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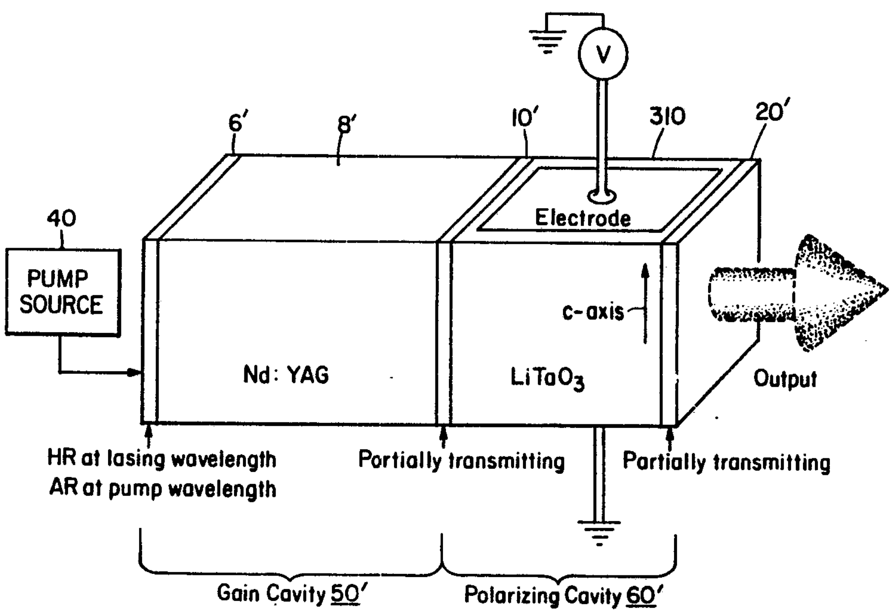
(54) Title: POLARIZATION CONTROLLING SYSTEM FOR LASERS



(57) Abstract

A system for controlling the polarization of lasers is described in which the polarization of laser radiation generated in a gain cavity is controlled by feedback of a controlled amount of polarized light from a polarizing cavity. The output mirror of the gain cavity forms an input mirror of the polarizing cavity. The polarizing cavity includes a polarizing element and an optical medium of variable optical length.

POLARIZATION CONTROLLING SYSTEM FOR LASERS

Background of the Invention

This invention relates generally to lasers, and more particularly to optically pumped solid state lasers.

A large number of different kinds of solid state lasers have been discovered, distinguished from one another by host material, by active lasing ions with which the host is doped, and by output characteristics. (See U.S. 4,872,177 issued 3 October 1989 and U.S. 4,860,304 to Mooradian issued 22 August 1989).

Solid state optically pumped lasers comprise, in general, a solid state lasing material sometimes called the gain medium which is disposed within an optical cavity formed between two mirrors. An optical source, such as a laser diode or array of diodes, generates a pump beam which is focused onto the lasing material. Photon energy from the pump laser is absorbed by the gain medium. When a threshold level of absorbed light is achieved stimulated emission of light from the gain medium occurs. In the microchip laser of Mooradian the cavity length, or separation between mirrors, may be as small as 10 to 100 microns to obtain the desirable property that the resulting light oscillates in a single axial mode within the laser cavity.

However, in such microchip lasers and in many conventional lasers it is possible to obtain oscillation in two different polarization modes.

Polarization relates to the direction of the electric field vector $\bar{E}$ of a light wave. This vector is perpendicular both to the propagation vector $\bar{k}$ which describes the direction of travel of the wave and to the instantaneous direction of the magnetic field of the wave, $\bar{H}$. The direction of the electric field vector is referred to as the "direction of polarization". Randomly polarized light, i.e. light from incandescent lamps, is unoriented and hence unpolarized, whereas light from lasers is generally highly oriented and hence "polarized".

In many lasers, including microchip lasers, two orthogonally polarized modes are present and have nearly the same threshold. This is due to the fact that a 90 degree rotation of a light wave about its propagation vector results in an optical field orthoganal to the original wave which sees the same amount of net gain (gain minus loss). As a result, the laser may oscillate in both polarizations, or may switch polarizations in response to a small amount of feedback provided by optics external to the laser cavity. One way of controlling the polarization of a laser is to introduce a polarizing element within the cavity, such as a Brewster's angle window. While this is a viable alternative for large lasers, it is not an acceptable solution for microchip lasers, which rely on a short cavity length to perform properly. Conventional polarizing elements made to be compact, flat, and thin for microchip applications are often too lossy to use intracavity.

