0404**] As mentioned above, because the wavelength λ of light propagating through the active layer **1***a* is sometimes varied, it is desirable that the center wavelength λ_c of the wavelength band for which the power reflectivity R falls within the allowable reflectivity range be equal to or close to the design wavelength λ_t. For example, the center wavelength λ_c takes on a value equal to the design wavelength λ_t of 980 nm when the thickness of the coating film **21** is determined using the basic thicknesses d_1 and d_2 obtained by setting the basic amounts of phase change ϕ_1 and ϕ_2 at "1.43423" and "0.68016," respectively, in a similar manner to the above instance and substituting 948 nm, rather than the design wavelength λ_t, for λ in Equations (5a) and (5b). **FIG. 78** shows the wavelength dependence of the power reflectivity R in this case.

[**0405**] As illustrated in **FIG. 78**, the power reflectivity R falls within a range from 11.3% to 14.0% for the wavelength λ ranging from 907 nm to 1052 nm. The wavelength band for which the power reflectivity R falls within ±2% from the design reflectivity of 12% is also from 907 nm to 1052 nm, to provide a wavelength bandwidth W of 145 nm. The center wavelength λ_c of the wavelength band is 980 nm, which is equal to the design wavelength of 980 nm. The value obtained by dividing the wavelength bandwidth W (145 nm) by the center wavelength λ_c (980 nm) is approximately 0.148, which is greater than 0.06 and shows that the wavelength band for which the power reflectivity R falls within the allowable reflectivity range is a wide band.

[**0406**] In this case, the thicknesses of the first to seventh layer films **14** to **20** of the coating film **21** are 127.72 nm, 431.33 nm, 147.17 nm, 292.43 nm, 99.78 nm, 292.43 nm and 99.78 nm, respectively. The optical thickness t of the coating film **21** is 2479.91 nm. This value is approximately 10.12 times the value t_r (245 nm) which is a quarter of the center wavelength λ_c. Thus, the coating film **21** is a very thick film.

[**0407**] The semiconductor photonic device shown in **FIG. 2** will be considered for comparison. For the semiconductor photonic device shown in **FIG. 2**, the power reflectivity R is 12% for the wavelength λ equal to λ_c (980 nm) when the coating film **2** having the above-mentioned refractive index n_f of "1.27902" and a thickness d_f of five times 191.55 nm, i.e. five times $\lambda_c/(4n_f)$, is provided on the end surface **1***b* of the semiconductor photonic element **1**. **FIG. 79** shows the wavelength dependence of the power reflectivity R in this case. As illustrated in **FIG. 79**, the wavelength band for which the power reflectivity R falls within ±2% from the design reflectivity of 12% is from 943 nm to 1020 nm, to provide a wavelength bandwidth W_r of 77 nm.

[**0408**] Thus, even when the center wavelength λ_c is made equal to the design wavelength λ_t, the wavelength bandwidth W (145 nm) for the coating film **21** is greater than the wavelength bandwidth W_r (77 nm) for the coating film **2** shown in **FIG. 2**.

Eighteenth Preferred Embodiment

[**0409**] **FIG. 80** shows the wavelength dependence of the power reflectivity R of the coating film **21** such that the power reflectivity R is 16% when the wavelength λ equals

the design wavelength of 980 nm in the semiconductor photonic device of the above-mentioned seventeenth preferred embodiment of the present invention.

[0410] For designing the thickness of the coating film **21** having the power reflectivity R of 16% when the wavelength λ equals the design wavelength of 980 nm, a point which provides a phase angle θ of 165 degrees is selected, for example, in Step s**1** so that the reflection amplitude vector rv is located in the second quadrant (or the upper left quadrant) of the complex plane according to the above-mentioned seventeenth preferred embodiment. Then, because the magnitude of the complex number at the selected point is 0.4, the values of the real and imaginary parts r_r and r_i of the complex number inputted as the value of the amplitude reflectivity r are "−0.38637033" and "+0.103527618," respectively, in Step s**2**.

[0411] When O=2.50, A=3.75, B=3.37 and C=1.80 are set, the basic amounts of phase change ϕ_1 and ϕ_2 determined in Step s**5** are "0.651305" and "0.381901," respectively. Accordingly, the thicknesses of the first to seventh layer films **14** to **20** determined in Step s**6** are 72.39 nm, 257.40 nm, 108.59 nm, 231.31 nm, 97.59 nm, 123.55 nm and 52.12 nm, respectively.

