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(54) Title: LAMINATED DIFFRACTIVE OPTICAL ELEMENT AND OPTICAL SYSTEM

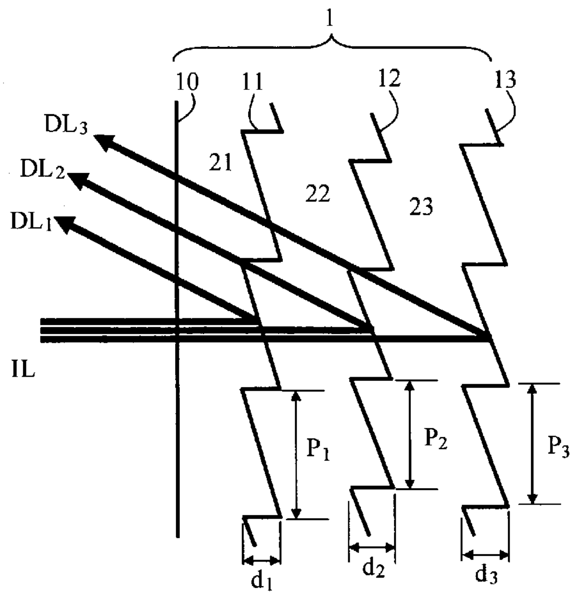

FIG. 1

(57) Abstract: The laminated diffractive optical element includes plural diffraction gratings 21, 22 and 23 laminated with each other, the respective diffraction gratings being formed of a same light-transmissive material. In the element, reflective films are formed on grating surfaces 11 and 12 of the respective diffraction gratings, each of the reflective films being disposed between the diffraction gratings. Each of the reflective films reflects light in a specific wavelength range and transmits light in a wavelength range different from the specific wavelength range, the specific wavelength ranges of the respective reflective films being different from each other. The grating surfaces of the respective diffraction gratings are formed in shapes different from each other according to the specific wavelength ranges corresponding to the respective reflective films.

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DESCRIPTION

TITLE OF INVENTION

LAMINATED DIFFRACTIVE OPTICAL ELEMENT AND OPTICAL SYSTEM

TECHNICAL FIELD

The present invention relates to a laminated diffractive optical element, and particularly to a laminated diffractive optical element with reduced chromatic aberration.

BACKGROUND ART

Diffractive optical elements (hereinafter referred to as DOEs) provide arbitrary optical powers and have anomalous dispersion characteristics that can effectively reduce chromatic aberration of a refractive optical system.

However, the DOEs are nearly always provided with reduced optical powers to be used in optical systems for multicolor lights so as to correct the chromatic aberration well. This is because a dispersion of the DOE is extremely larger than that of refraction and therefore a DOE having an optical power significantly contributing to image-formation increases differences of diffraction powers for various wavelengths, which increases chromatic aberration generated by the DOE. Thus, performances of the DOEs are not utilized enough.

Japanese Patent No. 3966303 discloses a pickup lens having on its each surface binary step with different heights. This pickup lens sets the height of binary steps on one surface to a value equal to an integral multiple of a wavelength that is not desired to be diffracted through the binary steps and to a value different from an integral multiple of a wavelength that is desired to be diffracted therethrough, thereby diffracting only light of the desired wavelength.

Moreover, Japanese Patent Laid-Open No. 9-189892 discloses a displaying optical system including a liquid crystal DOE. The displaying optical system performs high-speed time division switching of a wavelength of light from a light source such as R→G→B→R→..., and switches parameters of the liquid crystal DOE in synchronization with the time division switching, thereby suppressing generation of aberration.

Description will be made of an example of a transmissive DOE in which concentric annular zones are formed on a transparent flat substrate whose refractive index $n(\lambda_d)$ is 1.5168 (λ_d=587.56nm). When a diffraction order of the DOE is +1st order and a focal length thereof is 50mm, if an entrance pupil is disposed coaxially with the annular zones and a diameter of the entrance pupil is 5mm, a longitudinal chromatic aberration of R-B (λ_R=640nm and λ_B=480nm) increases to 15.704mm. In a case of a refractive lens having a refractive index identical to that of the DOE and a focal length of 50mm, a curvature radius is -28.63mm and the longitudinal chromatic aberration of R-B is 0.775mm.

Furthermore, description will be made of an example of a reflective DOE that converts an incident angle of 25° into a reflection angle of 60° and whose diffraction order is +1st order and focal length is 50mm. In this DOE, the longitudinal chromatic aberration of R-B increases to 40mm or more.

These descriptions were made of the cases where the DOE is used alone. However, in a case where the DOE having a strong power is used in an optical system including lenses or mirrors, an extremely large chromatic aberration is generated due to diffraction by the DOE, which may prevent formation of the optical system.

The DOEs disclosed in Japanese Patent No. 3966303 and Japanese Patent Laid-Open No. 9-189892 may solve the above-described problem. However, the DOE disclosed in Japanese Patent No. 3966303 is a multi-level zone plate DOE, which may obtain an insufficient diffraction efficiency. Further, the liquid crystal DOE disclosed in Japanese Patent Laid-Open No. 9-189892 involves a problem that accuracy of an annular zone interval depends on a size of a pixel cell and a problem that temporal responsiveness thereof cannot be sufficiently improved.

SUMMARY OF INVENTION

The present invention provides a laminated diffractive optical element having a strong power and being capable of reducing chromatic aberration generated due to diffraction.

The present invention provides as one aspect thereof a laminated diffractive optical element including plural diffraction gratings laminated with each other, the respective diffraction gratings being formed of a same light-transmissive material, and plural reflective films formed on grating surfaces of the respective diffraction gratings, each of the reflective films being disposed between the diffraction gratings. Each of the reflective films reflects light in a specific wavelength range and transmits light in a wavelength range different from the specific wavelength range, the specific wavelength ranges for the respective reflective films being different from each other. The grating surfaces of the respective diffraction gratings are formed in shapes different from each other according to the specific wavelength ranges for the respective reflective films.

The present invention provides as another aspect thereof a laminated diffractive optical element including plural diffraction gratings laminated with each other, the respective diffraction gratings being formed of light-transmissive materials different from each other. Grating surfaces of the respective diffraction gratings are formed in shapes different from each other. Refractive indices of the diffraction gratings adjacent to each other in a lamination direction in which the diffraction gratings are laminated have mutually different dispersion characteristics for one specific color light. Each of the grating surfaces diffracts the specific color light.

The present invention provides as still another aspect thereof an optical system including the above-described laminated diffractive optical element.

Further features and aspects of the present invention will become apparent from the following description of exemplary examples (embodiments) with reference to the attached drawings.

BRIEF DESCRIPTION OF DRAWINGS

FIG. 1 schematically shows a structure of a reflective DOE that is Example 1 of the present invention.

FIG. 2 schematically shows a structure of a transmissive DOE that is Example 2 of the present invention.

FIG. 3 schematically shows a structure of a reflective DOE that is Example 3 of the present invention.

FIG. 4 shows an optical system including the reflective DOE of Example 3.

FIG. 5 is a graph showing a reflectance characteristic of a dichroic film being used in the reflective DOE of Example 3.

FIG. 6 is a graph showing a reflective diffraction efficiency of the reflective DOE of Example 3 for a wavelength λ_B.

FIG. 7 is a graph showing transmissive diffraction efficiencies of the reflective DOE of Example 3 for wavelengths λ_G and λ_R.

FIG. 8 schematically shows a structure of a reflective DOE that is Example 4 of the present invention.

FIG. 9 schematically shows a structure of a reflective DOE that is Example 4 of the present invention.

FIG. 10 is a graph showing diffraction efficiencies at a grating surface.

FIGS. 11 and 12 are graphs showing dispersion characteristics of materials used for the transmissive DOE of Example 2.

FIG. 13 shows an optical system that is Example 5 of the present invention.

FIG. 14 shows an optical system that is Example 6 of the present invention.

FIG. 15 is a graph showing dispersion characteristics of a material used for a transmissive DOE included in the optical system of Example 6.

DESCRIPTION OF EMBODIMENTS

Exemplary embodiments (examples) of the present invention will hereinafter be described with reference to the accompanying drawings.

Example 1

FIG. 1 shows a reflective laminated DOE (laminated diffractive optical element) 1 that is a first example (Example 1) of the present invention. The DOE 1 is constituted by laminating three diffraction grating layers (diffraction gratings) including a first layer 21, a second layer 22 and a third layer 23. The three diffraction grating layers are formed of a same light-transmissive medium (material), and refractive indices (n(λ)) thereof are also equal to each other.

A dichroic film as a reflective film that reflects light in a first wavelength range is formed on a grating surface 11 disposed between the first layer 21 and the second layer 22. A dichroic film as a reflective film that reflects light in a second wavelength range is formed on a grating surface 12 disposed between the second layer 22 and the third layer 23.

Moreover, a grating surface 13 is formed as a mirror surface that reflects light transmitted through the first to third layers 21-23. This mirror surface may be formed of a reflective film vapor-deposited on a back surface of the third layer 23 or may be formed of a metal plate.

The reflective films formed on the grating surfaces 11 and 12 are not limited to the dichroic film, and only have to be a film that reflects light in a specific wavelength range (such as the light in the first wavelength range or the light in the second wavelength range) and transmits light in a wavelength range different from the specific wavelength range. The reflection of the light in the specific wavelength range and the transmission of the light in the wavelength range different from the specific wavelength range in this example do not necessarily require 100 percent reflection and 100 percent transmission, that is, may include slight transmission and reflection (for example, 5 or 10 percent transmission and reflection).

Forming the first to third layers 21-23 with the same material as described above makes the entire DOE 1 thin. In a case where the first to third layers 21 to 23 are formed of resin, forming the grating surface 13 that includes the mirror surface on a substrate and then sequentially forming thereon the third layer 23, the dichroic film, the second layer 22, the dichroic film and the first layer 21 can produce the DOE. In this case, an anti-reflection film may be formed on a light entrance side surface 10 of the first layer 21. Furthermore, disposing a transparent substrate further on a light entrance side than the surface 10 and then sequentially forming thereon the first layer 21, the dichroic film, the second layer 22, the dichroic film, the third layer 23 and the reflective film can produce the DOE as a back-surface mirror.

The grating surfaces 11 and 12 on which the dichroic films are formed and the grating surface 13 on which the mirror surface is formed include gratings formed as grating annular zones having a blazed shape (hereinafter, the dichroic films are also denoted by reference numerals 11 and 12, and the mirror surface is also denoted by reference numeral 13). The annular zones are formed with an annular zone interval set based on a phase difference function calculated so as to provide a required optical power.

In this example, to simplify the explanation, the DOE 1 is assumed to be formed in a flat plate shape as a whole, and an envelope surface of edges of the gratings formed on each of the grating surfaces 11-13 and the surface 10 are assumed to be a plane.

