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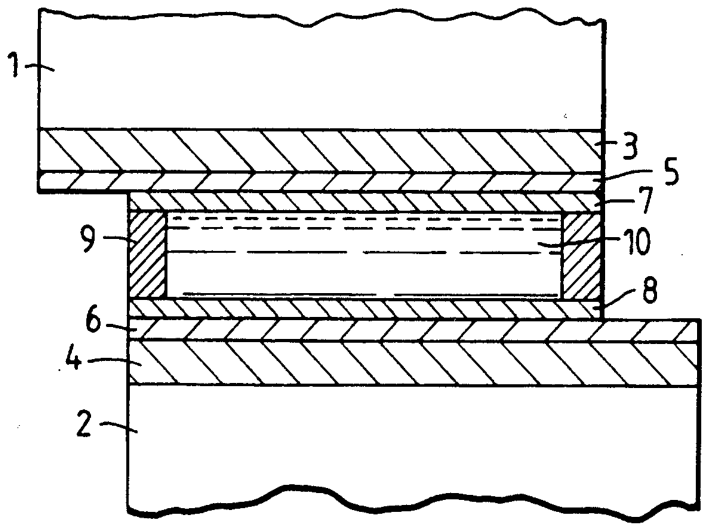
(57) Abstract

An electrically-controllable liquid crystal filter device comprises two partially-reflecting substrate structures (1 and 2) mounted substantially parallel to each other with a space therebetween to form a Fabry-Perot filter. A layer of ferroelectric liquid crystal material (10) is disposed in the space, the liquid crystal material (10) being switchable, by application of an electric field, between different refractive index values whereby the device is switchable between transmissive and reflective states for light of a particular narrow wavelength band. The spacing of the substrate structures (1 and 2) is selected in relation to the wavelength of light to be transmitted, such that the Fabry-Perot filter operates in a low order state, which may be the first order.



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Optical Devices

This invention relates to optical devices and particularly to a liquid crystal shutter for operation in the infrared or other long light wavelength region.

Liquid crystal (LC) shutters operating in the visible region of the light spectrum are well known, and there are several alternative types, which have different characteristics. The simplest is the common twisted nematic shutter which has a switching time of about 30msec. Fast response using a nematic liquid crystal material can be obtained from the π-cell (British Patent Application No. 2184860A) which achieves a switching time of about 1msec. However, the fastest commonly available liquid crystal shutter relies on ferroelectric liquid crystal technology and switches in less than 100 usec. In all cases, a critical parameter of the design of the device is the product of birefringence (Δn) x thickness (d) and in particular its ratio with the wavelength of operation. All of the above devices ideally require Δnd to equal $\lambda/2$ where λ is the light wavelength of interest, normally taken as 550nm for operation in the visible light spectrum.

It will therefore be apparent that there is considerable difficulty in implementing a fast shutter to operate at long wavelengths, such as 10.6μm, the most common wavelength of the CO_2 laser. This is because the product Δnd is now required to be about

20 times larger than is required for visible light operation. Since the birefringence Δn varies only slightly, and if anything it decreases at longer wavelengths, the thickness of the liquid crystal layer must be increased. However, in nematic devices, the response time varies as the square of the LC layer thickness, whereas ferroelectric LC devices (FLCDs) cease to function correctly if the layer becomes too thick. Hence, no fast-acting shutter can be implemented using conventional LC shutter technology which can be used at long wavelengths.

Shutters can be classified into two types, namely those which operate over a broad range of wavelengths, and those which are effective over only a restricted range of wavelengths. All of the devices described above are broadband operating; although they are most efficient at the design wavelength, λ_0, they have useful performance for a range, say, $\lambda_0 \pm \lambda_0/4$. However, in some cases such a broadband capability is not needed, for example when modulating a laser line. Then the shutter needs to be effective only at a single wavelength, or over a very narrow band of wavelengths. Such a device would, for example, be of great value in controlling the output of the CO_2 laser mentioned above, which is used for a variety of marking, cutting and welding operations in fields ranging from surgery to ceramic circuit board manufacture.

It is an object of the present invention to provide a fast-acting LC shutter suitable for use with lasers or other narrow-band light sources.

According to the invention there is provided an electrically-controllable liquid crystal filter device comprising two partially-reflecting substrate structures mounted substantially parallel to each other with a space therebetween to form a Fabry-Perot filter; a layer of ferroelectric liquid crystal material disposed in said space, said liquid crystal material being switchable, by application of an electric field thereto, between different refractive index values whereby the device is switchable between transmissive and reflective states for light of a particular narrow wavelength band, the spacing of the substrate structures being selected in relation to the wavelength of light to be transmitted, such that the Fabry-Perot filter operates in a low order state (as hereinafter defined).

