

**POLARIZATION INSENSITIVE FABRY-PEROT WAVELENGTH
TUNABLE FILTER WITH NEMATIC LIQUID CRYSTAL**

TECHNICAL FIELD

The present invention relates to a polarization insensitive
5 Fabry-Perot wavelength tunable filter with a nematic liquid
crystal and, more particularly, to a polarization insensitive
Fabry-Perot wavelength tunable filter with a nematic liquid
crystal in an axially symmetrical configuration in a transmissive
or reflective mode, whose wavelength tuning property is
10 completely independent of the polarization state of the input
light, so that the FP wavelength tunable filter can provide a low
operating voltage, a wide range of wavelength tuning, and simple
fabrication.

BACKGROUND ART

15 A Fabry-Perot wavelength tunable filter with a nematic
liquid crystal, which uses the electro-optic effect of a liquid
crystal, is constructed in such a manner that dielectric mirrors
having a high reflective index in the operation wavelength range
are coated on the inner surfaces of two glass substrates,
20 alignment layers for aligning the liquid crystal are coated on
the dielectric mirrors, and the liquid crystal is inserted
between the two glass substrates to be aligned. This structure
in which the dielectric mirrors face to each other is called a
Fabry-Perot structure which selectively transmits the light with
25 a specific wavelength. The wavelength dependence of the light
transmitted in the Fabry-Perot structure is given by

$$T(\lambda) = \frac{t^2}{(1-r)^2} \frac{1}{1 + \frac{4r}{(1-r)^2} \sin^2\left(\frac{2\pi nd}{\lambda}\right)} \quad (1)$$

where t and r represent the transmittance and the reflectance of the dielectric mirror, respectively. Here, λ denotes the wavelength of the incident light, n and d denote the refractive index and the thickness of a material which exists between the dielectric mirrors, respectively. It is known--that the transmission T reaches its peak whenever the condition of $nd/\lambda = m/2$ (m is an integer) is satisfied in Eq. (1). This condition represents that the transmission depends on the wavelength of the incident light, meaning that the Fabry-Perot structure can be used as a wavelength tuning filter which selectively transmits the light with a specific wavelength. This Fabry-Perot filter has wavelength tuning capability of controlling the transmission peak by varying the refractive index (n) or the thickness (d) of the material.

A conventional Fabry-Perot wavelength tuning filter mostly uses an electro-mechanical material or inorganic electro-optical material. When the electro-mechanical material exists between the two dielectric mirrors, the distance d between the dielectric mirrors is controlled as a function of the applied voltage so as to tune the wavelength of the light transmitted. On the other hand, when the inorganic electro-optical material is placed between the dielectric mirrors, the refractive index n is varied with the applied voltage so as to tune the wavelength of the transmitted light. Recently, a nonlinear optical material has been used to change the refractive index n according to the intensity of the incident light, resulting in the wavelength tunability of the transmitted light.

In all the aforementioned cases, however, a very high voltage or a very intense light is essential for the operation of the wavelength tunable filter, and a thick medium between the dielectric mirrors is required for wavelength tunability in a

wider range. Furthermore, the transmission property is sensitive to the polarization direction of the incident light and the complex fabrication processes are needed.

5 A wavelength tuning Fabry-Perot filter using a nematic liquid crystal can be used as a high density wavelength-division-multiplexing (HD-WDM) device in the next-generation optical communications because of its low operation voltage, wide wavelength selection range, and simple fabrication, compared with the conventional filter using the electro-mechanical or inorganic
10 electro-optical material. However, the wavelength tuning property of the conventional liquid crystal Fabry-Perot structure with homogeneous alignment is sensitive to the polarization direction of the incident light. Supposing that the refractive index along the longer axes of the liquid crystal molecules is n_e , and the
15 refractive index along the shorter axis is n_o , in a case that the liquid crystal is homogeneously aligned, the wavelength having the maximum transmission depends on the polarization direction of incident light, which can be seen from the above Eq. (1). This polarization dependence gives lots of limitations to application
20 of the wavelength tunable filter when the actual polarization state of an optical fiber is difficult to predict in the field of optical communications.

There have been proposed several methods of removing the polarization dependence of transmission in the wavelength tunable
25 Fabry-Perot filter with a nematic liquid crystal. These include a method of controlling the thickness of the surface layer in a twisted nematic structure with homogeneous alignment, and a method of using a multidomain structure. The method in the twisted nematic structure with homogeneous alignment is to
30 control two polarization modes whose incident polarization directions are perpendicular or parallel to the liquid crystal

director by varying the thickness of the surface layer in a specific voltage range. However, to perfectly control the two polarization modes, the conditions for fabrication of the twisted liquid crystal structure must be accurately designed. Moreover, the polarization dependence is not removed completely in a wide range of wavelength tuning.