[0412] **FIG. 80** described above shows the wavelength dependence of the power reflectivity R of the coating film **21** thus designed. As illustrated in **FIG. 80**, the power reflectivity R is 16% when the wavelength λ equals the design wavelength of 980 nm. A wavelength band for which the power reflectivity R is approximately equal to the design reflectivity of 16% is wide. The power reflectivity R falls within a range from 15.0% to 18.0% for the wavelength λ ranging from 945 nm to 1219 nm.

[0413] When the allowable reflectivity range is, for example, ±2% from the design reflectivity of 16%, the wavelength band for which the power reflectivity R falls within the allowable reflectivity range is also from 945 nm to 1219 nm, to provide a wavelength bandwidth W of 274 nm. The center wavelength λ_c of the wavelength band is 1082 nm. The value obtained by dividing the wavelength bandwidth W by the center wavelength λ_c is approximately 0.253, which is greater than 0.06. It may be said that the wavelength band for which the power reflectivity R falls within the allowable reflectivity range is a wide band.

[0414] Because the thicknesses of the first to seventh layer films **14** to **20** take on the above-mentioned values, the optical thickness t of the coating film **21** is 1586.37 nm. This value is approximately 5.85 times the value t_r (271 nm) which is a quarter of the center wavelength λ_c. Thus, the coating film **21** is a very thick film. This improves heat dissipation characteristics at the end surface **1***b* of the semiconductor photonic element **1** to suppress the increase in temperature of the end surface **1***b*.

[0415] The semiconductor photonic device shown in **FIG. 2** will be considered for comparison. For the semiconductor photonic device shown in **FIG. 2**, the power reflectivity R is 16% for the wavelength λ equal to λ_c (1082 nm) when the coating film **2** having a refractive index n_f of "1.20178." and a thickness d_f of five times 225.08 nm, i.e. five times $\lambda_c/(4n_f)$, is provided on the end surface **1***b* of the semiconductor photonic element **1**. **FIG. 81** shows the wavelength dependence of the power reflectivity R in this case. As illustrated in **FIG. 81**, the wavelength band for which the power reflectivity R falls within ±2% from the design reflectivity of 16% is from 1034 nm to 1134 nm, to provide a wavelength bandwidth W_r of 100 nm.

[0416] The above-mentioned value "1.20178" of the refractive index n_f is obtained by substituting R_t=0.16 and n_c=3.37 into Equation (8).

[0417] Thus, the wavelength bandwidth W (274 nm) for the coating film **21** of the eighteenth preferred embodiment of the present invention is greater than the wavelength bandwidth W_r (100 nm) for the coating film **2** shown in **FIG. 2**.

[0418] As mentioned above, because the wavelength λ of light propagating through the active layer **1***a* is sometimes varied, it is desirable that the center wavelength λ_c of the wavelength band for which the power reflectivity R falls within the allowable reflectivity range be equal to or close to the design wavelength λ_t. For example, the center wavelength λ_c takes on a value equal to the design wavelength λ_t of 980 nm when the thickness of the coating film **21** is determined using the basic thicknesses d_1 and d_2 obtained by setting the basic amounts of phase change ϕ_1 and ϕ_2 at "0.651305" and "0.381901," respectively, in a similar manner to the above instance and substituting 887 nm, rather than the design wavelength λ_t, for λ in Equations (5a) and (5b). **FIG. 82** shows the wavelength dependence of the power reflectivity R in this case.

[0419] As illustrated in **FIG. 82**, the power reflectivity R falls within a range from 15.0% to 18.0% for the wavelength λ ranging from 856 nm to 1103 nm. The wavelength band for which the power reflectivity R falls within ±2% from the design reflectivity of 16% is from 856 nm to 1103 nm, to provide a wavelength bandwidth W of 247 nm. The center wavelength λ_c of the wavelength band is 980 nm, which is equal to the design wavelength of 980 nm. The value obtained by dividing the wavelength bandwidth W (247 nm) by the center wavelength λ_c (980 nm) is approximately 0.252, which is greater than 0.06 and shows that the wavelength band for which the power reflectivity R falls within the allowable reflectivity range is a wide band.