Embodiments of the invention will now be described, by way of example, with reference to the accompanying drawings, in which

Figure 1 is a schematic cross-sectional view of a liquid crystal shutter device in accordance with the invention,

Figures 2(a) and 2(b) are schematic pictorial views illustrating the operation of the device, and

Figure 3 comprises curves showing the transmission spectra obtained in two operating states of the device.

Referring to Figure 1, a liquid crystal shutter device comprises two flat substrates 1 and 2, which are transparent to light at the required operating wavelength. For example, for operation at a wavelength of 10.6μm, germanium or zinc selenide may be used as the substrate material. The substrate 1 has a partially-reflecting mirror 3 on its lower surface (as viewed in Figure 1) and the substrate 2 has such a mirror 4 on its upper surface. The mirrors 3 and 4 may be multilayer dielectric stacks, which provide a reflectivity of, say, 95%. The precise value of reflectivity is preferably selected to optimise the performance of the device. Each mirror is then coated with an electrode layer 5,6, respectively, of transparent electrically-conductive material, although such layers may be omitted if the substrates and/or the mirrors include conductive layers. The layers 5 and 6 are preferably thin (for example less than 30nm thickness) layers of, for example, Indium Oxide (In_2O_3) or Indium Tin Oxide (ITO), the material being selected to have minimum light absorption at the wavelength of interest. Alternatively, the electrode layers 5, 6 if provided, may be disposed between the substrates 1, 2 and the mirrors 3, 4. The mirror surfaces, or the surfaces of the electrode layers 5,6 if provided, are treated with thin layers 7,8, respectively, which act to align the molecules of a liquid crystal layer 10 which is enclosed therebetween. The layers 7 and 8 may be, for example, rubbed polymer layers or evaporated silicon oxide layers. The two halves of the structure are held apart by spacers (not shown), and the liquid crystal material 10 is retained in the space between the layers 7 and 8 by an adhesive seal 9, which may be an epoxy resin.

The device of the present invention comprises primarily a Fabry-Perot (FP) filter. This comprises two parallel, partially-reflecting mirrors, separated by a small distance, d. The transmission spectrum is comb-like, with the peaks separated uniformly in inverse wavelength by 1/2nd, where n is the refractive index of the medium in the cavity between the mirrors. If this is a liquid crystal material, as in the present invention, transmission wavelength can be altered, because the refractive index can be controlled. The sharpness of the peaks is determined by the reflectivity of the mirror. Normally, FP filters are operated in high order, i.e. the peak wavelength λ_m is much smaller than the mirror separation d, where λ_m is given by $m\lambda_m = 2nd$ where m is a large integer (typically 50).

In the present invention, however, the device is operated in a low order state, which may be the first order. The term "low order state" in this specification means that the optical thickness of the Fabry-Perot cavity is an integer number, which is less than 5, of the wavelength of interest. This allows a thin layer of liquid crystal material to be used, thereby achieving the desired speed of operation of the device. In common with most other liquid crystal devices, the device of the present invention requires polarised light to operate correctly. However, the majority of lasers generate polarised light, so this is not a disadvantage.

The material of the layer 10 is a ferroelectric smectic C liquid crystal material, selected such that the smectic C cone angle is 45°. An example of such material is a mixture designated CS2004 which is available from Chisso Petrochemical Corporation of Ichihara, Japan. Using this material in the structure of Figure 1, the resulting device has two stable states, the optic axes of which are 90° apart. Switching between these two states is controlled by the sign of the voltage applied between the conductive electrode layers; one optic axis orientation is selected by a voltage of one polarity, the other by the opposite polarity.

When polarised light from a laser impinges on the liquid crystal layer 10, the light experiences, in one operating state of the device, a Fabry-Perot cavity of optical thickness n_0d, whereas in the other state the optical thickness is n_ed, where n_0 and n_e are the ordinary and extraordinary refractive indices, respectively, of the liquid crystal material, and d is the mirror separation.

Although the difference between n_e and n_0 may vary for different liquid crystal materials over a range of, say, 0.05 to 0.2, typical values of n_e and n_0 are about 1.6 and about 1.5, respectively, even at a wavelength of 10.6µm. Taking the latter values, a device using a liquid crystal layer 3.313µm thick will be light transmissive for light of wavelength 10.6µm if the light is polarised parallel to the optic axis of the liquid crystal material. Figure 2(a) illustrates this situation, wherein an arrow 11 indicates the direction of polarisation of the light and an arrow 12 indicates the optic axis of the liquid crystal material. On the other hand, if the liquid crystal is switched so that the light is polarised perpendicular to the optic axis as shown in Figure 2(b), the transmissive peak wavelength moves to about 9.94µm and blocks the laser beam, transmitting only a small fraction of the light at 10.6µm. For example, if the mirror reflectivity is 95%, only 1.7% of the light is transmitted in this state, leading to a contrast ratio of 58.