In a conventionally known multidomain structure, the nematic liquid crystal has at least two aligned regions orthogonal to each other, and incident light passes simultaneously through these two regions. In this case, the optical anisotropies of the two aligned regions should be cancelled exactly with each other to remove the polarization dependence. However, the process of fabricating such multidomain structure is complicated more than that of fabricating the homogeneous alignment structure. In other words, at least two alignment processes using optical masks are required for obtaining the multidomain structure having two different alignment directions. Furthermore, the polarization dependence still exists depending on the size of the two regions on which the light is incident.

DISCLOSURE OF INVENTION

Accordingly, the present invention is directed to a polarization insensitive Fabry-Perot wavelength tunable filter with a nematic liquid crystal that substantially obviates one or more of the problems due to limitations and disadvantages of the related art.

An object of the present invention is to provide a Fabry-Perot wavelength tunable filter with a nematic liquid crystal, which has the excellent wavelength selection properties such as a wide wavelength tunability and complete removal of the polarization dependence of incident light using axially

symmetrical alignment.

To accomplish the object of the present invention, there is provided a polarization insensitive Fabry-Perot wavelength tunable filter with a nematic liquid crystal, in which two substrates are coated with transparent electrodes and-dielectric mirrors, respectively. One of two substrates has a homeotropic alignment layer coated thereon, and the other has a homogeneous alignment layer coated thereon which the liquid crystal is axially aligned. A nematic liquid crystal having the positive dielectric anisotropy is inserted between the two substrates to tune the wavelength of the incident light depending on the magnitude of the voltage applied thereto.

Instead of the nematic liquid crystal having the positive dielectric anisotropy, a nematic liquid crystal having the negative dielectric anisotropy may be employed.

In the polarization insensitive Fabry-Perot wavelength tunable filter with a nematic liquid crystal having the positive dielectric anisotropy, when the pretilt angle at the homogeneous alignment layer is θ_1 , $0^\circ \leq \theta_1 \leq 10^\circ$ is satisfied, and when the pretilt angle at the homeotropic alignment layer is θ_2 , $75^\circ \leq \theta_2 \leq 90^\circ$ is satisfied. In the case of the liquid crystal having the negative dielectric anisotropy, the pretilt angle at the homogeneous alignment layer satisfies $0^\circ \leq \theta_1 \leq 15^\circ$, and the pretilt angle at the homeotropic alignment layer satisfies $80^\circ \leq \theta_2 \leq 90^\circ$.

In the case that a liquid crystal containing a chiral additive is inserted between the two substrates, when the thickness of the liquid crystal layer is d and the pitch of the liquid crystal according to the chiral additive is p , the ratio of the thickness to the pitch satisfies $0 \leq d/p \leq 0.5$. A polarization plate or an optical compensation film may be attached to at least one of the outer surfaces of the substrates.

It is to be understood that both the foregoing general description and the following detailed description are exemplary and explanatory and are intended to provide further explanation of the invention as claimed.

5 **BRIEF DESCRIPTION OF THE DRAWINGS**

10 The accompanying drawings, which are included to provide a further understanding of the invention and are incorporated in and constitute a part of this specification, illustrate embodiments of the invention and together with the description serve to explain the principles of the invention:

 In the drawings:

 Fig. 1 is a cross-sectional view showing a Fabry-Perot wavelength tunable filter using a nematic liquid crystal according to the present invention;

15 Fig. 2 is a perspective view showing the polarization insensitive Fabry-Perot wavelength tunable filter using a nematic liquid crystal according to the present invention;

20 Fig. 3 shows the coordinate system of the liquid crystal director in the Fabry-Perot wavelength tunable filter using a nematic liquid crystal;

 Fig. 4 shows the symmetrical relation between the geometry of the liquid crystal director on an axially aligned lower substrate and the polarization direction of the linearly polarized incident light;

25 Fig. 5 shows the polarization dependence of the incident light in the Fabry-Perot wavelength tunable filter using the homeotropically axially aligned nematic liquid crystal E7;

30 Fig. 6 shows the wavelength tuning property as a function of the applied voltage in the Fabry-Perot wavelength tunable filter using the homeotropically axially aligned nematic liquid

crystal E7; and

Fig. 7 illustrates the continuous wavelength tuning property actually applied in Fig. 6.