[0420] In this case, the thicknesses of the first to seventh layer films **14** to **20** of the coating film **21** are 65.52 nm, 232.97 nm, 98.29 nm, 209.36 nm, 88.33 nm, 111.83 nm and 47.18 nm, respectively. The optical thickness t of the coating film **21** is 1435.86 nm. This value is approximately 5.86 times the value t_r (245 nm) which is a quarter of the center wavelength λ_c. Thus, the coating film **21** is a very thick film.

[0421] The semiconductor photonic device shown in **FIG. 2** will be considered for comparison. For the semiconductor photonic device shown in **FIG. 2**, the power reflectivity R is 16% for the wavelength λ equal to λ_c (980 nm) when the coating film **2** having the above-mentioned refractive index n_f of "1.20178" and a thickness d_f of five times 203.86 nm, i.e. five times $\lambda_c/(4n_f)$, is provided on the end surface **1***b* of the semiconductor photonic element **1**. **FIG. 83** shows the wavelength dependence of the power reflectivity R in this case. As illustrated in **FIG. 83**, the wavelength band for which the power reflectivity R falls within ±2% from the design reflectivity of 16% is from 937 nm to 1027 nm, to provide a wavelength bandwidth W_r of 90 nm.

[0422] Thus, even when the center wavelength λ_c is made equal to the design wavelength λ_t, the wavelength band-

width W (247 nm) for the coating film **21** is greater than the wavelength bandwidth W_r (90 nm) for the coating film **2** shown in **FIG. 2**.

Nineteenth Preferred Embodiment

[**0423**] **FIG. 84** shows the wavelength dependence of the power reflectivity R of the coating film **21** such that the power reflectivity R is 20% when the wavelength λ equals the design wavelength of 980 nm in the semiconductor photonic device of the above-mentioned seventeenth preferred embodiment of the present invention.

[**0424**] For designing the thickness of the coating film **21** having the power reflectivity R of 20% when the wavelength λ equals the design wavelength of 980 nm, a point which provides a phase angle θ of 255 degrees is selected, for example, in Step s**1** so that the reflection amplitude vector rv is located in the third quadrant (or the lower left quadrant) of the complex plane according to the above-mentioned seventeenth preferred embodiment. Then, because the magnitude of the complex number at the selected point is 0.447213595, the values of the real and imaginary parts r_r and r_i of the complex number inputted as the value of the amplitude reflectivity r are "−0.115747395" and "−0.431975161," respectively, in Step s**2**.

[**0425**] When O=2.00, A=2.00, B=2.71 and C=1.02 are set, the basic amounts of phase change ϕ_1 and ϕ_2 determined in Step s**5** are "1.01212" and "0.703719," respectively. Accordingly, the thicknesses of the first to seventh layer films **14** to **20** determined in Step s**6** are 106.72 nm, 213.33 nm, 106.72 nm, 289.06 nm, 144.60 nm, 108.80 nm and 54.43 nm, respectively.

[**0426**] **FIG. 84** described above shows the wavelength dependence of the power reflectivity R of the coating film **21** thus designed. As illustrated in **FIG. 84**, the power reflectivity R is 20% when the wavelength λ equals the design wavelength of 980 nm. A wavelength band for which the power reflectivity R is approximately equal to the design reflectivity of 20% is wide. The power reflectivity R falls within a range from 18.0% to 22.0% for the wavelength λ ranging from 911 nm to 1365 nm.

[**0427**] When the allowable reflectivity range is, for example, ±2% from the design reflectivity of 20%, the wavelength band for which the power reflectivity R falls within the allowable reflectivity range is also from 911 nm to 1365 nm, to provide a wavelength bandwidth W of 454 nm. The center wavelength λ_c of the wavelength band is 1138 nm. The value obtained by dividing the wavelength bandwidth W by the center wavelength λ_c is approximately 0.399, which is greater than 0.06. It may be said that the wavelength band for which the power reflectivity R falls within the allowable reflectivity range is a wide band.

[**0428**] Because the thicknesses of the first to seventh layer films **14** to **20** take on the above-mentioned values, the optical thickness t of the coating film **21** is 1753.01 nm. This value is approximately 6.15 times the value t_r (285 nm) which is a quarter of the center wavelength λ_c. Thus, the coating film **21** is a very thick film. This improves heat dissipation characteristics at the end surface **1***b* of the semiconductor photonic element **1** to suppress the increase in temperature of the end surface **1***b*.