The transmission spectra of the two cases are shown in Figure 3, curves (a) and (b) showing the spectra for the Figure 2(a) and Figure 3(a) situations, respectively. The contrast ratio (CR) of this device depends on the mirror reflectivity and the refractive indices of the liquid crystal material, as follows:-

$$CR = 1 + \frac{4R}{(1-R)^2} \quad \mathrm{Sin}^2\pi\left[\frac{n_0}{n_e}\right]$$

where R is the reflectivity of the mirror. This ratio can therefore be altered by selecting the appropriate liquid crystal and mirror combination. Moreover, because the liquid crystal layer is thin, the material operates within the so-called surface-stabilised regime and switching is fast, for example much less than 100μsec.

To summarise, the embodiment which has been described provides a fast-acting liquid crystal shutter suitable for operating on polarised light at long wavelength. This device would be ideally suited for use with a CO_2 laser at a light wavelength of 10.6μm. It comprises a liquid crystal Fabry-Perot device designed to operate in low order and to exploit the effects of multiple interference to achieve rapid switching using a thin layer of ferroelectric liquid crystal material.

Claims

1. An electrically-controllable liquid crystal filter device comprising two partially-reflecting substrate structures mounted substantially parallel to each other with a space therebetween to form a Fabry-Perot filter; a layer of ferroelectric liquid crystal material disposed in said space, said liquid crystal material being switchable, by application of an electric field thereto, between different refractive index values whereby the device is switchable between transmissive and reflective states for light of a particular narrow wavelength band, the spacing of the substrate structures being selected in relation to the wavelength of light to be transmitted, such that the Fabry-Perot filter operates in a low order state (as hereinbefore defined).

2. A device as claimed in Claim 1, wherein the liquid crystal material is a smectic C ferroelectric liquid crystal material having a cone angle of 45°.

3. A device as claimed in Claim 2, wherein the spacing (d) of partially-reflecting surfaces of the substrate structures is such that $\lambda_m = 2nd$, where λ_m is the peak operating wavelength and n is either refractive index of the liquid crystal material.

4. A device as claimed in any preceding claim, wherein the wavelength of the light to be transmitted is 10.6μm.

5. An electrically-controllable liquid crystal filter device substantially as hereinbefore described with reference to the accompanying drawings.