The present invention provides a way of selecting the polarization of a laser without the use of intracavity polarizing elements. In addition it provides a method and apparatus for controllably switching a laser between two orthogonal polarizations. Polarization control of lasers is important because many optical systems (including systems with birefringent elements, gratings, optical surfaces which are not normal to the propagation vector of the light, nonlinear optical elements, or polarizing elements) have different properties for different polarizations of light. By switching a laser between orthoganal polarizations information can be encoded on the output light beam.

Summary of the Invention

The invention comprises a polarization controlled laser formed by a gain cavity coupled to a polarizing cavity. The gain cavity is comprised of a laser gain medium disposed in a cavity formed between a pair of mirrors. Note: The term "mirror" is used herein, in a general sense, to include any surface which is partly, or highly, reflective at a particular wavelength. One of the mirrors is an input mirror for the gain cavity and is disposed adjacent to a pump source. The input mirror is highly reflective at the lasing wavelength of the gain medium and antireflective at the pump wavelength. The second, or more remote mirror from the pump, is partially transmitting and forms a first partial reflector for a polarizing cavity which is comprised of the first partial reflector, a spacer, a polarizing element or a birefringent element (which has a different refractive index for the two orthoganal polarizations), and a second partial reflector, assembled in that order. The first partial reflector provides the dominant part of the reflective feedback seen by the laser gain medium. The small amount of feedback provided by the second partial reflector is polarization dependent, however. The spacer is an optical element which has a variable optical length (physical length times refractive index). The optical length of the spacer determines whether the feedback from the second partial reflector in a given polarization is in phase or out of phase with the light reflected by the first partial reflector. By controlling the optical length of the spacer (electro-optically or piezoelectrically, for example) the reflected light from the second partial reflector in a given polarization can be made to add constructively or destructively to the light reflected by the first partial reflector.

The reflectivity of the second partial reflector is chosen to provide sufficient feedback to split the degeneracy of the two orthogonally polarized laser modes of the gain cavity, and to overcome the effects of feedback from the external optics. The polarization of the laser gain cavity that sees the highest net reflectivity from the two partially reflecting mirrors will experience the most net gain. As a result, it will be the first polarization mode to oscillate, and will deplete the gain for the orthogonally polarized mode. In this way, the polarization of the laser gain cavity is controlled by the polarizing cavity.

Brief Description of the Drawings

Figure 1 is a schematic drawing of a laser in accordance with a first embodiment of the invention.

Figure 2 is a schematic drawing of a laser according to an alternative embodiment of the invention.

Figure 3 is a plot of the reflectivity of the polarizing cavity for two orthogonally polarized light waves (solid and dashed lines) versus frequency.

Detailed Description of the Invention

The first embodiment of the invention will be described in connection with Figure 1. Note that while this embodiment is illustrated in connection with a solid state laser, any suitable laser will benefit from the polarization control and switching capabilities of the invention.

The polarization controlled laser system of the invention comprises, in general, a pump source 4, a gain cavity 50 and a polarizing cavity 60. Pump source 4 may comprise any power source able to bring the gain medium 8 in cavity 50 to a level at which stimulated light emission occurs. Preferably source 4 is a diode laser or the like. Source 4 may be physically adjacent to input mirror 6 of cavity 60, as shown, or light from the source may be collimated and focused onto the gain medium by suitable lens elements (not shown).

Gain cavity 50 is comprised of input mirror 6, gain medium 8 and partial reflector 10.

Input mirror 6 is highly reflective to light at the wavelength of the laser emission from cavity 50 and anti-reflective at the wavelength of the light from pump 4. Mirror 6 may comprise a dielectric coating deposited on the gain medium 8 or on a thin glass sheet bonded to the medium or other suitable reflector.