[**0429**] The semiconductor photonic device shown in **FIG. 2** will be considered for comparison. For the semiconductor photonic device shown in **FIG. 2**, the power reflectivity R is 20% for the wavelength λ equal to λ_c (1138 nm) when the coating film **2** having a refractive index n_f of "1.13456" and a thickness d_f of five times 250.76 nm, i.e. five times $\lambda_c/(4n_f)$, is provided on the end surface **1***b* of the semiconductor photonic element **1**. **FIG. 85** shows the wavelength dependence of the power reflectivity R in this case. As illustrated in **FIG. 85**, the wavelength band for which the power reflectivity R falls within ±2% from the design reflectivity of 20% is from 1076 nm to 1207 nm, to provide a wavelength bandwidth W_r of 131 nm.

[**0430**] The above-mentioned value "1.13456" of the refractive index n_f is obtained by substituting R_t=0.20 and n_c=3.37 into Equation (8).

[**0431**] Thus, the wavelength bandwidth W (454 nm) for the coating film **21** of the nineteenth preferred embodiment of the present invention is greater than the wavelength bandwidth W_r (131 nm) for the coating film **2** shown in **FIG. 2**.

[**0432**] As mentioned above, because the wavelength λ of light propagating through the active layer **1***a* is sometimes varied, it is desirable that the center wavelength λ_c of the wavelength band for which the power reflectivity R falls within the allowable reflectivity range be equal to or close to the design wavelength λ_t. For example, the center wavelength λ_c takes on a value equal to the design wavelength λ_t of 980 nm when the thickness of the coating film **21** is determined using the basic thicknesses d_1 and d_2 obtained by setting the basic amounts of phase change ϕ_1 and ϕ_2 at "1.01212" and "0.703719," respectively, in a similar manner to the above instance and substituting 844 nm, rather than the design wavelength λ_1, for λ in Equations (5a) and (5b). **FIG. 86** shows the wavelength dependence of the power reflectivity R in this case.

[**0433**] As illustrated in **FIG. 86**, the power reflectivity R falls within a range from 18.0% to 22.0% for the wavelength λ ranging from 784 nm to 1176 nm. The wavelength band for which the power reflectivity R falls within ±2% from the design reflectivity of 20% is also from 784 nm to 1176 nm, to provide a wavelength bandwidth W of 392 nm. The center wavelength λ_c of the wavelength band is 980 nm, which is equal to the design wavelength of 980 nm. The value obtained by dividing the wavelength bandwidth W (392 nm) by the center wavelength λ_c (980 nm) is approximately 0.400, which is greater than 0.06 and shows that the wavelength band for which the power reflectivity R falls within the allowable reflectivity range is a wide band.

[**0434**] In this case, the thicknesses of the first to seventh layer films **14** to **20** of the coating film **21** are 91.91 nm, 183.72 nm, 91.91 nm, 248.94 nm, 124.54 nm, 93.70 nm and 46.87 nm, respectively. The optical thickness t of the coating film **21** is 1509.72 nm. This value is approximately 6.16 times the value t_r (245 nm) which is a quarter of the center wavelength λ_c. Thus, the coating film **21** is a very thick film.

[**0435**] The semiconductor photonic device shown in **FIG. 2** will be considered for comparison. For the semiconductor photonic device shown in **FIG. 2**, the power reflectivity R is 20% for the wavelength λ equal to λ_c (980 nm) when the coating film **2** having the above-mentioned refractive index n_f of "1.13456" and a thickness d_f of five times 215.94 nm, i.e. five times $\lambda_c/(4n_f)$, is provided on the end surface **1***b* of

the semiconductor photonic element **1**. **FIG. 87** shows the wavelength dependence of the power reflectivity R in this case. As illustrated in **FIG. 87**, the wavelength band for which the power reflectivity R falls within ±2% from the design reflectivity of 20% is from 927 nm to 1040 nm, to provide a wavelength bandwidth W_r of 113 nm.

[0436] Thus, even when the center wavelength λ_c is made equal to the design wavelength λ_t, the wavelength bandwidth W (392 nm) for the coating film **21** is greater than the wavelength bandwidth W_r (113 nm) for the coating film **2** shown in **FIG. 2**.

Twentieth Preferred Embodiment

[0437] **FIG. 88** shows the wavelength dependence of the power reflectivity R of the coating film **21** such that the power reflectivity R is 24% when the wavelength λ equals the design wavelength of 980 nm in the semiconductor photonic device of the above-mentioned seventeenth preferred embodiment of the present invention.