BEST MODE FOR CARRYING OUT THE INVENTION

5 Reference will now be made in detail to the preferred embodiments of the present invention, examples of which are illustrated in the accompanying drawings.

10 Fig. 1 is a cross-sectional view showing a polarization insensitive Fabry-Perot wavelength tunable filter using a nematic liquid crystal according to the present invention, and Fig. 2 is a perspective view showing the polarization insensitive Fabry-Perot wavelength tunable filter using a nematic liquid crystal according to the present invention. As shown in Figs. 1 and 2, in the polarization insensitive Fabry-Perot wavelength tunable
15 filter with a nematic liquid crystal, a homogeneous alignment material of the liquid crystal (AL-1051; Japan Synthetic Rubber Co., pretilt angle $\theta_1 \approx 2^\circ$) is coated on the inner surface of one substrate to be axially aligned, and a homeotropic alignment
20 material (JALS-204; Japan Synthetic Rubber Co., pretilt angle $\theta_2 \approx 90^\circ$) is coated on the inner surface of the other substrate. This new alignment structure is symmetrical in all directions for an arbitrary incident polarization with respect to the normal incidence, so that the polarization dependence of the transmission property is completely removed.

25 Specifically, a material such as indium-tin-oxide (ITO) is coated on the upper and the lower substrates 1 to form transparent electrodes 2, and reflecting layers (dielectric mirrors) 3 are respectively coated on transparent electrodes 2, reflecting layers 3 having a high reflectance (above 98%) in the
30 wavelength range where the Fabry-Perot filter of the present

invention to be used. An alignment layer 4 for homeotropically aligning the liquid crystal is coated on the reflecting layer 3 formed on one substrate, and alignment layer 5 for homogeneously aligning the liquid crystal is coated on the reflecting layer 3 formed on the other substrate. In this hybrid aligned structure, the homogeneous alignment layer 5 is additionally treated to produce axially symmetrical alignment with respect to the direction perpendicular to its surface. The surface treatment for axial alignment can be accomplished by axial rubbing or illuminating a circularly polarized ultraviolet light on an optical alignment layer. In this embodiment, axially symmetrical rubbing is performed to allow the liquid crystal molecules to have axially symmetrical arrangement. The thickness between the two substrates is maintained using a spacer 6 for having an appropriate distance. This new alignment structure is axially symmetrical so that it can always show the transmission property insensitive to the polarization of the light in an arbitrary direction incident thereon.

As an example, the transmission property of the polarization insensitive Fabry-Perot wavelength tunable filter of the present invention is explained below when a light linearly polarized in an arbitrary direction is incident thereon. Fig. 3 shows the coordinate system of the liquid crystal director in the Fabry-Perot wavelength tunable filter using a nematic liquid crystal. As shown in Fig. 3, when the direction perpendicular to the surface of the device is defined as the direction along the z axis, the thickness of the liquid crystal layer is defined as d , and the tilt angle of the liquid crystal director to the substrate surface at an arbitrary point on the z axis is defined as $\theta(z)$, the following Eq. (2) represents the effective refractive index for a ray of light with polarization parallel

to the direction projected by the liquid crystal director onto the substrate surface when the light is incident on the surface of the device.

$$n_{eff} = \frac{1}{d} \int_0^d dz \frac{n_e n_o}{\sqrt{n_e^2 \sin^2 \theta(z) + n_o^2 \cos^2 \theta(z)}} \quad (2)$$

In the above equation, the effective refractive index becomes n_e when the tilt angle is 0° , that is, when the liquid crystal is homogeneously aligned. On the other hand, the effective refractive index becomes n_o when the tilt angle is 90° , that is, when the liquid crystal is homeotropically aligned. In the case of hybrid alignment, the effective refractive index at an arbitrary point in the liquid crystal layer can be calculated according to the Eq. (2).