Fig. 1

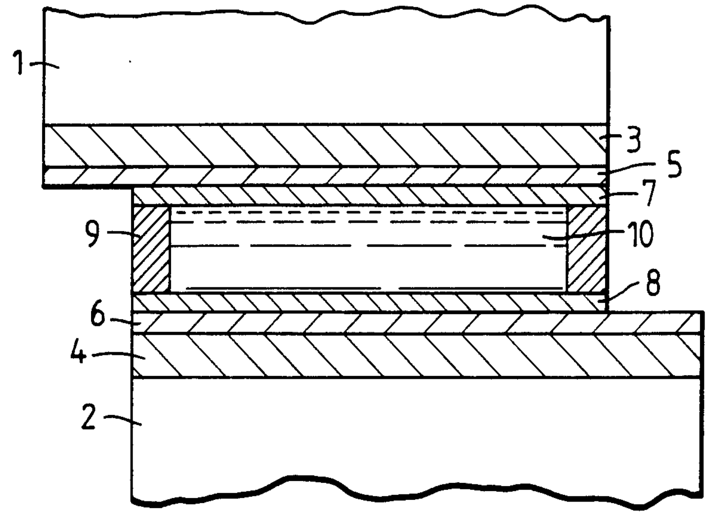


Fig. 2

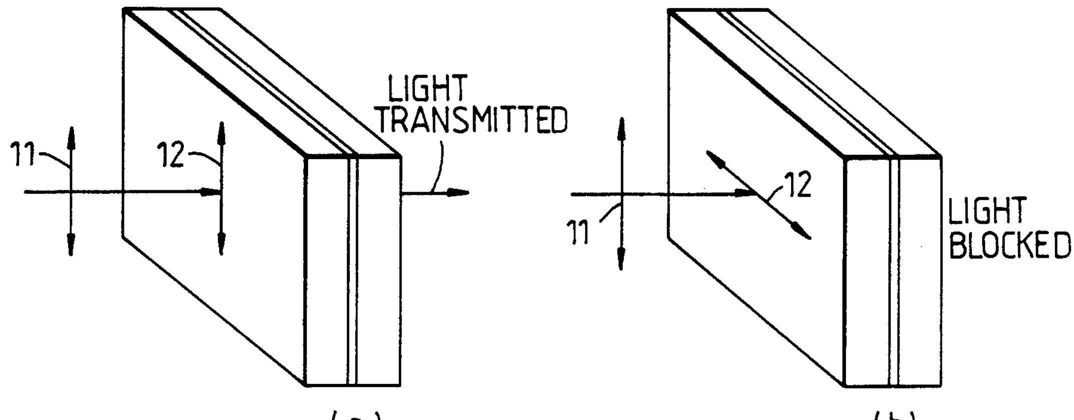
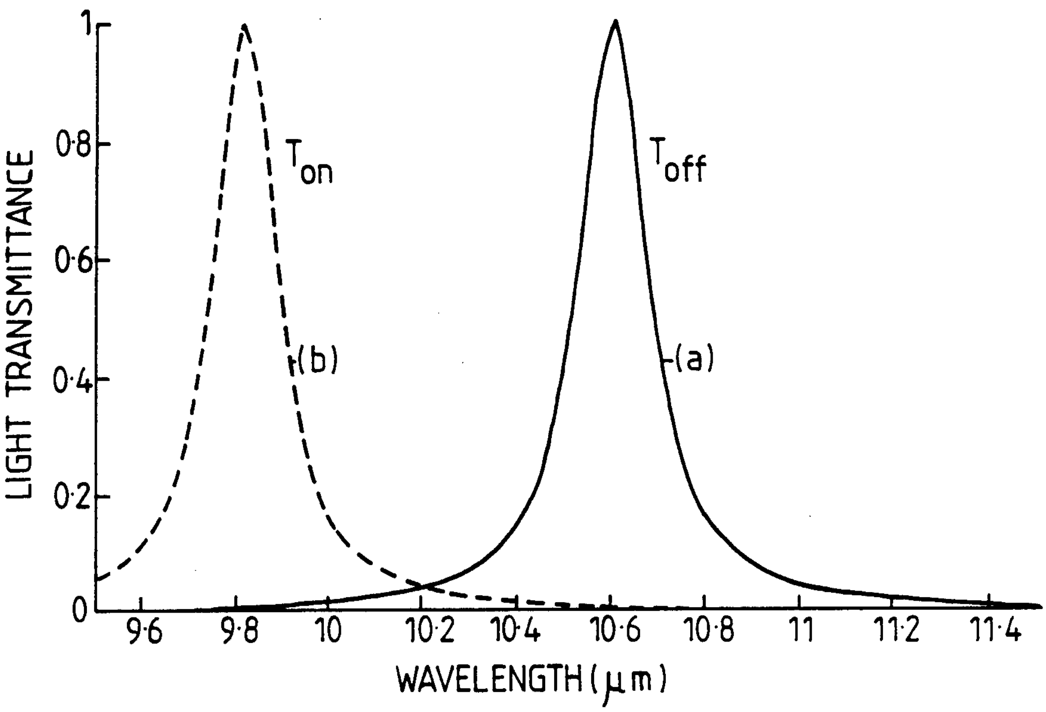


Fig. 3


LIGHT TRANSMITTANCE
1
0·8
0·6
0·4
0·2
0
9·6
9·8
10
10·2
10·4
10·6
10·8
11
11·2
11·4
WAVELENGTH (μm)
T on
T off
(b)
(a)

INTERNATIONAL SEARCH REPORT

International Application No
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A. CLASSIFICATION OF SUBJECT MATTER
IPC 5 G02F1/21 G02F1/137

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

B. FIELDS SEARCHED

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IPC 5 G02F

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

Electronic data base consulted during the international search (name of data base and, where practical, 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.
X	OPTICS LETTERS., vol.17, no.6, March 1992, NEW YORK US pages 456 - 458, XP000258278 Patel J S 'Electrically tunable ferroelectric liquid-crystal Fabry-Perot filter' see the whole document ---	1-5
P,X	WO,A,93 10477 (UNIV COLORADO FOUNDATION) 27 May 1993 see page 6, line 1 - page 7, line 33 see page 15, line 7 - page 22, line 4 see page 43, line 9 - line 32 see claims 1-4,7; figures 3,12 -----	1

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WO-A-9310477	27-05-93	AU-A- 3072692	15-06-93

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