[0438] For designing the thickness of the coating film **21** having the power reflectivity R of 24% when the wavelength λ equals the design wavelength of 980 nm, a point which provides a phase angle θ of 345 degrees is selected, for example, in Step s**1** so that the reflection amplitude vector rv is located in the fourth quadrant (or the lower right quadrant) of the complex plane according to the above-mentioned seventeenth preferred embodiment. Then, because the magnitude of the complex number at the selected point is 0.489897948, the values of the real and imaginary parts r_r and r_i of the complex number inputted as the value of the amplitude reflectivity r are "+0.47320508" and "−0.126794919," respectively, in Step s**2**.

[0439] When O=1.95, A=1.85, B=0.10 and C=1.96 are set, the basic amounts of phase change ϕ_1 and ϕ_2 determined in Step s**5** are "1.40351" and "0.680892," respectively. Accordingly, the thicknesses of the first to seventh layer films **14** to **20** determined in Step s**6** are 100.68 nm, 273.64 nm, 95.51 nm, 14.79 nm, 5.16 nm, 289.91 nm and 101.19 nm, respectively.

[0440] **FIG. 88** described above shows the wavelength dependence of the power reflectivity R of the coating film **21** thus designed. As illustrated in **FIG. 88**, the power reflectivity R is 24% when the wavelength λ equals the design wavelength of 980 nm. A wavelength band for which the power reflectivity R is approximately equal to the design reflectivity of 24% is wide. The power reflectivity R falls within a range from 22.0% to 24.0% for the wavelength λ ranging from 961 nm to 1153 nm.

[0441] When the allowable reflectivity range is, for example, ±2% from the design reflectivity of 24%, the wavelength band for which the power reflectivity R falls within the allowable reflectivity range is also from 961 nm to 1153 nm, to provide a wavelength bandwidth W of 192 nm. The center wavelength λ_c of the wavelength band is 1057 nm. The value obtained by dividing the wavelength bandwidth W by the center wavelength λ_c is approximately 0.182, which is greater than 0.06. It may be said that the wavelength band for which the power reflectivity R falls within the allowable reflectivity range is a wide band.

[0442] Because the thicknesses of the first to seventh layer films **14** to **20** take on the above-mentioned values, the optical thickness t of the coating film **21** is 1478.27 nm. This value is approximately 5.60 times the value t_r (264 nm) which is a quarter of the center wavelength λ_c. Thus, the coating film **21** is a very thick film. This improves heat dissipation characteristics at the end surface **1***b* of the semiconductor photonic element **1** to suppress the increase in temperature of the end surface **1***b*.

[0443] The semiconductor photonic device shown in **FIG. 2** will be considered for comparison. For the semiconductor photonic device shown in **FIG. 2**, the power reflectivity R is 24% for the wavelength λ equal to λ_c (1057 nm) when the coating film **2** having a refractive index n_f of "1.07415" and a thickness d_f of five times 246.01 nm, i.e. five times $\lambda_c/(4n_f)$, is provided on the end surface **1***b* of the semiconductor photonic element **1**. **FIG. 89** shows the wavelength dependence of the power reflectivity R in this case. As illustrated in **FIG. 89**, the wavelength band for which the power reflectivity R falls within ±2% from the design reflectivity of 24% is from 978 nm to 1150 nm, to provide a wavelength bandwidth W_r of 172 nm.

[0444] The above-mentioned value "1.07415" of the refractive index n_f is obtained by substituting R_t=0.24 and n_c=3.37 into Equation (8).

[0445] Thus, the wavelength bandwidth W (192 nm) for the coating film **21** of the twentieth preferred embodiment of the present invention is greater than the wavelength bandwidth W_r (172 nm) for the coating film **2** shown in **FIG. 2**.

[0446] As mentioned above, because the wavelength λ of light propagating through the active layer **1***a* is sometimes varied, it is desirable that the center wavelength λ_c of the wavelength band for which the power reflectivity R falls within the allowable reflectivity range be equal to or close to the design wavelength λ_t. For example, the center wavelength λ_c takes on a value approximately equal to the design wavelength λ_t of 980 nm when the thickness of the coating film **21** is determined using the basic thicknesses d_1 and d_2 obtained by setting the basic amounts of phase change ϕ_1 and ϕ_2 at "1.40351" and "0.680892," respectively, in a similar manner to the above instance and substituting 909 nm, rather than the design wavelength λ_t, for λ in Equations (5a) and (5b). **FIG. 90** shows the wavelength dependence of the power reflectivity R in this case.