The gain medium 8 is preferably a solid state material, such as Nd:YAG or Nd pentaphosphate or the like. The polarizing cavity 60 is comprised in general of a partial reflector or mirror 10,variable optical length spacer or element 12, thin polarizer 18 and output mirror 20. Partial reflector 10 is positioned adjacent to spacer 12. The spacer 12 is preferably transparent to the laser radiation from cavity 50. The first partial reflector 10 may also be formed by a dielectric coating on the spacer 12. The transparent spacer 12 may be an electro-optic material (such as $LiTaO_3$ or GaAlAs) in which the refractive index can be controlled electrically, or a transparent piezoelectric material (such as PLZT or Quartz) in which the length of the spacer can be controlled electrically. In either case, the spacer 12 is processed so as to be conductive along the surfaces 14 and 16 while being insulating in the bulk. The conductive surfaces 14 and 16 may be produced through the deposition of a transparent, conductive material (such as Indium Tin Oxide) on the surface of the spacer 12. Alternatively, the spacer 12 may be a semiconducting material (as in the case of GaAlAs or Si), in which case the conductive layers 14 and 16 could be produced by growing thin conductive semiconductor layers on both sides of an insulating substrate.

A thin polarizer 18 is attached to the side of the spacer 12 remote from the first partial reflector 10. The polarizing cavity is completed by attaching a second partial reflector,or mirror, 20 to the free side of the polarizer 18. The second partial reflector 20 may also be formed by dielectric deposition directly onto the polarizer 18. The optical length of the spacer 12 in the polarizing cavity 60 is controlled through the application of a voltage (not shown) between contacts 22 and 24 formed on the conductive surfaces 14 and 16 of the spacer 12.

The polarizing cavity 60 can be used as the output coupler of a laser. The first partial reflector 10 faces the laser gain cavity 50, and provides the dominate part of the reflectivity seen by the laser gain cavity 50. The small amount of feedback provided by the second partial reflector 20 is polarized, however. The reflectivity of the second partial reflector 20 is chosen to provide sufficient polarized feedback to split the polarization degeneracy of the two orthogonally polarized laser modes, and overcome the effects of feedback from external optics. The optical length of the spacer 12 (physical length times refractive index) determines whether the polarized feedback from the second partial reflector 20 is in phase or out of phase with the light reflected by the first partial reflector 10. By controlling the optical length of the spacer 12, the polarized component of the reflected light can be made to add constructively or destructively to the light reflected by the first partial reflector 10, and the polarization of the laser can be controlled. Note that the polarizer 18 may be placed anywhere between the first partial reflector 10 and the second partial reflector 20. Note also that if a reflective polarizing element (a material which reflects one polarization and transmits the other) is used the second partial reflector 20 may not be required. If the polarizer 18 is strongly reflecting (a very good reflective polarizer) it may be appropriate to use the polarizing cavity as an end mirror of a laser cavity with a different output coupler.

In a variation on the above described embodiment the spacer 12 may comprise a piezoelectric material which is not transparent to the laser radiation. In this option a hole 210 (shown by the dotted lines in Fig. 1) is cut in the spacer 12 and the conductive surfaces 14 and 16 to provide a via for the laser radiation. In this case the conductive surfaces 14 and 16 need not be transparent. Alternatively, with an appropriate spacer material, such as a material with a transverse piezoelectric or electro-optic effect, the conductive surfaces 14 and 16 may be deposited on surfaces of the spacer 12 parallel to the cavity axis, in which case they need not be transparent.

In another embodiment of the invention, as shown in Figure 2, a piezoelectric or electro-optic birefringent element 310 is placed between two partially reflecting mirrors 10' and 20' so that the net reflectivity of the etalon formed by the two partially reflecting mirrors is different for the two orthogonal polarizations of the laser as a result of the coherent addition of the light reflected by the two partial reflectors. Note that elements with counterparts in Figure 1 contain the same numeral designation with a prime suffix and need not be described further herein. The optical length of the birefringent element 310 may be changed piezoelectrically or electro-optically (for one or both polarizations) in order to change the phase relationship between the light reflected by the two partial reflectors and thereby control the polarization of the laser.

In yet another embodiment the polarizing cavity may be formed by a partially reflecting mirror, a spacer, a birefringent element and a second partially reflecting mirror in such a way that the optical length of the spacer is changed to control the net reflectivity of the composite mirror in the two orthogonal polarizations. In this embodiment the piezoelectric or electro-optic element of the previous embodiments is replaced by two elements, a spacer having a controllable optical length and a birefringent element.