Thus, non-monochromatic light entering the DOE 1 from the surface 10 is transmitted through the first layer 21, and then light in the first wavelength range included in the non-monochromatic light is reflected and diffracted at a predetermined diffraction order by the grating surface 11. The reflected and diffracted light is again transmitted through the first layer 21 to exit from the DOE 1 through the surface 10. Light in a wavelength range other than the first wavelength range included in the non-monochromatic light is transmitted through the grating surface 11 without being diffracted since the refractive indices of the first and second layers 21 and 22 are equal to each other.

Of the light transmitted through the grating surface 11 and the second layer 22, light in the second wavelength range is reflected and diffracted at the predetermined diffraction order by the grating surface 12, and then is again transmitted through the second layer 22 and the first layer 21 to exit from the DOE 1 through the surface 10 without being diffracted by the grating surface 11. Of the light transmitted through the second layer 22, light in a wavelength range other than the second wavelength is transmitted through the grating surface 12 without being diffracted since the refractive indices of the second and third layers 22 and 23 are equal to each other.

The light transmitted through the grating surface 12 and the third layer 23 is reflected and diffracted at the predetermined diffraction order by the grating surface 13, and is again transmitted through the third to first layers 23-21 to exit from the DOE 1 through the surface 10 without being diffracted by the grating surfaces 12 and 11.

In conventional reflective DOEs, since a grating surface set such that a diffraction efficiency becomes maximum for a certain wavelength range diffracts light in the entire wavelength range, it is difficult to reduce the above-described wavelength dependency of power. In contrast, the DOE 1 of this example can set, if optimizing the shape of each of the grating surfaces for the wavelength range which is desired to be diffracted by that grating surface (that is, the specific wavelength range), a power to diffract light in that wavelength range independently. As a result, the DOE 1 of this example can reduce chromatic aberration. That is, the grating surfaces 11 and 12 in the DOE 1 of this example have mutually different shapes according to the specific wavelength ranges for the reflective films respectively formed on the grating surfaces 11 and 12.

Moreover, the DOE 1 of this example can optimize the diffraction efficiency at each grating surface in an arbitrary wavelength range, therefore making it possible to ensure a high diffraction efficiency in a limited wavelength range to be reflected and diffracted as shown in FIG. 10.

Furthermore, in FIG. 1, reference character IL denotes non- monochromatic light (incident light) that impinges on a certain point on the DOE 1. The grating surface 11 reflects and diffracts the light in the first wavelength range including a wavelength λ_1, and transmits the light in the wavelength range other than the first wavelength range. The grating surface 12 reflects and diffracts the light in the second wavelength range including a wavelength λ_2, and transmits the light in the wavelength range other than the second wavelength range. The grating surface 13 reflects and diffracts the light in the wavelength range transmitted through the grating surfaces 11 and 12 including a wavelength λ_3.

Reference characters DL_1, DL_2 and DL_3 respectively denote light rays reflected and diffracted at the grating surfaces 11, 12 and 13. Reference characters P_1, P_2 and P_3 and d_1, d_2 and d_3 respectively denote annular zone intervals (pitches of the annular zones) P and grating heights d at the incident points of the light rays DL_1, DL_2 and DL_3 on the grating surfaces 11, 12 and 13. That is, the annular zone intervals P_1, P_2 and P_3 and the grating heights d_1, d_2 and d_3 on the grating surfaces 11, 12 and 13 are mutually different on a same incident ray axis along which the light rays DL_1, DL_2 and DL_3 trace.

Setting the annular zone intervals P_1, P_2 and P_3 such that the powers at the respective grating surfaces are equivalent to each other enables reduction of differences of the powers depending on wavelengths. Since in the DOE the power increases as the wavelength becomes longer, it is only necessary to set the annular zone intervals on the respective grating surfaces so as to satisfy the following relationship if the wavelengths are $\lambda_3<\lambda_2<\lambda_1$ ...(1):

$P_3<P_2<P_1$ ...(2).

When the DOE is an axisymmetric element, a phase difference function φ is generally expressed as follows:

$$\phi(r)=\sum_{n}^{N} C_n \cdot r^{2n} \cdot \cdot \cdot \cdot \cdot \quad (3).$$

(r: distance from annular zone center)

The annular zone interval P(r) is expressed as follows:

$P(r)=\lambda/\{d\varphi(r)/dr\}$ ...(4),

and therefore it is only necessary to set the annular zone intervals P_1, P_2 and P_3 as follows:

$(P_1:P_2:P_3)=(\lambda_1:\lambda_2:\lambda_3)$ ...(5).

Moreover, to improve the diffraction efficiency, it is only necessary to set the grating heights of the respective grating surfaces so as to become maximum at the wavelengths λ_1, λ_2 and λ_3. The wavelengths λ_1, λ_2 and λ_3 are not necessarily required to coincide with the wavelengths when the above-described annular zone intervals are set, and may be appropriate values for wavelength spectra to be reflected at the respective grating surfaces.

The grating height d is expressed as follows:

$d=m\cdot\lambda/\psi$ ...(6)

(ψ represents an optical path difference),

and therefore the grating heights d_1, d_2 and d_3 only have to be set as follows if the wavelengths are $\lambda_3<\lambda_2<\lambda_1$,

$d_3<d_2<d_1$ ...(7).

That is, the grating heights d_1, d_2 and d_3 only have to approximately satisfy the following relationship:

$(d_1:d_2:d_3)=(\lambda_1:\lambda_2:\lambda_3)$ ...(8).

As to wavelength dependency of the diffraction efficiency at each grating surface, as shown in FIG. 10, the diffraction efficiency shown by a vertical axis decreases as a wavelength of diffracted light (shown by a horizontal axis) departs further from a wavelength at which the diffraction efficiency is peak (hereinafter referred to as a "peak wavelength"). Therefore, it is desirable that a spectrum of light entering the DOE have a peak near the peak wavelengths of the respective grating surfaces and be as narrow as possible. For example, using a light source such as a laser and an LED whose peak of the spectrum is near the respective peak wavelengths enables reduction of unnecessary diffracted light. On the other hand, even if the spectrum of the light source is wide, providing plural color filters periodically with respect to pixels of a display element or an image pickup element enables acquisition of similar effects.

Example 2

FIG. 2 shows a transmissive laminated DOE 2 that is a second example (Example 2) of the present invention.

This DOE 2 is also constituted by laminating plural diffraction grating layers (diffraction gratings) each diffracting monochromatic light, which is the same as the DOE 1 of Example 1. The DOE 2 has a color correction function for two wavelengths.

The DOE 2 is constituted by laminating three light-transmissive media including a first layer 41, a second layer 42 and a third layer 43. The three light-transmissive media are different from each other, and refractive indices thereof are also mutually different. The refractive indices of the light-transmissive media forming the first layer 41, the second layer 42 and the third layer 43 are respectively represented by $n_1(\lambda)$, $n_2(\lambda)$ and $n_3(\lambda)$.

A grating surface 11 disposed between the first layer 41 and the second layer 42 and a grating surface 12 disposed between the second layer 42 and the third layer 43 are formed as grating surfaces having a blazed structure. However, the shapes of the blazed structures of the grating surfaces 11 and 12 are mutually different.

Light IL including at least light in wavelengths λ_1 and λ_2 enters the DOE 2 through a surface 10, and then exits from the DOE 2 through a surface 14. The grating surfaces 11 and 12 and the surface 10 and 14 may be provided with an anti-reflection film. Moreover, in order to make the first layer 41 and the third layer 43 thin, a light-transmissive substrate may be disposed further on a light entrance side than the surface 10 or further on a light exit side than the surface 14. The light-transmissive substrate serves as a holding member, which makes it possible to thin the layer on the light entrance side or on the light exit side.

The refractive indices $n_1(\lambda)$ and $n_2(\lambda)$ of the first and second layers 41 and 42 adjacent to each other in a lamination direction in which the first to third layers 41-43 are laminated with each other are at least different from each other for the wavelength λ_1 (one color light) and equal to each other for the other wavelength λ_2. That is, the first and second layers 41 and 42 have dispersion characteristics such that the following relationships are satisfied:

$n_1(\lambda_1)<n_2(\lambda_1)$

$n_1(\lambda_2)=n_2(\lambda_2)$ ...(9).

The grating surface 11 is formed such that an annular zone interval P_1 and a grating height d_1 can provide a required diffraction power and a required diffraction efficiency for the wavelength λ_1. Therefore, at the grating surface 11, the light in the wavelength λ_1 is transmitted therethrough and diffracted in a predetermined direction, and the light in the wavelength λ_2 is transmitted therethrough without being diffracted to enter the second layer 42.

Moreover, the refractive indices $n_2(\lambda)$ and $n_3(\lambda)$ of the second layer 42 and the third layer 43 adjacent to each other in the lamination direction are different from each other for at least the wavelength λ_2 (one color light) and equal to each other for the other wavelength λ_1. That is, the second layer 42 and the third layer 43 have dispersion characteristics satisfying the following relationships:

$n_2(\lambda_2)<n_3(\lambda_2)$

$n_2(\lambda_1)=n_3(\lambda_1)$ ...(10).

Moreover, the grating surface 12 is formed such that an annular zone interval P_2 and a grating height d_2 can provide a required diffraction power and a required diffraction efficiency for the wavelength λ_2. Therefore, at the grating surface 12, the light in the wavelength λ_2 is transmitted therethrough and diffracted in a predetermined direction, and the light in the wavelength λ_1 is transmitted therethrough without being diffracted to enter the third layer 43.

FIG. 11 shows the dispersion characteristics of the light-transmissive media forming the first to third layers 41-43. In these characteristics, λ_1 is 640nm and λ_2 is 410nm. Forming the DOE 2 using materials having such dispersion characteristics enables application of the DOE 2 to an optical element such as a pickup lens that converges two laser light fluxes in the wavelengths λ_1 and λ_2 on focal points different from each other on a same axis.

Although description was made of the case where the DOE independently transmits and diffracts two color lights of mutually different wavelengths, it is only necessary to satisfy the following condition when the DOE independently transmits and diffracts three or more color lights of mutually different wavelengths.

In a case where light entering the DOE includes N spectra each having a wavelength λi as a peak ($i=1$ to N, $\lambda_i>\lambda_{i+1}$ and $N\geq2$), the DOE is constituted by at least N+1 layers formed of mutually different light-transmissive media each having a refractive index n_j ($j=1$ to $N+1$). The light-transmissive medium is disposed as a layer further on the light entrance side as the index j is smaller. In this case, it is only necessary that a wavelength characteristic of each layer is as follows:

when $j=i$, $n_j(\lambda_i)<n_{j+1}(\lambda i)$,

when $j>i$, $n_j(\lambda_i)=n_{i+1}(\lambda_i)$, and

when $j<i$, $n_j(\lambda_i)=n_i(\lambda_i)$ … (11).