[0447] As illustrated in **FIG. 90**, the power reflectivity R falls within a range from 22.0% to 26.0% for the wavelength λ ranging from 891 nm to 1070 nm. The wavelength band for which the power reflectivity R falls within ±2% from the design reflectivity of 24% is also from 891 nm to 1070 nm, to provide a wavelength bandwidth W of 179 nm. The center wavelength λ_c of the wavelength band is 981 nm, which is approximately equal to the design wavelength of 980 nm. The value obtained by dividing the wavelength bandwidth W (179 nm) by the center wavelength λ_c (981 nm) is approximately 0.182, which is greater than 0.06 and shows that the wavelength band for which the power reflectivity R falls within the allowable reflectivity range is a wide band.

[0448] In this case, the thicknesses of the first to seventh layer films **14** to **20** of the coating film **21** are 93.38 nm, 253.81 nm, 88.59 nm, 13.72 nm, 4.79 nm, 268.90 nm and 93.86 nm, respectively. The optical thickness t of the coating film **21** is 1371.15 nm. This value is approximately 5.60 times the value t_r (245 nm) which is a quarter of the center wavelength λ_c. Thus, the coating film **21** is a very thick film.

[0449] The semiconductor photonic device shown in **FIG. 2** will be considered for comparison. For the semiconductor photonic device shown in **FIG. 2**, the power reflectivity R is 24% for the wavelength λ equal to λ_c (981 nm) when the coating film **2** having the above-mentioned refractive index n_f of "1.07415" and a thickness d_f of five times 228.32 nm, i.e. five times $\lambda_c/(4n_f)$, is provided on the end surface **1***b* of the semiconductor photonic element **1**. **FIG. 91** shows the wavelength dependence of the power reflectivity R in this case. As illustrated in **FIG. 91**, the wavelength band for which the power reflectivity R falls within ±2% from the design reflectivity of 24% is from 907 nm to 1066 nm, to provide a wavelength bandwidth W_r of 159 nm.

[0450] Thus, even when the center wavelength λ_c is made close to the design wavelength λ_t, the wavelength bandwidth W (179 nm) for the coating film **21** is greater than the wavelength bandwidth W_r (159 nm) for the coating film **2** shown in **FIG. 2**.

[0451] Although the center wavelength λ_c is close to the design wavelength λ_t in the above instance, the center wavelength λ_c may be made exactly equal to the design wavelength λ_t by adjusting the values of the parameters A, B, C and O or the value substituted for λ in Equations (5a) and (5b).

[0452] The conditions and results according to the first to twentieth preferred embodiments described hereinabove are listed in **FIGS. 92 and 93**.

[0453] As described hereinabove, the first to twentieth preferred embodiments of the present invention employ an imaginary number as the value of the amplitude reflectivity r of the coating film provided on the end surface **1***b* of the semiconductor photonic element **1**, to make it possible to design the thickness of the coating film having the predetermined power reflectivity R in consideration for more complex numbers having the same amplitude as the value of the amplitude reflectivity r than real numbers. This improves the design flexibility of the thickness of the coating film to make the coating film having a desired characteristic easy to design.

[0454] Additionally, the first to twentieth preferred embodiments determine the thicknesses of the respective layers included in the coating film so that the center wavelength λ_c of the wavelength band for which the power reflectivity R of the coating film falls within the allowable reflectivity range is equal to the design wavelength λ_t. This provides the coating film whose power reflectivity R is varied slightly even if the wavelength λ in the actual device is changed from the design wavelength λ_t.

[0455] In the semiconductor photonic device according to the first to twentieth preferred embodiments, the power reflectivity R of the coating film is varied slightly even if the wavelength λ of light propagating through the active layer **1***a* is varied, because of the wide wavelength band for which the power reflectivity R of the coating film falls within the allowable reflectivity range. This achieves the provision of the semiconductor photonic device having characteristics less susceptible to the wavelength dependence of the power reflectivity R of the coating film.

[0456] The first to twentieth preferred embodiments reliably suppress the variation in the power reflectivity R of the coating film even if the wavelength λ is varied because the allowable reflectivity range is set at ±2% from the median value thereof (the design reflectivity R_t).