Any of the above embodiments can be used with a laser that supports several longitudinal cavity modes that are equally spaced, or spaced by multiples of a common frequency. In such a case the free spectral range of the etalon formed by the two partially reflecting surfaces should be approximately equal to the cavity mode spacing, or said common frequency, as illustrated in Figure 3 which shows the reflectivity of a birefringent etalon in two orthogonal polarizations (solid and dashed lines), where the length of the etalon was chosen so that the net reflectivity of the etalon is low for one of the polarizations (the solid line) and high for the other (the dashed line), at all the potential lasing frequencies of a laser (indicated by the large vertical tic marks at the top of the figure). The polarization of the resulting laser structure can be switched by moving either the resonant transmission frequencies of the polarizing cavity (for one or both of the orthogonal polarizations) or by changing the frequencies of the longitudinal modes of the laser.

CLAIMS

1. A polarization controlled laser comprising:
   a) a gain cavity for producing laser radiation comprised of first and second mirrors with a gain medium disposed between the mirrors;
   b) a polarizing cavity with polarizing means for polarizing said radiation comprised of said second mirror and a third mirror with a spacer of controllable optical length disposed between the second and third mirrors; and
   c) a source for pumping the gain medium to produce said laser radiation, the polarization of which is controlled by the optical length of the spacer.

2. The laser of Claim 1 wherein the reflectivity of the third mirror provides feedback of polarized radiation to the gain cavity to control the polarization of the radiation.

3. The laser of Claim 1 wherein the polarizing means absorbs light polarized in a first direction and transmits light polarized in a second direction.

4. The laser of Claim 1 wherein the polarizing means reflects light polarized in a first direction and transmits light polarized in a second direction.

5. The laser of Claim 1 wherein the spacer is an electro-optic material and the electro-optic effect is used to change the optical length of the spacer.

6. The laser of Claim 1 wherein the spacer is a piezoelectric material and the piezoelectric effect is used to control the optical length of the spacer.

7. The laser of Claim 1 wherein the spacer is opaque and a hole is formed therein to allow light to pass through.

8. The laser of Claim 1 wherein the spacer is formed of a semiconductor material and the optical length of the spacer is controlled by an electric field applied to the element.

9. The laser of Claim 8 wherein the semiconductor material has formed thereon transparent conductive layers for applying said electric field across the element.

10. The laser of Claim 1 wherein the gain medium is a solid state material.

11. The laser of Claim 10 wherein the distance between the first and second mirrors produces a frequency separation of the modes of oscillation in the gain cavity which is less than the gain bandwidth of the gain medium.

12. The laser of Claim 1 wherein the polarizing means is a birefrigent element.

13. The laser of Claim 1 wherein said polarizing means is formed by said spacer.

14. The laser of Claim 1 wherein said polarizing means is formed by one of the second and third mirrors.

15. The laser of Claim 1 wherein said polarizing means comprises a separate polarizing element.

16. A method of controlling the polarization of a laser comprising:
    a) forming a gain cavity for producing laser radiation by disposing a gain medium between first and second mirrors;
    b) forming a polarizing cavity with polarizing means for polarizing said radiation by disposing a spacer of controllable optical length between the second mirror and a third mirror; and
    c) optically pumping the gain medium to produce said laser radiation within the gain cavity and wherein the polarization of the radiation is controlled by the optical length of the spacer medium.

17. The method of Claim 16 wherein the reflectivity of the third mirror provides sufficient feedback of polarized light to the gain cavity to control the polarization of the radiation.

18. The method of Claim 16 wherein the polarizing means absorbs light polarized in a first direction and transmits light polarized in a second direction.

19. The method of Claim 16 wherein the polarizing means reflects light polarized in a first direction and transmits light polarized in a second direction.

20. The method of Claim 16 wherein the spacer is an electro-optic material and the electro-optic effect is used to change the optical length of the spacer.

21. The method of Claim 16 wherein the polarizing means is birefringent element.

22. The method of Claim 16 wherein the polarizing means is formed by said spacer.

23. The method of Claim 16 wherein the polarizing means is formed by one of said second and third mirrors.

24. The method of Claim 16 wherein the polarizing means is formed by a separate polarizing element.

25. The method of Claim 16 wherein the spacer is a piezoelectric material and the piezoelectric effect is used to control the optical length of the spacer.