The above-described example of the DOE 2 corresponds to a case where N=2 ($i=1$ to 2, $j=1$ to 3). Such a DOE transmits and diffracts in a predetermined direction light of a certain wavelength $\lambda_{i=k}$ at respective grating surfaces, and transmits light of other wavelengths $\lambda_{i\neq k}$ without diffracting it.

FIG. 12 shows dispersion characteristics of the respective light-transmissive media required for a case of N=3 as an example. This example assumes that three wavelengths are λ_1=640nm, λ_2=530nm and λ_3=470nm. The DOE has a structure including four layers. Light of the wavelength λ_1 is diffracted by a grating surface between a first layer and a second layer independently, light of the wavelength λ_2 is diffracted by a grating surface between the second layer and a third layer independently, and light of the wavelength λ_3 is diffracted by a grating surface between the third layer and a fourth layer independently.

Methods for providing the dispersion characteristics required for the respective light-transmissive media include, for example, a method that dopes inorganic nanoparticles into a light-transmissive organic material.

Example 3

FIG. 3 shows a specific example of the reflective laminated DOE 1 described in Example 1. This DOE 1 is constituted by laminating three layers of diffraction gratings including the first layer 21 to the third layer 23, the layers being formed of the same light-transmissive media. The grating surface 11 is formed between the first layer 21 and the second layer 22, the grating surface 12 is formed between the second layer 22 and the third layer 23, and the grating surface 13 is formed on the back surface of the third layer 23.

A dichroic film is formed on the grating surface 11. This dichroic film reflects and diffracts light in a wavelength range (first wavelength range) from red (R) to infrared. Another dichroic film is formed on the grating surface 12. This dichroic film reflects and diffracts light in a wavelength range (second wavelength range) from ultraviolet to blue (B). The grating surface 13 reflects and diffracts at least light in a wavelength range of green (G) (third wavelength range) transmitted through the grating surfaces 11 and 12.

This structure enables the two dichroic films to independently reflect and diffract the light in the first wavelength range that is a short side wavelength range and the light in the second wavelength range that is a long side wavelength range. Furthermore, this structure enables at least the grating surface that reflects the light in the third wavelength range between the first and second wavelength ranges to diffract that light with a required power.

Moreover, this structure only requires to set reflectance characteristics of the two light-entrance side surfaces like a low-pass filter (some nm or less) or a high-pass filter (some nm or more), that is, does not require to set them like a band-pass filter, which enables simplification of the structure of the dichroic film. Even in a case where the grating surface 11 reflects the light in the wavelength range from blue to ultraviolet and the grating surface 12 reflects the light in the wavelength range from red to infrared, this effect is similarly obtained.

In other words, in this DOE 1, one and the other of the first grating surface 11 that reflects the light in the wavelength range from blue to ultraviolet and the second grating surface 12 that reflects the light in the wavelength range from red to infrared are arranged in no particular order from the light entrance side.

Furthermore, the third grating surface 13 that reflects the light in a wavelength range transmitted through the dichroic films formed on the first and second grating surfaces 11 and 12 may be formed on a side opposite to the light entrance side with respect to the first and second grating surfaces 11 and 12.

FIG. 4 shows an optical system that forms an image by using a reflective DOE 50 which is decentered, the optical system having a diameter of an entrance pupil of 5mm and an angle of view of 20 degrees. Numerical data of the optical system is shown below.

An origin of coordinates is set to a center of the entrance pupil, and an axis passing the center of the pupil and extending in a direction orthogonal to the pupil is defined as a Z axis. An axis extending in a direction orthogonal to the Z axis and in a direction along a decentering cross section (meridional cross section) is defined as a Y axis. An axis extending in directions orthogonal to the Y axis and the Z axis is defined as an X axis, and θ represents a rotational decentering angle around the X axis.

SURFACE NUMBER	CURVATURE RADIUS	Y POSITION	Z POSITION	θ
OBJECT	∞	0.000	∞	
1:(PUPIL)	∞	0.000	0.000	
2:	∞	0.000	50.000	
3:	∞	0.000	50.000	

4:	∞	-0.7714	50.000(DOE)	30°
5:	∞	-0.7714	50.000	90°
6:	∞	-50.7714	50.000	90°
IMAGE PLANE:	∞	-50.7714	50.000	90°

This optical system is configured such that an incident angle is larger than a reflection angle. Design wavelengths are λ_R=640nm, λ_G=530nm and λ_B=480nm, and a design diffraction order is +5th order. A phase difference function of each layer is expressed as follows:

$$\psi(x, y)=\sum_{m}^{N}\sum_{n}^{N} C_{nm} x^n y^m \quad (n, m: \text{integers})$$

When an axis on which a light ray passing the center of the pupil and forming an angle of view of zero proceeds is defined as a z axis, axes orthogonal to the z axis and orthogonal to each other are defined as an x axis and a y axis, and the DOE is decentered and rotated about the x axis, a y-z plane is referred to as the meridional cross section and a x-z plane is referred to as a sagittal cross section. The following description will be made only in the meridional cross section. In this case, since only a term of y has to be considered, the phase difference function is expressed as follows:

$$\psi(y)=\sum_{m}^{N} C_m y^m$$

$C_1 = -3.75050\cdot10^{-3}$

$C_2 = -1.28103\cdot10^{-3}$

$C_3 = 1.18215\cdot10^{-5}$

$C_4 = 2.30640\cdot10^{-8}$

$C_5 = -1.35259 \cdot 10^{-7}$

$C_6 = 1.03332 \cdot 10^{-8}$

$C^7 = 1.79335 \cdot 10^{-10}$

$C_8 = -5.01001 \cdot 10^{-11}$

$C_9 = 2.06563 \cdot 10^{-12}$

$C_{10} = -2.77163 \cdot 10^{-14}$

The annular zone interval $P_k(y)$ is expressed as follows based on the expression (4):

$$P_k(y) = \lambda_k / \{d\varphi(r)/dr\}$$

$$= \lambda_k / \{\Sigma m \cdot C_m y^{m-1}\} \text{ (k denotes color) ...(12).}$$

As to a principal ray forming an angle of view of +5°, the incident angle thereof on the DOE (that is, on the surface 10) is 25° and a distance y from an optical axis of the optical system to an incident point of the principal ray on the DOE is 5.65mm. The above-described principal ray exits from the DOE at a reflection angle of 30.65°. The annular zone intervals P_k on the grating surfaces that reflect and diffract the respective color lights are as follows:

P_R=36.7μm,

P_G=33.7μm, and

P_B=27.5μm.

Grating heights d_k are as follows:

d_R=2.15μm,

d_G=1.97μm, and

d_B=1.61μm.

In this case, if the annular zone intervals are equal to each other, a chromatic aberration of magnification (R-B) increases to about 1.8mm and a longitudinal chromatic aberration (R-B) increases to 19mm. However, the above-described setting of the annular zone intervals enables suppression of these aberrations to theoretically zero.

Next, description will be made of a configuration of the dichroic film. Description herein will be made of a case where the dichroic film reflects and diffracts light in the wavelength from ultraviolet to blue, and transmits light in the wavelengths of red and green without diffracting them. When the wavelength is represented by λ_B, a high refractive index layer is denoted by H, and a low refractive index layer is denoted by L, the configuration of the dichroic film is expressed as follows:

$(0.5HL0.5H)^9$.

This shows a configuration in which a combination of the layer H with a layer thickness of $\lambda_B/8$, the layer L with a layer thickness of $\lambda_B/4$ and the layer H with a layer thickness of $\lambda_B/8$ is repeated nine times from the light entrance side.

FIG. 5 shows wavelength dependency of reflectance of P-polarized light when assuming that the wavelength λ_B is 480nm, a refractive index n_H of the layer H is 1.7 and a refractive index n_L of the layer L is 1.5. The reflectance is approximately 0% in a wavelength range of 475 nm or less and approximately 100% in a wavelength range of 575 nm or more.

FIG. 6 shows a reflective diffraction efficiency of the principal ray of the wavelength λ_B when the incident angle thereof is 45° and the incident point (y) thereof is 3.0mm. FIG.7 shows transmissive diffraction efficiencies of principal rays of the wavelengths λ_G and λ_R. The transmissive diffraction efficiencies are calculated by rigorous coupled wave analysis. The reflective diffraction efficiency of the +5th order diffracted light of the wavelength λ_B is 82.39%, and the transmittances of the 0th order diffracted lights of the wavelengths λ_R and λ_G are 94.6% and 90.1%, respectively. Moreover, relative intensities of the transmissive diffracted lights of diffraction orders other than the 0th order in the wavelengths λ_R and λ_G are less than 0.2%, which means that most of the light of the wavelength λ_B is reflected and diffracted and most of the lights of the other wavelengths are transmitted without being diffracted.

Although the intensities of diffracted lights of the wavelength λ_B whose diffraction orders are other than the +5th order are about 1%, such slightly high intensities can be reduced by adjustment of the shape of the grating such as tilting of a grating side face.

EXAMPLE 4

FIG. 8 shows a fourth example (Example 4) as another specific example of the reflective laminated DOE 1 described in Example 1. Although Example 3 forms portions between the grating surfaces by using a single (same) light-transmissive medium to reduce the thickness of the DOE, this example respectively forms diffraction gratings on light-transmissive substrates and combines these diffraction gratings to produce the reflective laminated DOE.

In FIG. 8, a reflective DOE in which a dichroic film is formed on a grating surface 11 between layers 21 and 22 formed of a same light-transmissive medium whose refractive index is $n(\lambda)$ is formed on a light-transmissive substrate 30 whose refractive index is $n_p(\lambda)$, which constitutes a first reflective diffraction unit. The refractive index $n(\lambda)$ may be equal to the refractive index $n_p(\lambda)$ or may be different therefrom. The dichroic film formed on the grating surface 11 reflects and diffracts light of a wavelength λ_R (R-light).

Further, another reflective DOE in which a dichroic film is formed on a grating surface 12 between layers 23 and 24 formed of the same light-transmissive medium whose refractive index is $n(\lambda)$ is formed on another light-transmissive substrate 30 whose refractive index is $n_p(\lambda)$, which constitutes a second reflective diffraction unit. The refractive index $n(\lambda)$ may be equal to the refractive index $n_p(\lambda)$ or may be different therefrom. The dichroic film formed on the grating surface 12 reflects and diffracts light of a wavelength λ_B (B-light).

Moreover, still another reflective DOE in which a dichroic film is formed on a grating surface 13 of a layer 25 formed of the light-transmissive medium whose refractive index is $n(\lambda)$ is formed on still another light-transmissive substrate 30 whose refractive index is $n_p(\lambda)$, which constitutes a third reflective diffraction unit. The refractive index $n(\lambda)$ may be equal to the refractive index $n_p(\lambda)$ or may be different therefrom. The grating surface 13 is formed as a mirror surface that reflects and diffracts light of a wavelength λ_G (G-light).

The first to third reflective diffraction units are disposed adjacently to each other so as to form air layers 31 therebetween to be laminated with each other.