Fig. 4 shows the symmetrical relation between the geometry of the liquid crystal director on the axially aligned lower substrate and the polarization direction of the incident light polarized linearly. As shown in Fig. 4, when a laboratory coordinate system is defined as the x-y coordinate system, and a ray of light, which is linearly polarized at the angle of ϕ_i to the x axis over the entire liquid crystal layer, is incident along the surface normal of the device, the polarization at a position where the radial direction makes an angle ϕ to the x axis with the symmetry axis located in the center can be represented by the sum of two components, one of which $\sin(\phi - \phi_i)$ is parallel to the liquid crystal director and the other $\cos(\phi - \phi_i)$ perpendicular to it. The corresponding transmitted intensities $T_{n_{eff}}$ and T_n are then calculated from Eq.(1) replacing the refractive index n by n_{eff} and n in Eq.(1). Accordingly, the total transmitted intensity corresponding the two components is given by

$$T(\Phi) = \sin^2(\Phi - \Phi_0) T_{n_{eff}} + \cos^2(\Phi - \Phi_0) T_{n_0} \quad (3)$$

Thus, the average transmitted intensity over the whole angle of the light incident on the device is given by

$$T = \frac{1}{2\pi} \int_0^{2\pi} T(\Phi) d\Phi = \frac{1}{2} (T_{n_{eff}} + T_{n_0}) \quad (4)$$

Here, T_{n_0} is independent of the magnitude of the voltage applied to the device, and only $T_{n_{eff}}$ depends on it. However, the sum of the two values, given by the average value T , is always independent of the angle Φ_0 of incident polarization because of the axially symmetric alignment of the liquid crystal molecules.

In Eq. (2), the tilt angle $\theta(Z)$ of the liquid crystal director, which varies continuously from one substrate to the other substrate, can be numerically calculated in the elastic continuum theory of liquid crystals. The transmission property of the liquid crystal Fabry-Perot wavelength tunable filter can be theoretically calculated from the tilt angle profiles as described above. Based on the theoretical results, the material constants of the liquid crystal and the device parameters can be optimized.

Table 1 illustrates the specification of the device parameters, and Figs. 5, 6 and 7 show experimental results of the device having the specification presented in the Table 1. In this embodiment, the nematic liquid crystal E7 containing no chiral additive. The nematic liquid crystal E7 is a material that does not form a spiral structure spontaneously, in which the spiral pitch length $p = \infty$ and the ratio of the thickness of the liquid crystal layer to the pitch $d/p = 0$.

Table 1

Liquid crystal	E7
n_e	1.728
n_o	1.513
Δn	14.33
Thickness of the liquid crystal layer (μm)	50

Fig. 5 shows the polarization dependence of the incident light in the polarization insensitive Fabry-Perot wavelength tunable filter using the homeotropically axially aligned nematic liquid crystal E7. As shown in Fig. 5, the transmission property of the device is independent of the polarization of the incident light. (I), (II), and (III) of Fig. 5 correspond to the cases that the angles between the polarization direction of the incident light and an arbitrary reference direction are 0° , 45° and 90° , respectively.

Fig. 6 shows the wavelength tuning property as a function of the applied voltage in the polarization insensitive Fabry-Perot wavelength tunable filter using the homeotropically axially aligned nematic liquid crystal E7. As shown in Fig. 6, there exists a mode with no wavelength variation, which has the maximum transmitted intensity independent of the applied voltage near the wavelengths of 1535nm and 1549nm. This results from the polarization component perpendicular to the liquid crystal director, i.e., the corresponding refractive index is n_o . In the case of the polarization component parallel to the liquid crystal director the effective refractive index n_{eff} is varied as a function of the magnitude of the applied voltage, resulting in

the change of the wavelength having the maximum transmitted intensity. When the liquid crystal has the positive dielectric anisotropy, the molecules tend to orient along the direction parallel to the applied electric field. This orientation of the liquid crystal molecules changes the magnitude of the effective refractive index, and the wavelength of the transmitted varies continuously as a function of the applied voltage through the Fabry-Perot structure.

Fig. 7 illustrates the continuous wavelength tuning property actually applied in Fig. 6. This shows that the mode whose tuning wavelength ranges from 1526nm to 1551nm and the mode whose tuning wavelength ranges from 1541nm to 1560nm can be selectively tuned when the applied voltage varies from 2V to 7V.

It will be apparent to those skilled in the art that various modifications and variations can be made in the polarization insensitive Fabry-Perot wavelength tunable filter using a nematic liquid crystal of the present invention without departing from the spirit or scope of the invention. For example, though the nematic liquid crystal E7 containing no chiral additive was used in the aforementioned embodiment, a nematic liquid crystal containing a chiral additive may be used. In the case that the liquid crystal mixed with a chiral additive is used, the chiral additive produces a spiral structure which has the ratio of the thickness of the liquid crystal layer to the pitch larger than 0.