26. The method of Claim 16 wherein the spacer is opaque and a hole is formed therein to allow light to pass through.

27. The method of Claim 16 wherein the spacer is formed of a semiconductor material and the optical length of the is controlled by applying an electric field to the element.

28. The method of Claim 27 wherein the semiconductor material has formed thereon transparent conductive layers for applying said electric field across the element.

29. A polarizing cavity comprised of:
   a) a first partially reflecting surface;
   b) a spacer of variable optical length;
   c) a polarizing element; and
   d) a second partially reflecting surface, and wherein light reflected from the cavity is partially polarized.

30. The cavity of Claim 29 wherein the polarizing element absorbs light polarized in a first direction and transmits light polarized in a second direction.

31. The cavity of Claim 29 wherein the polarizing element reflects light polarized in a first direction and transmits light polarized in a second direction.

32. The cavity of Claim 29 wherein the polarizing element is birefringent.

33. A polarizing cavity comprised of:
   a) a first partially reflecting surface;
   b) a birefringent element; and
   c) a second partially reflecting surface, and wherein light reflected from the cavity is partially polarized.

34. The cavity of Claim 29 wherein the optical length of the spacer can be controlled to control the partial polarization of the reflected light.

35. The cavity of Claim 33 wherein the optical length of the birefringent element can be controlled to control the partial polarization of the reflected light.

36. The cavity of Claim 34 wherein the spacer is formed of a transparent electro-optic material.

37. The cavity of Claim 36 wherein the electro-optic effect is used to change the optical length of the spacer for both of the two orthogonal polarizations of light.

38. The cavity of Claim 36 wherein the electro-optic effect is used to change the optical length of the spacer for only one of the two orthogonal polarizations of light.

39. The cavity of Claim 34 wherein the spacer is formed of a transparent piezoelectric material.

40. The cavity of Claim 34 wherein the spacer is formed of a piezoelectric material with a hole cut in it, through which light may pass.

41. The cavity of Claim 34 wherein the spacer is a semiconducting material.

42. The cavity of Claim 41 wherein an electric field is applied across the spacer to control its optical length.

43. The cavity of Claim 41 wherein the electric field is applied to transparent electrodes deposited on the faces of the spacer through which light passes.

44. The cavity of Claim 41 wherein the electric field is applied to conductive semiconducting layers grown on the faces of the spacer.

45. The cavity of Claim 35 wherein the birefringent element is also an electro-optic material.

46. The cavity of Claim 45 wherein the electro-optic effect is used to change the optical length of the birefringent element for both of the two orthogonal polarizations of light.

47. The cavity of Claim 45 wherein the electro-optic effect is used to change the optical length of the birefringent element for only one of the two orthogonal polarizations of light.

48. The cavity of Claim 35 wherein the birefringent element is also a piezoelectric material.

49. The cavity of Claim 35 wherein the birefringent element is a semiconducting material.

50. The cavity of Claim 35 wherein an electric field is applied across the birefringent element in order to control its optical length.

51. The cavity of Claim 35 wherein the electric field is applied to transparent electrodes deposited on the faces of the birefringent element through which light passes.

52. The cavity of Claim 49 wherein the electric field is applied to conductive semiconducting layers grown on the faces of the birefringent element.

53. The cavity of Claim 29 optically coupled to a laser gain cavity to control the polarization of the oscillating mode of light produced in the gain cavity.

54. The cavity of Claim 53 in which the free spectral range of the polarizing cavity is equal to the longitudinal mode spacing of the gain cavity.

55. The cavity of Claim 53 in which the spacings between the longitudinal modes of the gain cavity are a multiple of the free spectral range of the polarizing cavity.

56. The cavity of Claim 29 coupled to a laser to control the polarization of the laser through changes in the frequency of the lasers longitudinal modes.

57. The cavity of Claim 29 for controlling the polarization of a microchip laser.

58. The cavity of Claim 33 optically coupled to a laser gain cavity to control the polarization of the oscillating mode of light produced in the gain cavity.

59. The cavity of Claim 33 coupled to a laser to control the polarization of the laser through changes in the frequency of the lasers longitudinal modes.

60. The cavity of claim 33 for controlling the polarization of a microchip laser.

61. The cavity of Claim 58 in which the full spectral range of the polarizing cavity is equal to the longitudinal mode spacing of the gain cavity.