Boundaries of the substrates 30 and the layers (diffraction gratings) do not influence diffraction. If the substrates 30 are parallel plain plates, an incident angle of the light on each layer does not change. Even when the substrates 30 are curved plates and thereby have refractive powers, it is only necessary to optimize a phase difference function for each layer according to the refractive powers.

The first to third reflective diffraction units may be disposed in contact with each other so as not to form the air layers 31 therebetween to be laminated with each other, as shown in FIG. 9.

In each of the above-described examples, as well as in Examples 1 and 3, a diffraction power can be set independently for each color light.

Example 5

Description will be made of a fifth example (Example 5) as still another specific example of the reflective laminated DOE 1 described in Example 1. Although in Examples 3 and 4 the reflective laminated DOE is used alone in the optical system, the reflective laminated DOE may be used in combination with refractive elements or reflective elements.

FIG. 13 shows an optical system in which the reflective laminated DOE is formed on one of three surface of a prism element 60. This optical system can be used as an image taking optical system of a camera with an image pickup element such as a CCD sensor or a CMOS sensor disposed at a surface 65. Furthermore, this optical system can be used as a displaying optical system of an image display apparatus with a display element such as a liquid crystal panel disposed at the surface 65, the displaying optical system enlarging an image formed on the display element such that the enlarged image can be observed from a pupil 61.

In the image taking optical system, external light from an entrance pupil 61 enters the prism element 60 through its surface 62, is reflected by a backside of a surface 63 to exit from the prism element 60 through its surface 64, and then is introduced to the image pickup element disposed at the surface 65. The surface 63 is provided with the DOE.

This example has a relationship that a reflection angle is larger than an incident angle to reduce a thickness and a size of the prism element 60. Numerical data of the above-described optical system is shown below. A coordinate system in the numerical data is the same as that described in Example 3.

SURFACE NUMBER	CURVATURE RADIUS	Y POSITION	Z POSITION	θ	refractive index
OBJECT	∞	0.000	∞	0.000°	
1:(PUPIL)	∞	0.000	0.000	0.000°	
2:	∞	0.000	0.000	0.000°	
3:	-200.000	0.000	25.000	30.000°	1.57090
4:	-80.000	2.676	34.000	90.000°	1.57090
				(DOE, reflection)	
5:	∞	2.676	34.000	90.000°	1.57090
6:	40.000	-17.324	34.000	90.000°	
7:	∞	-22.324	34.000	90.000°	
IMAGE PLANE:	∞	-22.324	34.000	90.000°	

The optical system has an angle of view of ±20 degrees and a diameter of the entrance pupil of 5mm. As in Example 3, in the decentering cross section (meridional cross section), when only the term of y is considered, a phase difference function of the DOE is expressed as follows:

$$\psi(y)=\sum_{m}^{N} C_m y^m$$

$C_1 = -1.13323 \cdot 10^{-1}$

$C_2 = 9.94878 \cdot 10^{-4}$

$C_3 = 2.14809 \cdot 10^{-6}$

$C_4 = -2.88178 \cdot 10^{-6}$

$C_5 = -6.97048 \cdot 10^{-8}$

$C_6 = 2.17443 \cdot 10^{-8}$

$C_7 = 6.51869 \cdot 10^{-10}$

$C_8 = -5.24502 \cdot 10^{-11}$

$C_9 = -2.56617 \cdot 10^{-12}$

$C_{10} = -2.56520 \cdot 10^{-14}$.

In this case, for example, the annular zone intervals P_k on the DOE at an incident point where a light ray for an angle of view of 0° are calculated as follows, as in Example 3, since the incident angle thereof is 23.37° and a diffraction angle thereof is 45.4649°:

P_R=5.648μm,

P_G=5.185μm, and

P_B=4.236μm.

And, grating heights d_k are as follows:

d_R=1.37μm,

d_G=1.25μm, and

d_B=1.02μm.

Example 6

Description will be made of a transmissive laminated DOE as a specific example (Example 6) of the transmissive laminated DOE 2 described in Example 2. FIG. 14 shows an optical system that collects each of two beams emitted from laser light sources 71a and 71b on a same image plane 74 by using a lens 73, the two beams being lights of mutually different wavelengths. An exit surface 731 of the lens 73 is provided with the transmissive laminated DOE of this example.

Formation of two grating surfaces that transmit and diffract two lights of mutually different wavelengths independently requires three light-transmissive media having the characteristics shown in FIG. 11. In this example of the configuration shown in FIG. 2, E-FD8 is used as the light-transmissive medium for the first layer 41, LAC14 is used as the light-transmissive medium for the second layer 42, and E-FD15 is used as the light-transmissive medium for the third layer 43 (Those glasses are manufactured by HOYA corporation). The two wavelengths are set to λ_1=640nm and λ_2=473nm. FIG. 15 shows dispersion characteristics of E-FD8, LAC14 and E-FD15.

Moreover, numerical data of the optical system of this example is shown below. A coordinate system is also the same as that described in Example 3.

SURFACE NUMBER	CURVATURE RADIUS	Y POSITION	Z POSITION	θ	refractive index
OBJECT	∞	0.000	-8.000	0.000°	Air
1:	8.157	0.000	-3.000	0.000°	1.57090
2:(PUPIL)	-3.148	0.000	0.000	0.000°	(DOE)

ASPHERIC SURFACE:

K:-0.323650 A:0.474126E-02 B:-0.162703E-03

C:-0.711399E-05 D:-0.736135E-05 E:-0.799111E-06

F:-0.315013E-06 G:-0.413586E-07 H:-0.174572E-07

J:-0.275514E-08

3:	∞	0.000	0.000	0.000°	Air
IMAGE PLANE:	∞	0.000	10.000	0.000°	

An entrance pupil has a diameter of 5mm. The surface (DOE substrate surface) 2 is an aspheric surface (ASP) that is expressed by the following function:

$$z(r)=cr^2/[1+\{1-(1+K)\cdot c^2\cdot r^2\}]^{1/2}$$
$$\cdot(Ar^4+Br^6+Cr^8+Dr^{10}+Er^{12}+Fr^{14}+Gr^{16}+Hr^{18}+hr^{20})$$

where K represents a conic coefficient, and c represents a curvature radius. "E-XX" means "$\times 10^{-XX}$".

The surface 2 is a rotationally symmetric surface, and therefore the phase difference function of the DOE is expressed as follows:

$$\psi(r)=\sum_m^N C_m r^{2m}$$

The coefficients C_m of the grating surface 11 (for the wavelength λ_1) between the first second layers are set as follows:

$C_1=-8.13200\cdot 10^{-3}$

$C_2=7.11800\cdot 10^{-4}$

$C_3=9.45300\cdot 10^{-5}$

$C_4=6.77600\cdot 10^{-6}$

$C_5=4.32300\cdot 10^{-6}$

$C_6=5.87300\cdot 10^{-7}$

$C_7=9.39500\cdot 10^{-8}$

$C_8=3.30800\cdot 10^{-8}$

$C_9=9.40400\cdot 10^{-9}$

$C_{10}=1.48300\cdot 10^{-9}$.

Moreover, the coefficients C_m of the grating surface 12 (for the wavelength λ2) between the second and third layers are set as follows:

$C_1=-6.37900\cdot10^{-3}$

$C_2=7.10000\cdot10^{-4}$

$C_3=9.46700\cdot10^{-5}$

$C_4=7.49500\cdot10^{-6}$

$C_5=4.33200\cdot10^{-6}$

$C_6=5.92300\cdot10^{-7}$

$C_7=9.63500\cdot10^{-8}$

$C_8=3.34900\cdot10^{-8}$

$C_9=9.52100\cdot10^{-9}$

$C_{10}=1.51900\cdot10^{-9}$.

While the present invention has been described with reference to exemplary examples (embodiments), it is to be understood that the invention is not limited to the disclosed exemplary examples. The scope of the following claims is to be accorded the broadest interpretation so as to encompass all modifications, equivalent structures and functions.

This application claims the benefit of Japanese Patent Application No. 2009-241989, filed on October 21, 2009, which is hereby incorporated by reference herein in its entirety.

INDUSTRIAL APPLICABILITY

The present invention can provide a laminated diffractive optical element with reduced chromatic aberration generated due to diffraction while having a strong power.

CLAIMS

1. A laminated diffractive optical element comprising:

plural diffraction gratings laminated with each other, the respective diffraction gratings being formed of a same light-transmissive material; and

plural reflective films formed on grating surfaces of the respective diffraction gratings, each of the reflective films being disposed between the diffraction gratings,

wherein, each of the reflective films reflects light in a specific wavelength range and transmits light in a wavelength range different from the specific wavelength range, the specific wavelength ranges for the respective reflective films being different from each other, and

wherein the grating surfaces of the respective diffraction gratings are formed in shapes different from each other according to the specific wavelength ranges for the respective reflective films.

2. A laminated diffractive optical element according to claim 1, wherein annular zone intervals and grating heights on the grating surfaces of the respective diffraction gratings on a same incident ray axis are different from each other.

3. A laminated diffractive optical element according to claim 1 or 2,

wherein, in order from a light entrance side, one and the other of (a) a first grating surface on which the reflective film that reflects light in a wavelength range from ultraviolet to blue is formed and (b) a second grating surface on which the reflective film that reflects light in a wavelength range from red to infrared is formed are disposed, and

wherein a third grating surface on which the reflective film that reflects light in a wavelength range transmitted through the reflective films formed on the first and second grating surfaces is disposed on a side opposite to the light entrance side with respect to the first and second grating surfaces.

4. A laminated diffractive optical element comprising:

plural diffraction gratings laminated with each other, the respective diffraction gratings being formed of light-transmissive materials different from each other,

wherein grating surfaces of the respective diffraction gratings are formed in shapes different from each other, and

wherein refractive indices of the diffraction gratings adjacent to each other in a direction in which the diffraction gratings are laminated have mutually different dispersion characteristics for one specific color light, and

wherein each of the grating surfaces diffracts the one specific color light.

5. A laminated diffractive optical element according to claim 4, wherein annular zone intervals and grating heights on the grating surfaces of the respective diffraction gratings on a same incident ray axis are different from each other

6. A laminated diffractive optical element according to claim 4 or 5,

wherein (a) light entering the laminated diffractive optical element includes N spectra whose peak wavelengths are λ_i ($N \geq 2$, $i=1$ to N, $\lambda_i > \lambda_{i+1}$), (b) the diffraction gratings formed of N+1 light-transmissive materials whose refractive indices are $n_j(\lambda_i)$, ($j=1$ to $N+1$) are laminated with each other, and (c) the light-transmissive material is disposed further on the light entrance side as j is smaller, and

wherein wavelength characteristics of the light-transmissive materials satisfy the following relationships:

when $j=i$, $n_j(\lambda_i) < n_{j+1}(\lambda_i)$,

when $j>i$, $n_j(\lambda_i) = n_{i+1}(\lambda_i)$, and

when $j<i$, $n_j(\lambda_i) < n_i(\lambda_i)$.