[0457] The coating films described above have the six-layer structure, the seven-layer structure, the eight-layer structure, the nine-layer structure, and the ten-layer structure in the first to twentieth preferred embodiments. The present invention, however, is not limited to these coating films, but is applicable to coating films having other layer structures.

[0458] The values of the parameters A, B, C, D, E and O are merely examples. The parameters A, B, C, D, E and O may take on other values to produce similar effects.

[0459] The design wavelength λ_t is 410 nm, 650 nm, 808 nm, 980 nm, 1310 nm and 1550 nm in the first to twentieth preferred embodiments described above. The present invention, however, is not limited to this, but is applicable to other values of the wavelength.

[0460] Although only up to three material layers for the coating film are described, the present invention is applicable to four or more material layers for the coating film.

[0461] While the invention has been described in detail, the foregoing description is in all aspects illustrative and not restrictive. It is understood that numerous other modifications and variations can be devised without departing from the scope of the invention.

What is claimed is:

1. A method of designing the thickness of a coating film including a plurality of layers and provided on an end surface of a semiconductor photonic element including an active layer through which light propagates, said method comprising the steps of:

(a) selecting an imaginary number as a value of an amplitude reflectivity of said coating film; and

(b) determining the thickness of each of said plurality of layers of said coating film so that the value of said amplitude reflectivity of said coating film is equal to said imaginary number selected in said step (a).

2. The method according to claim 1, wherein

the thickness of each of said plurality of layers of said coating film is determined in said step (b) so that a center wavelength of a wavelength band for which a power reflectivity of said coating film falls within a predetermined range when the wavelength of light propagating through said active layer is hypothetically varied is equal to a design value of said wavelength.

3. A semiconductor photonic device comprising:

a semiconductor photonic element including an active layer through which light propagates; and

a coating film including a plurality of layers and provided on an end surface of said semiconductor photonic element,

said coating film having an amplitude reflectivity taking on a value set at an imaginary value.

4. The semiconductor photonic device according to claim 3, wherein

the width of a first wavelength band for which a power reflectivity of said coating film falls within a predetermined range when the wavelength of light propagating through said active layer is hypothetically varied is

greater than the width of a second wavelength band for which a power reflectivity of a single layer film obtained when said single layer film is provided on said end surface of said active layer falls within said predetermined range when said wavelength is hypothetically varied, said single layer film having a refractive index satisfying

$$R_t=((n_c-n_f^2)/(n_c+n_f^2))^2$$

where n_f is the refractive index of said single layer film, n_c is an effective refractive index of said semiconductor photonic element, and R_t is a median value of said predetermined range, said single layer film having a thickness $5/(4n_f)$ times the center wavelength of said first wavelength band.

5. The semiconductor photonic device according to claim 3, wherein

the value obtained by dividing the width of a wavelength band for which a power reflectivity of said coating film falls within a predetermined range when the wavelength of light propagating through said active layer is hypothetically varied by the center wavelength of said wavelength band is greater than 0.06.

6. The semiconductor photonic device according to claim 4, wherein

the sum of the products of the thicknesses and refractive indices of the respective layers of said coating film is greater than $3\lambda_c/4$ where λ_c is said center wavelength of said first wavelength band.

7. The semiconductor photonic device according to claim 5, wherein

the sum of the products of the thicknesses and refractive indices of the respective layers of said coating film is greater than $3\lambda_c/4$ where λ_c is said center wavelength of said wavelength band.

8. The semiconductor photonic device according to claim 4, wherein

said predetermined range is ±2% from the median value thereof.

9. The semiconductor photonic device according to claim 5, wherein

said predetermined range is ±2% from the median value thereof.

10. The semiconductor photonic device according to claim 3, wherein

a power reflectivity of said coating film is less than a power reflectivity at said end surface defined by the effective refractive index of said semiconductor photonic element and a refractive index in a free space contacting said end surface when said coating film is absent.

11. The semiconductor photonic device according to claim 3, wherein

said coating film includes two material layers, and the number of layers of said coating film is selected from the group consisting of six, seven, eight and nine.

12. The semiconductor photonic device according to claim 3, wherein

said coating film includes three material layers, and the number of layers of said coating film is selected from the group consisting of seven, eight and ten.

13. The semiconductor photonic device according to claim 3, wherein

said coating film includes at least two selected from the group consisting of a silicon oxide layer, a tantalum oxide layer, an alumina layer and an aluminum nitride layer.

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