Although there is no characteristic variation in the incident polarization direction in the polarization insensitive Fabry-Perot wavelength tunable filter using a nematic liquid crystal of the present invention, a polarization plate or an optical compensation film for controlling the characteristics of the transmitted light intensity may be attached to one of the surfaces of the substrates, if required. Furthermore, it is

preferable that an antireflecting layer preventing reflection in the range of wavelength to be used is coated on one of the outer surfaces of the two substrates in order to improve transmission efficiency.

5 As described above, according to the polarization insensitive Fabry-Perot wavelength tunable filter using a nematic liquid crystal of the present invention, the transmission or reflection property is completely insensitive to the polarization of the incident light in the whole operation voltage range,
10 compared with the conventional homogeneous alignment structure. Moreover, the fabrication process of the device is much simpler than that of the conventional multidomain structure. Therefore, the present invention is able to provide the polarization insensitive Fabry-Perot wavelength tunable filter with a nematic
15 liquid crystal, which has no polarization dependence of the incident light for the transmitted light, low operating voltage, relatively wide wavelength tuning range, and simple fabrication process.



WHAT IS CLAIMED IS:

1. A polarization insensitive Fabry-Perot wavelength tunable filter with a nematic liquid crystal, wherein transparent electrodes are respectively formed on the inner surfaces of two substrates, reflecting layers are respectively coated on the transparent electrodes, one reflecting layer having a homeotropic alignment layer coated thereon to homeotropically align a liquid crystal, the other reflecting layer having a homogeneous alignment layer coated thereon and being processed to axially align the liquid crystal, and a nematic liquid crystal having the positive dielectric anisotropy is inserted between the two substrates, to tune the wavelength of incident light depending on the magnitude of the voltage applied thereto.

2. The filter as claimed in claim 1, wherein, when the pretilt angle at the homogeneous alignment layer to the substrate plane is θ_1 , $0^\circ \leq \theta_1 \leq 10^\circ$ is satisfied.

3. The filter as claimed in claim 1, wherein, when the pretilt angle at the homeotropic alignment layer to the substrate plane is θ_2 , $75^\circ \leq \theta_2 \leq 90^\circ$ is satisfied.

4. The filter as claimed in claim 1, wherein, when the thickness of the liquid crystal layer containing a chiral additive is d , and the pitch of the liquid crystal according to the chiral additive is p , the ratio of the thickness to the pitch satisfies $0 \leq d/p \leq 0.5$.

5. The filter as claimed in claim 1, wherein a polarization plate is attached to at least one of the surfaces



of the substrates.

6. The filter as claimed in claim 1, wherein an optical compensation film is attached to at least one of the surfaces of the substrates.

5 7. The filter as claimed in claim 1, wherein an antireflecting layer is coated on at least one of the outer surfaces of the substrates.

10 8. A polarization insensitive Fabry-Perot wavelength tunable filter with a nematic liquid crystal, wherein transparent electrodes are respectively formed on the inner surfaces of two substrates, reflecting layers are respectively coated on the transparent electrodes, one reflecting layer having a homeotropic alignment layer coated thereon to homeotropically align a liquid crystal, the other reflecting layer having a homogeneous
15 alignment layer coated thereon and being processed to axially align the liquid crystal, and a nematic liquid crystal having the negative dielectric anisotropy is inserted between the two substrates, to tune the wavelength of incident light depending on the magnitude of the voltage applied thereto.

20 9. The filter as claimed in claim 8, wherein, when the pretilt angle at the homogeneous alignment layer to the substrate plane is θ_1 , $0^\circ \leq \theta_1 \leq 15^\circ$ is satisfied.

25 10. The filter as claimed in claim 8, wherein, when the pretilt angle at the homeotropic alignment layer to the substrate plane is θ_2 , $80^\circ \leq \theta_2 \leq 90^\circ$ is satisfied.



11. The filter as claimed in claim 8, wherein, when the thickness of a liquid crystal layer containing a chiral additive is d , and the pitch of the liquid crystal according to the chiral additive is p , the ratio of the thickness to the pitch satisfies

5 $0 \leq d/p \leq 0.5$.

12. The filter as claimed in claim 8, wherein a polarization plate is attached to at least one of the surfaces of the substrates.

10 13. The filter as claimed in claim 8, wherein an optical compensation film is attached to at least one of the surfaces of the substrates.

14. The filter as claimed in claim 8, wherein an antireflecting layer is coated on one of the outer surfaces of the substrates.