7. An optical system comprising:

a laminated diffractive optical element according to any one of claims 1 to 6.

AMENDED CLAIMS
received by the International Bureau on 21 February 2011 (21.02.11).

1.(Amended) A laminated diffractive optical element comprising:

plural diffraction gratings laminated with each other, the respective diffraction gratings being formed of a same light-transmissive material; and

plural reflective films formed on grating surfaces of the respective diffraction gratings, each of the reflective films being disposed between the diffraction gratings,

wherein, each of the reflective films reflects light in a specific wavelength range and transmits light in a wavelength range different from the specific wavelength range, the specific wavelength ranges for the respective reflective films being different from each other, and

wherein the grating surfaces of the respective diffraction gratings are formed in blazed shapes different from each other according to the specific wavelength ranges for the respective reflective films.

2. A laminated diffractive optical element according to claim 1, wherein annular zone intervals and grating heights on the grating surfaces of the respective diffraction gratings on a same incident ray axis are different from each other.

3. A laminated diffractive optical element according to claim 1 or 2,

wherein, in order from a light entrance side, one and the other of (a) a first grating surface on which the reflective film that reflects light in a wavelength range from ultraviolet to blue is formed and (b) a second grating surface on which the reflective film that reflects light in a wavelength range from red to infrared is formed are disposed, and

wherein a third grating surface on which the reflective film that reflects light in a wavelength range transmitted through the reflective films formed on the first and second grating surfaces is disposed on a side opposite to the light entrance side with respect to the first and second grating surfaces.

4. A laminated diffractive optical element comprising:

plural diffraction gratings laminated with each other, the respective diffraction gratings being formed of light-transmissive materials different from each other,

wherein grating surfaces of the respective diffraction gratings are formed in shapes different from each other, and

wherein refractive indices of the diffraction gratings adjacent to each other in a direction in which the diffraction gratings are laminated have mutually different dispersion characteristics for one specific color light, and

wherein each of the grating surfaces diffracts the one specific color light.

5. A laminated diffractive optical element according to claim 4, wherein annular zone intervals and grating heights on the grating surfaces of the respective diffraction gratings on a same incident ray axis are different from each other

6. A laminated diffractive optical element according to claim 4 or 5,

wherein (a) light entering the laminated diffractive optical element includes N spectra whose peak wavelengths are λi ($N \geq 2$, i=1 to N, $\lambda i > \lambda i+1$), (b) the diffraction gratings formed of N+1 light-transmissive materials whose refractive indices are $nj(\lambda i)$, (j=1 to N+1) are laminated with each other, and (c) the light-transmissive material is disposed further on the light entrance side as j is smaller, and

wherein wavelength characteristics of the light-transmissive materials satisfy the following relationships:

when $j=i$, $nj(\lambda i) < nj+1(\lambda i)$,

when $j>i$, $nj(\lambda i) = ni+1(\lambda i)$, and

when $j<i$, $nj(\lambda i) < ni(\lambda i)$.

7. An optical system comprising:

a laminated diffractive optical element according to any one of claims 1 to 6.