62. The cavity of Claim 58 in which the spacings between the longitudinal modes of the gain cavity are a multiple of the full spectral range of the polarizing cavity.

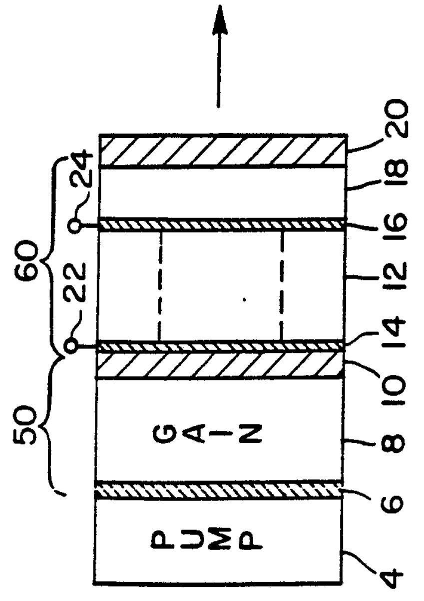

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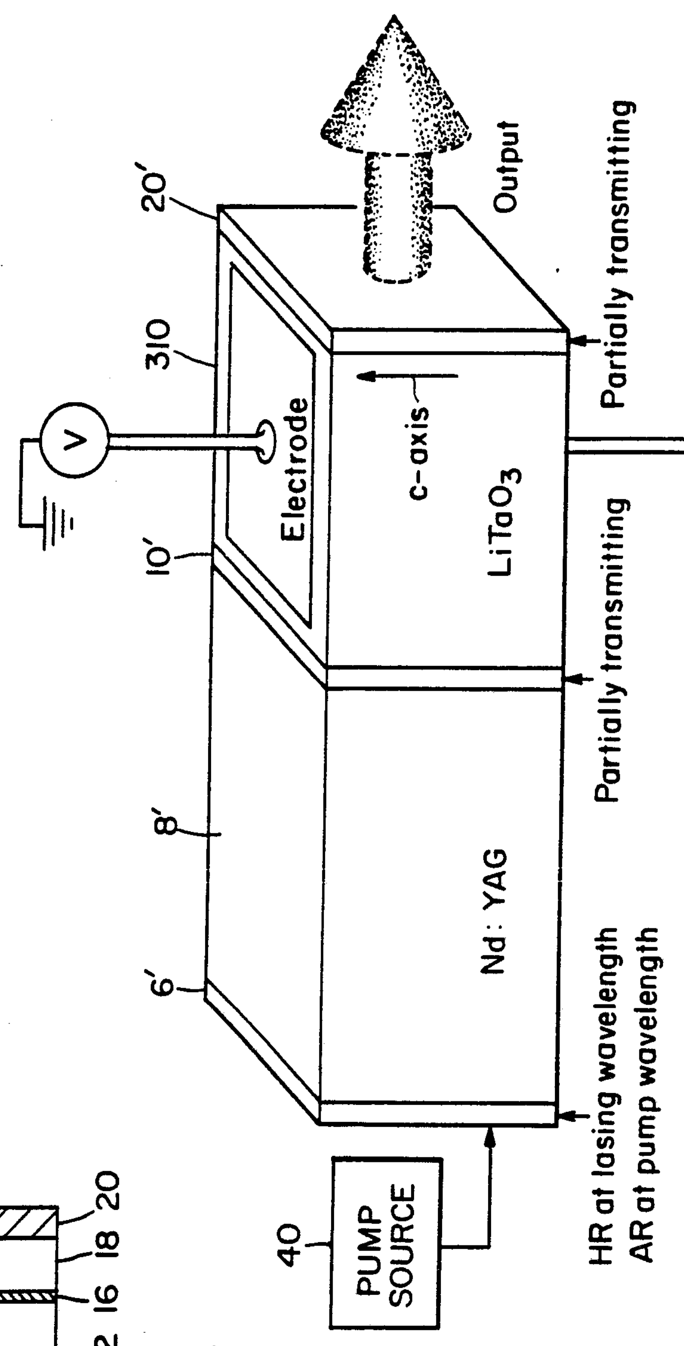
Fig. 1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10'
8'
6'
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c-axis
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Nd: YAG
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PUMP SOURCE
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Partially transmitting
HR at lasing wavelength
AR at pump wavelength
Polarizing Cavity 60'
Gain Cavity 50'