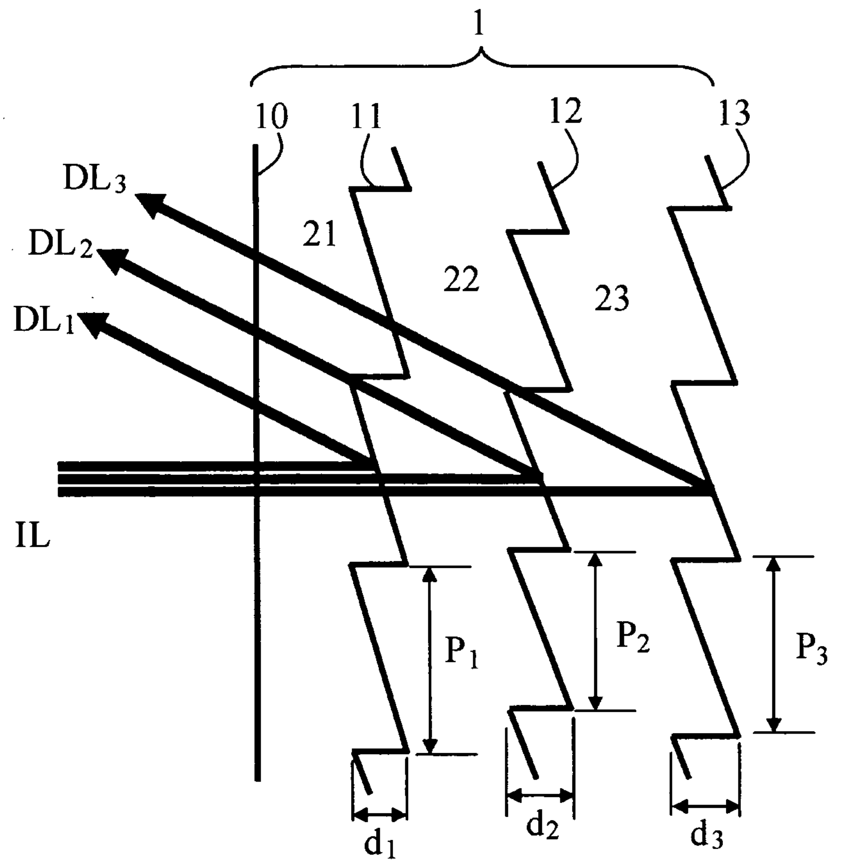

1
10
11
12
13
DL3
DL2
DL1
21
22
23
IL
P1
P2
P3
d1
d2
d3

FIG. 1

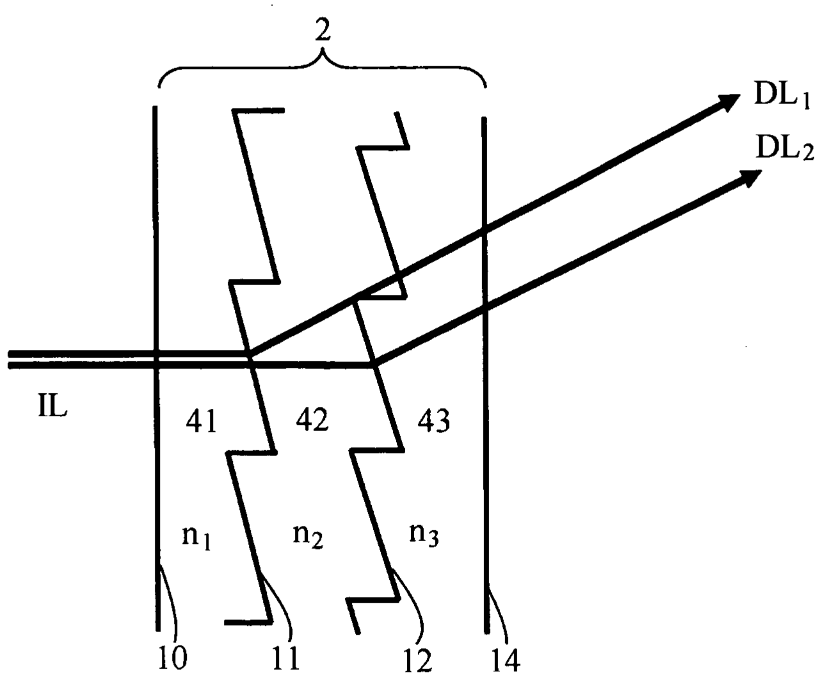

2
DL1
DL2
IL
41
42
43
n1
n2
n3
10
11
12
14

FIG. 2

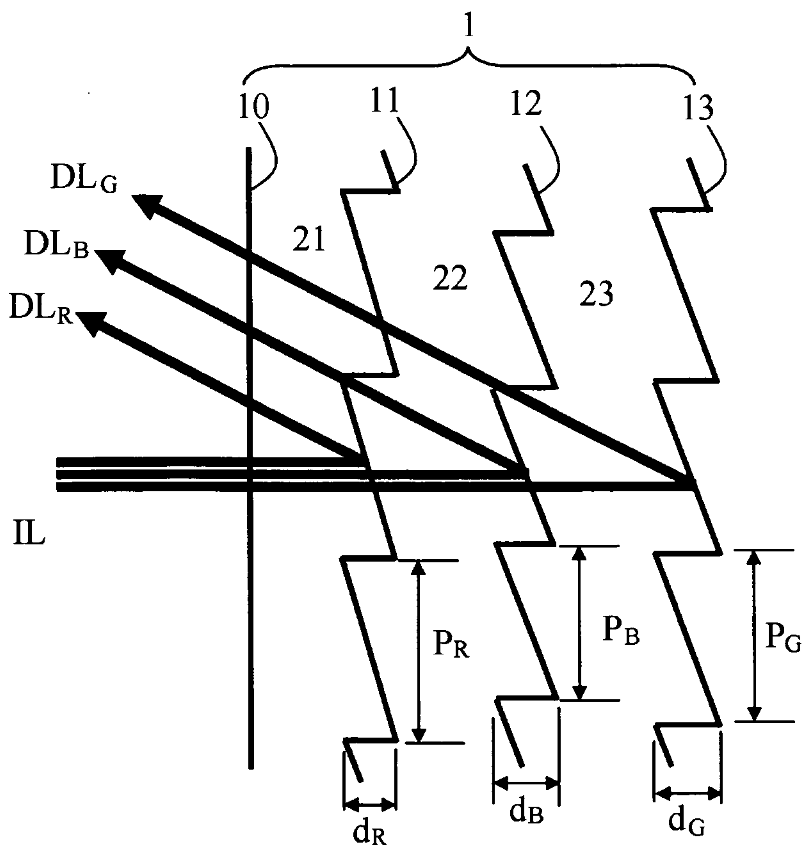


FIG. 3

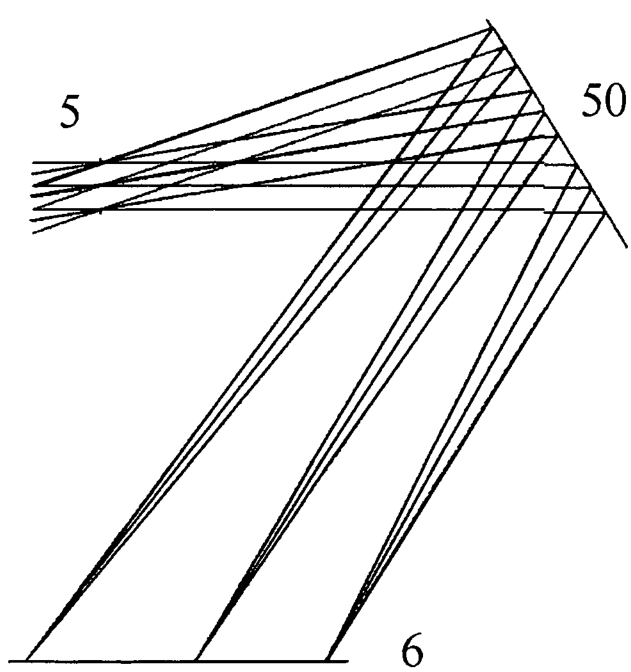


FIG. 4

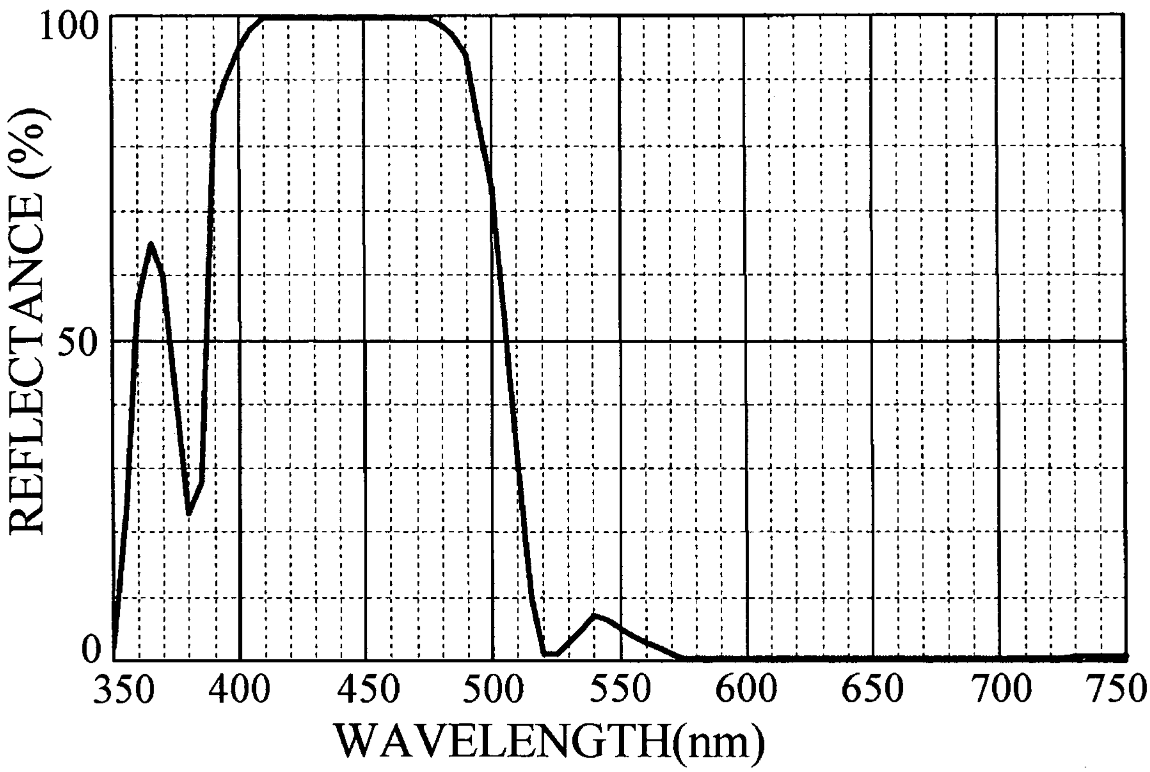

100
50
0
REFLECTANCE (%)
350
400
450
500
550
600
650
700
750
WAVELENGTH(nm)

FIG. 5

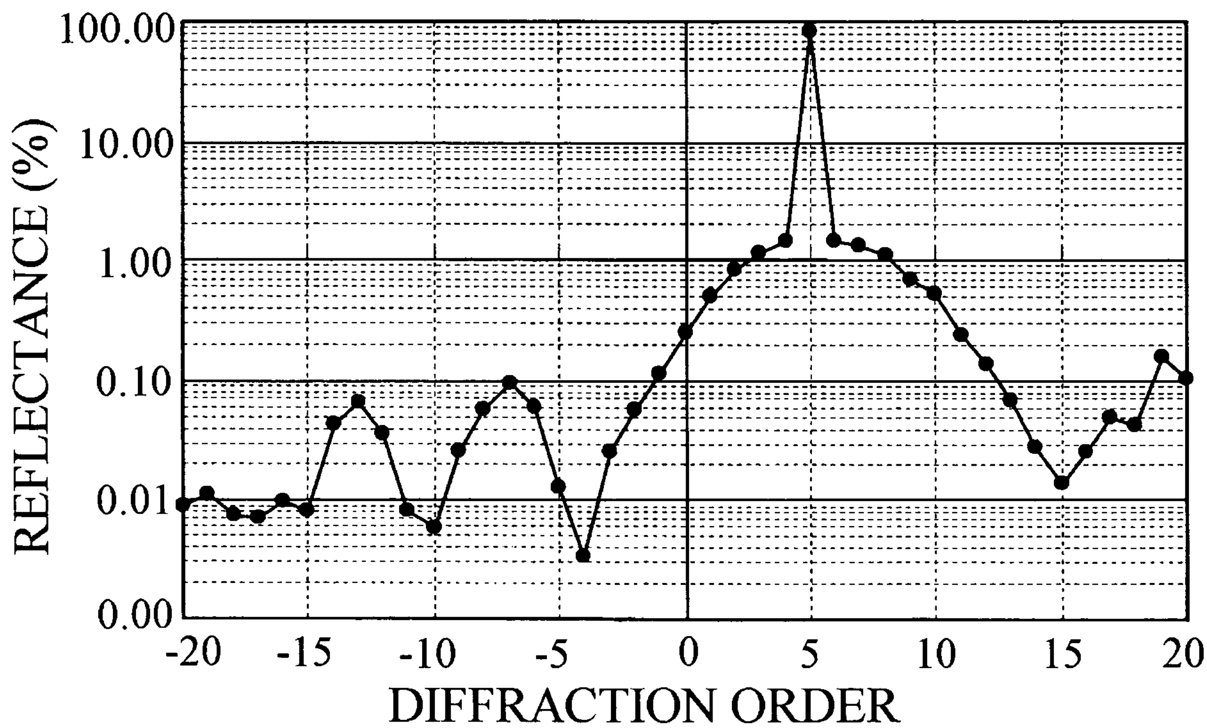

100.00
10.00
1.00
0.10
0.01
0.00
REFLECTANCE (%)
-20
-15
-10
-5
0
5
10
15
20
DIFFRACTION ORDER

FIG. 6

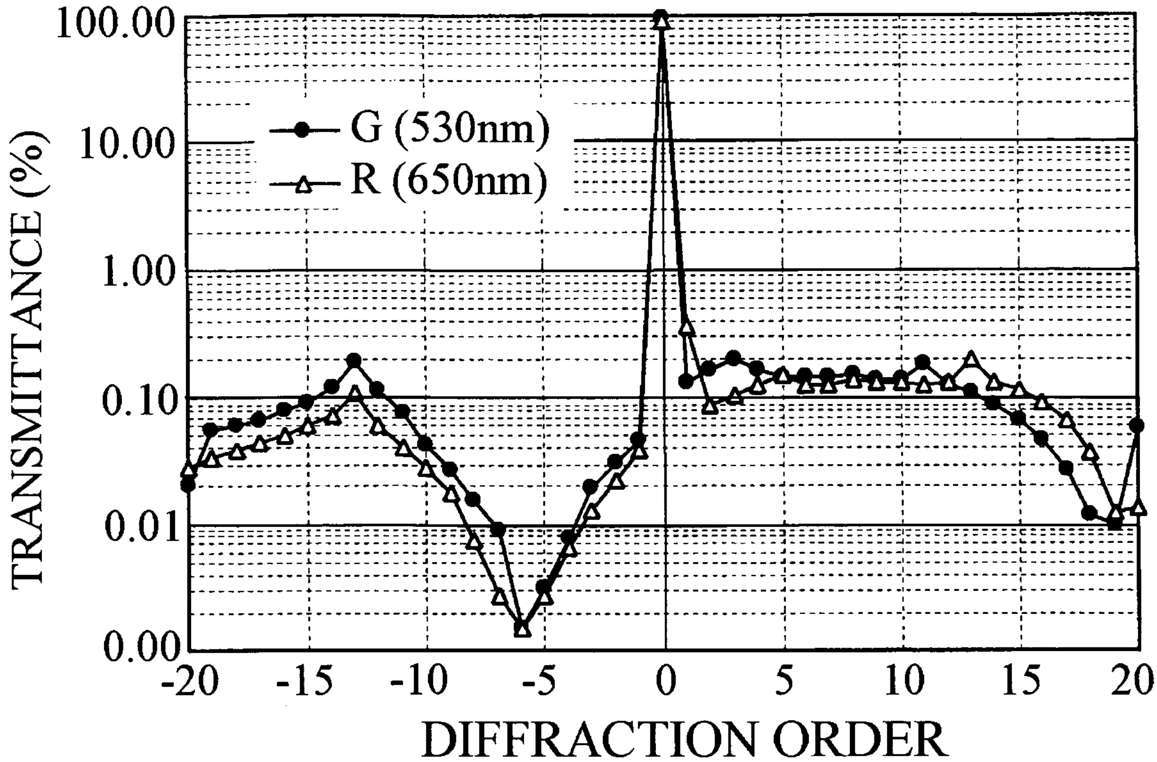

100.00
10.00
1.00
0.10
0.01
0.00
TRANSMITTANCE (%)
G (530nm)
R (650nm)
-20
-15
-10
-5
0
5
10
15
20
DIFFRACTION ORDER

FIG. 7

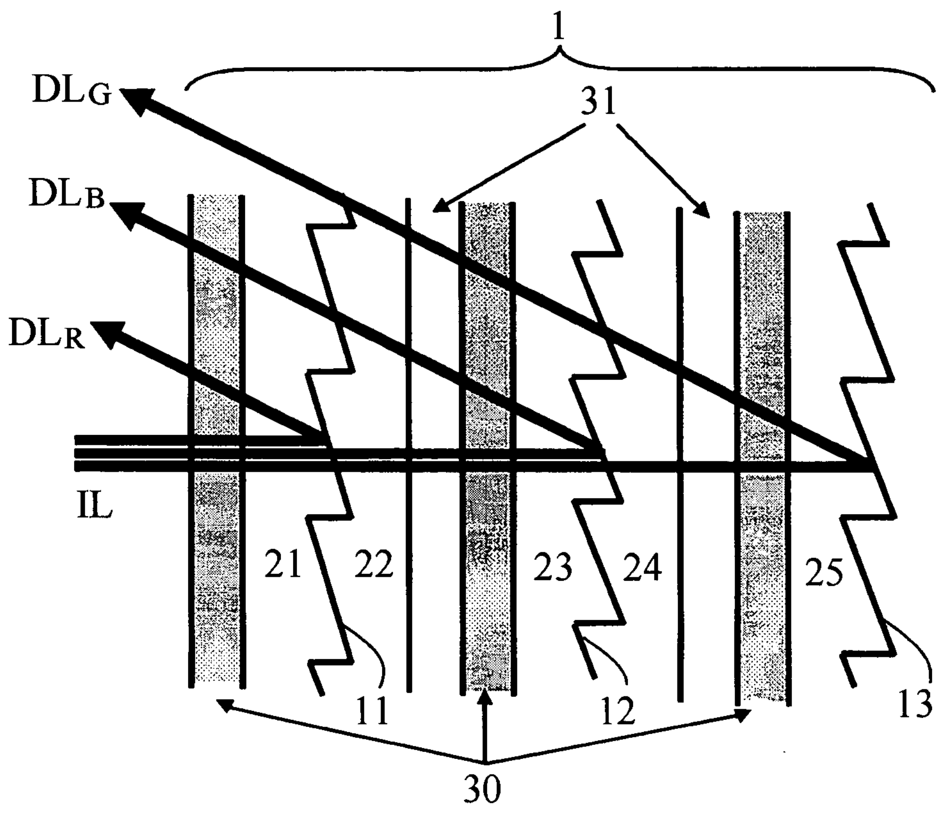

1
31
DLG
DLB
DLR
IL
21
22
23
24
25
11
12
13
30

FIG. 8

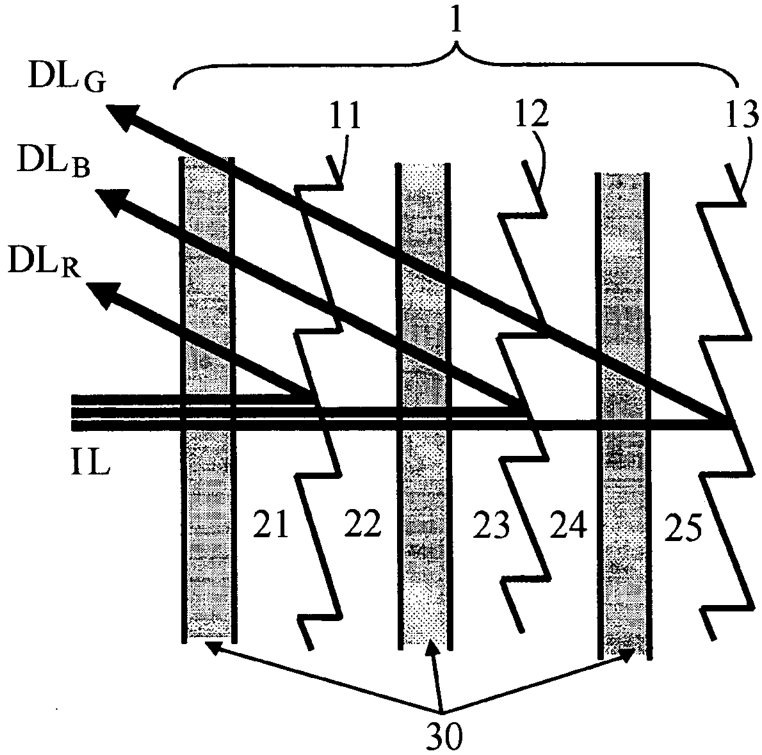

1
DLG
DLB
DLR
11
12
13
IL
21
22
23
24
25
30

FIG. 9

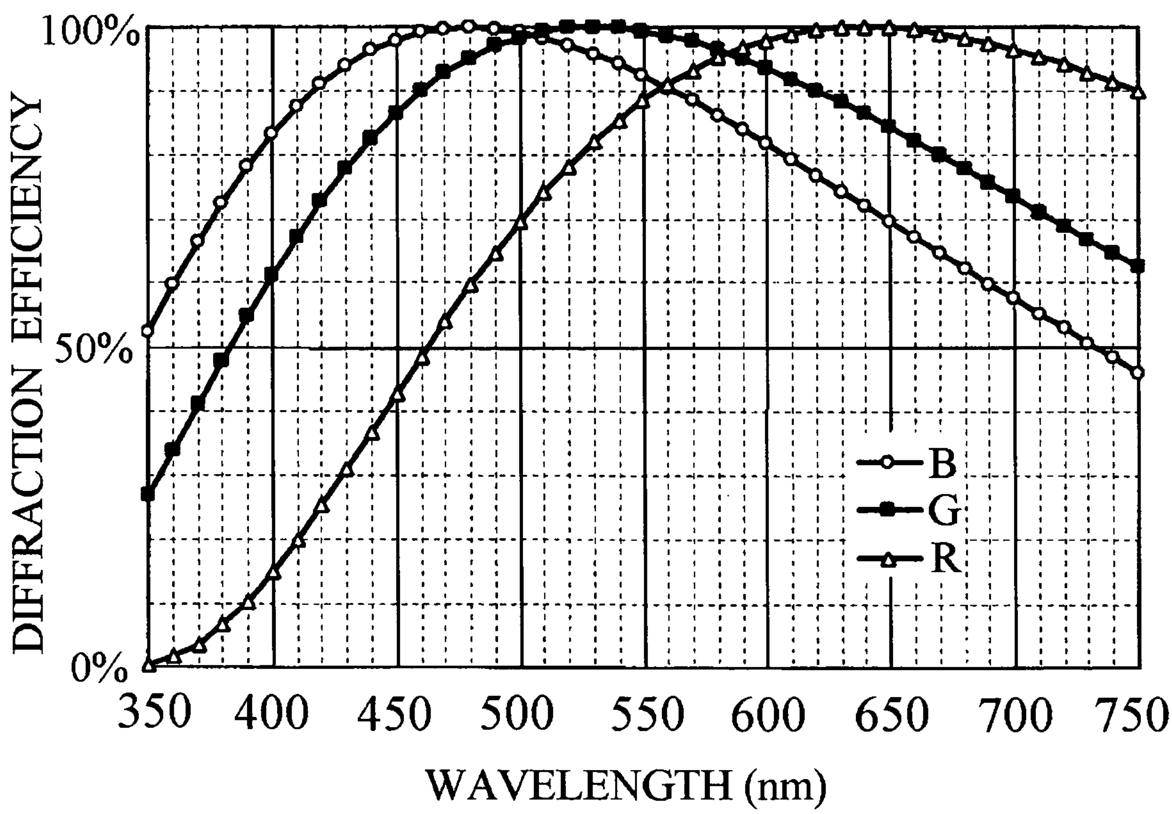
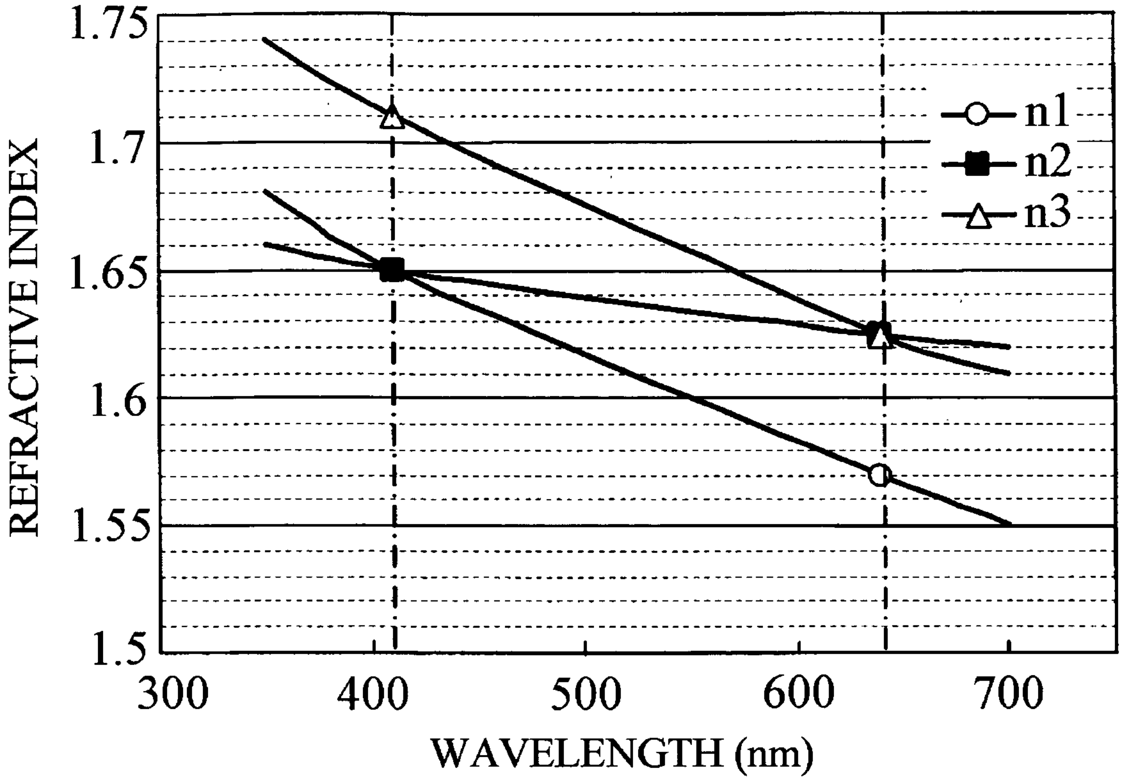
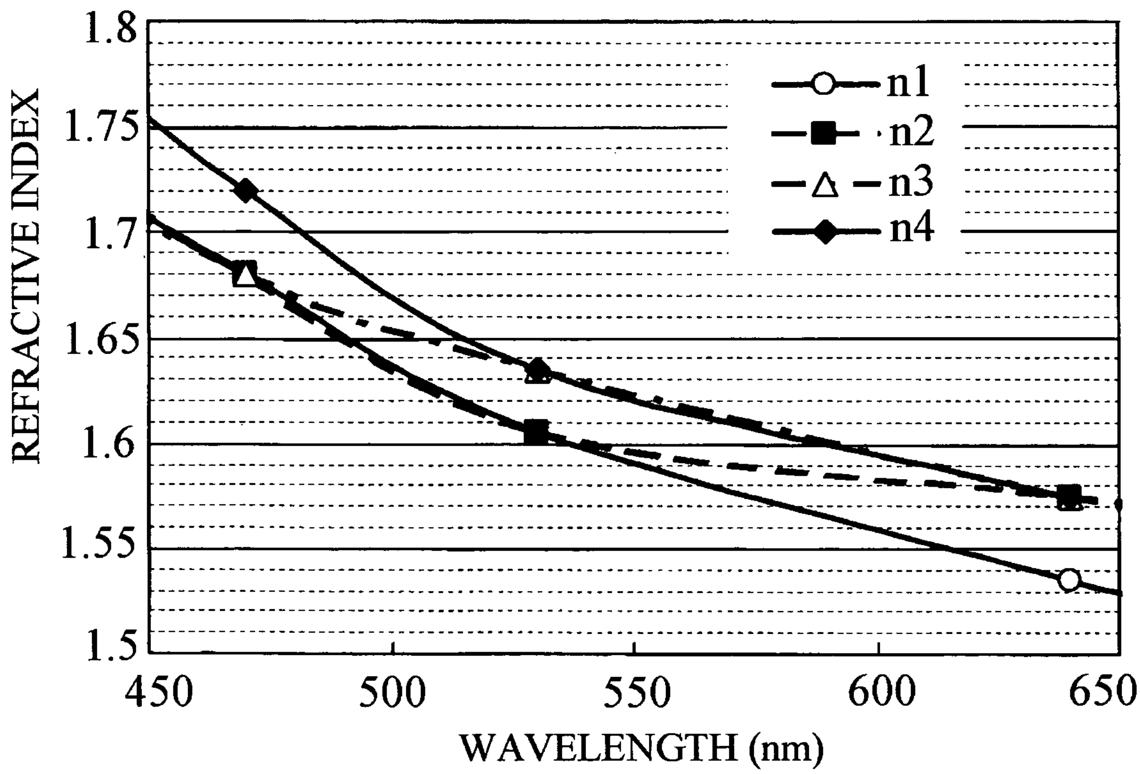