Fig. 2

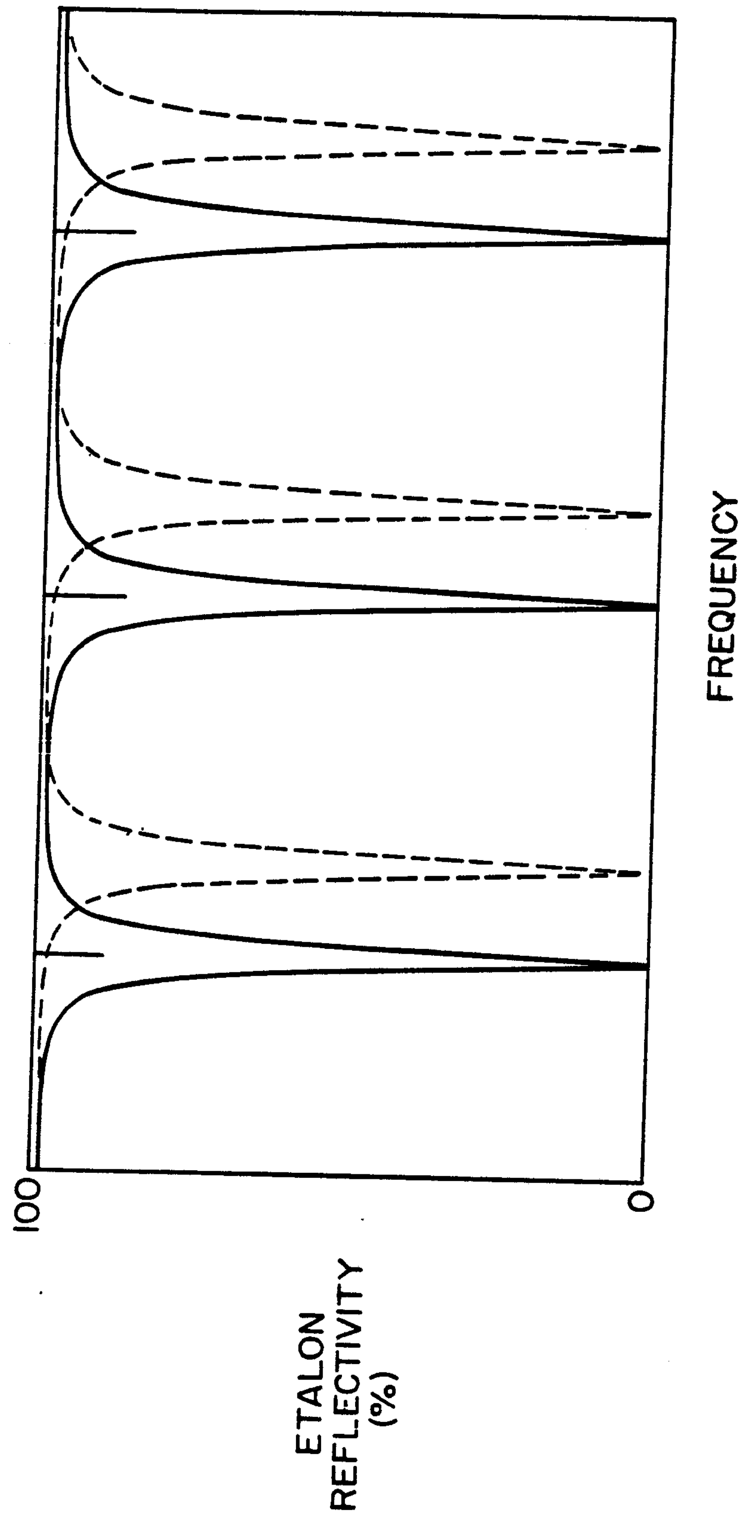

Fig. 3

INTERNATIONAL SEARCH REPORT

International Application No PCT/US 92/00233

I. CLASSIFICATION OF SUBJECT MATTER (if several classification symbols apply, indicate all)[6]

According to International Patent Classification (IPC) or to both National Classification and IPC

Int.Cl. 5 H01S3/106; H01S3/082

II. FIELDS SEARCHED

Minimum Documentation Searched[7]