100%
50%
0%
DIFFRACTION EFFICIENCY
350
400
450
500
550
600
650
700
750
WAVELENGTH (nm)
B
G
R

FIG. 10



1.75
1.7
1.65
1.6
1.55
1.5
REFRACTIVE INDEX
300
400
500
600
700
WAVELENGTH (nm)
n1
n2
n3

FIG. 11



1.8
1.75
1.7
1.65
1.6
1.55
1.5
REFRACTIVE INDEX
450
500
550
600
650
WAVELENGTH (nm)
n1
n2
n3
n4

FIG. 12

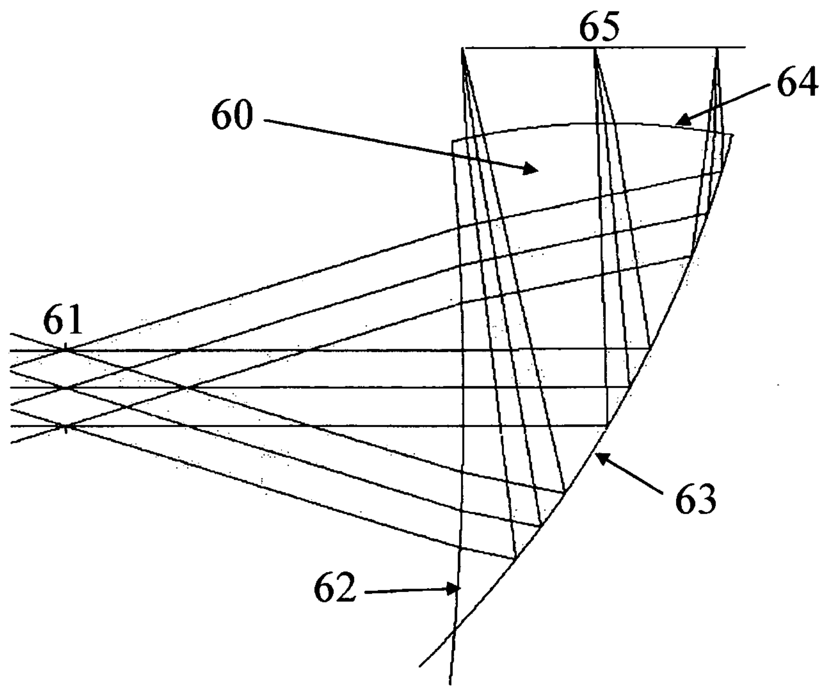


FIG. 13

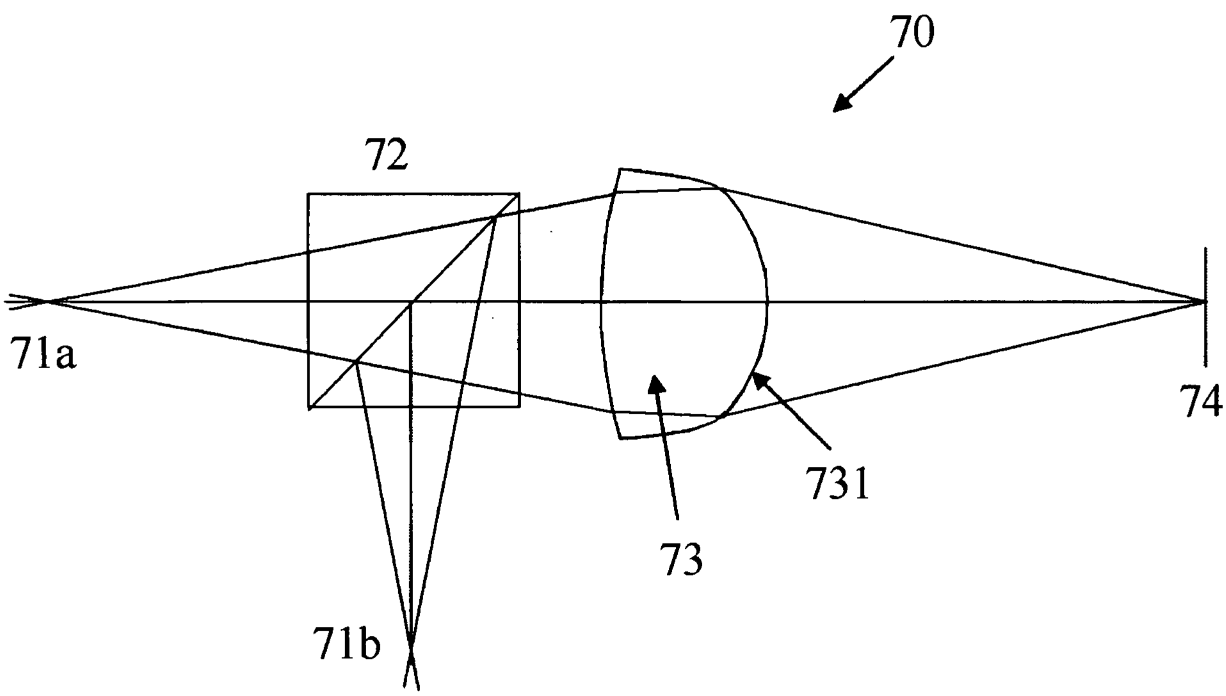


FIG. 14

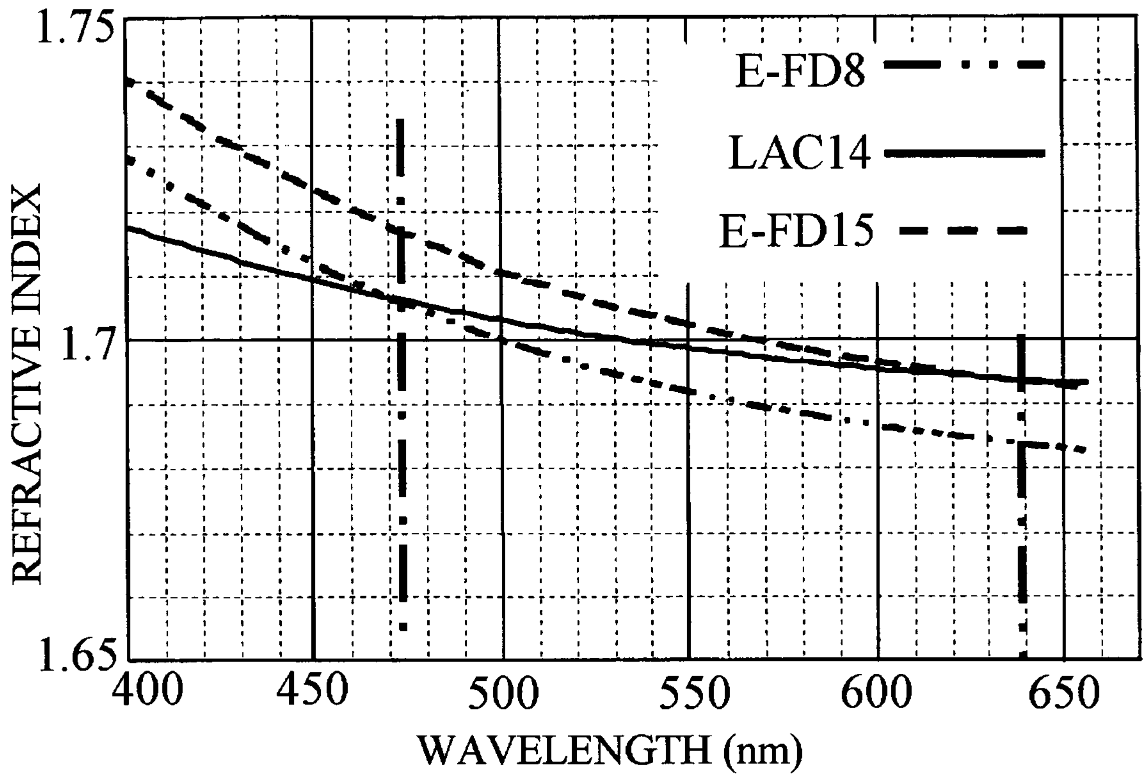

1.75
1.7
1.65
REFRACTIVE INDEX
400
450
500
550
600
650
WAVELENGTH (nm)
E-FD8
LAC14
E-FD15

FIG. 15

INTERNATIONAL SEARCH REPORT

International application No.
PCT/JP2010/067807

A. CLASSIFICATION OF SUBJECT MATTER

Int.Cl. G02B5/18(2006.01)i

According to International Patent Classification (IPC) or to both national classification and IPC

B. FIELDS SEARCHED

Minimum documentation searched (classification system followed by classification symbols)

Int.Cl. G02B5/18

Documentation searched other than minimum documentation to the extent that such documents are included in the fields searched

Published examined utility model applications of Japan 1922-1996
Published unexamined utility model applications of Japan 1971-2010
Registered utility model specifications of Japan 1996-2010
Published registered utility model applications of Japan 1994-2010

Electronic data base consulted during the international search (name of data base and, where practicable, search terms used)

C. DOCUMENTS CONSIDERED TO BE RELEVANT

Category*	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
P,X P,A	JP 2010-20855 A (Fujinon Kabushiki Kaisha) 2010.12.08, Whole document, all drawings no patent family	1-3, 7 4-6
A	JP 2004-348165 A (Olympus Kabushiki kaisha) 2004.12.09, Whole document, all drawings & US 6157488 A & US 6781756 B1 & US 2004/0263982 A1	4-6

☐ Further documents are listed in the continuation of Box C.　　☐ See patent family annex.

* Special categories of cited documents:
"A" document defining the general state of the art which is not considered to be of particular relevance
"E" earlier application or patent 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
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Date of the actual completion of the international search	Date of mailing of the international search report
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