Classification System	Classification Symbols
Int.Cl. 5	H01S

Documentation Searched other than Minimum Documentation to the Extent that such Documents are Included in the Fields Searched[8]

III. DOCUMENTS CONSIDERED TO BE RELEVANT[9]

Category °	Citation of Document,[11] with indication, where appropriate, of the relevant passages[12]	Relevant to Claim No.[13]
X,P	WO,A,9 100 631 (THE UNIVERSITY OF TORONTO INNOVATIONS FOUNDATION) 10 January 1991 see abstract see page 7, line 28 - line 36 see page 13, line 16 - line 22 see page 14, line 27 - page 15, line 11 see claims 1,7,9-11,15; figure 1	1-3,5, 10, 14-18, 20,23, 24,29, 30,34,36 37,53, 56,57
Y,P		4,8,12, 13,19, 21,22, 27,58-60
A,P	---	33,35
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° Special categories of cited documents :[10]

"A" document defining the general state of the art which is not considered to be of particular relevance

"E" earlier document but published on or after the international filing date

"L" document which may throw doubts on priority claim(s) or which is cited to establish the publication date of another citation or other special reason (as specified)

"O" document referring to an oral disclosure, use, exhibition or other means

"P" document published prior to the international filing date but later than the priority date claimed

"T" later document published after the international filing date or priority date and not in conflict with the application but cited to understand the principle or theory underlying the invention

"X" document of particular relevance; the claimed invention cannot be considered novel or cannot be considered to involve an inventive step

"Y" document of particular relevance; the claimed invention cannot be considered to involve an inventive step when the document is combined with one or more other such documents, such combination being obvious to a person skilled in the art.

"&" document member of the same patent family

IV. CERTIFICATION

Date of the Actual Completion of the International Search	Date of Mailing of this International Search Report
27 MAY 1992	23.06.92
International Searching Authority	**Signature of Authorized Officer**
EUROPEAN PATENT OFFICE	BATTIPEDE F. Battipede F.

III. DOCUMENTS CONSIDERED TO BE RELEVANT (CONTINUED FROM THE SECOND SHEET)		
Category °	Citation of Document, with indication, where appropriate, of the relevant passages	Relevant to Claim No.
X	US,A,4 498 179 (WAYNE ET AL.) 5 February 1985	29, 31-37, 41,42, 45,46, 49,50
	see abstract; figures 1,2 see column 1, line 45 - column 2, line 15 see column 3, line 57 - column 4, line 6	
Y		4,8,12, 13,19, 21,22, 27,38, 43,47, 51,58-60
A		1,15,16, 20,24, 27,28

Y	ELECTRONICS LETTERS. vol. 23, no. 15, 16 July 1987, STEVENAGE GB pages 803 - 804; T. FUJITA ET AL.: 'Polarization switching in a single-frequency external-cavity semiconductor laser' see abstract see page 803, left column, paragraph 3 - right column, paragraph 1; figure 1	38,47
A		1,16

Y	EP,A,0 012 439 (MTA KZPONTI FIZIKAI KUTATO INTEZETE) 25 June 1980 see page 3, line 19 - line 29 see page 8, line 19 - line 22	43,51
A		9,28

A	JOURNAL OF THE OPTICAL SOCIETY OF AMERICA - B. vol. 4, no. 8, August 1987, NEW YORK US pages 1276 - 1280; G. STEPHAN ET AL.: 'Competition effects in the polarization of light in a quasi-isotropic laser' see page 1276, left column, line 11 - right column, line 11; figures 1A,2B see page 1279, right column, line 23 - line 34	1-3, 15-18, 29,30, 33,34, 53,56, 58,59

ANNEX TO THE INTERNATIONAL SEARCH REPORT ON INTERNATIONAL PATENT APPLICATION NO. US 9200233 SA 57068

This annex lists the patent family members relating to the patent documents cited in the above-mentioned international search report.
The members are as contained in the European Patent Office EDP file on 27/05/92
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Patent document cited in search report	Publication date	Patent family member(s)		Publication date
WO-A-9100631	10-01-91	US-A-	5022034	04-06-91
		AU-A-	5923290	17-01-91
US-A-4498179	05-02-85	None		
EP-A-0012439	25-06-80	None		

For more details about this annex : see Official Journal of the European Patent Office, No. 12/82