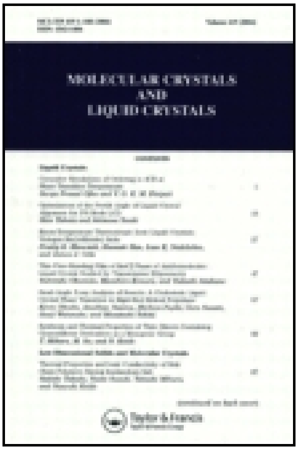

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Electro-optic Telecommunication Devices at 1550 nm Employing Electroclinic and Ferroelectric Switching of an Organosiloxane Liquid Crystal

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Electro-optic Telecommunication Devices at 1550 nm Employing Electroclinic and Ferroelectric Switching of an Organosiloxane Liquid Crystal

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We demonstrate three electro-optic telecommunication devices operating at a wavelength $\lambda = 1550$ nm: an optical switch or modulator, a variable attenuator, and a rotatable waveplate. These devices make use of the electroclinic and ferroelectric properties of a chiral smectic organosiloxane liquid crystal. Under moderate electric fields of ≤ 23 V/μm we observed an optical power modulation of up to 38 dB and a switching time of ~100 μs. The waveplate could be continuously rotated over 38°. We also present birefringence data of this liquid crystal at $\lambda = 1550$ nm as a function of temperature and the implications on the development of liquid crystal telecommunication devices.

Keywords: electroclinic; ferroelectric; liquid crystal; near-infrared; organosiloxane; telecommunication devices

1. INTRODUCTION

In addition to its widespread use in displays, liquid crystal technology gains an increasing significance in optical telecommunication applications. A recent overview of how this technology can be employed in telecommunication systems is given in [1]. A variety of liquid crystalline materials, e.g. nematic, smectic, and polymer dispersed liquid crystals (PDLC), and their associated electro-optic effects have found

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use in telecommunication applications. Response time, driving voltage, and contrast ratio are important design parameters common to display and telecommunication applications. In addition polarisation sensitivity, optical loss, and wavelength dependence are important specifications for telecommunication devices.

Two properties determine the optical response of a liquid crystal device: the re-orientation of the director as a function of an applied electric field and the birefringence of the liquid crystal. The former is independent of wavelength and is conventionally measured under a polarising microscope. The latter, however, is a function of wavelength and therefore has to be measured at the operating wavelength of the telecommunication device, typically around 850 nm, 1310 nm, or 1550 nm.

In this paper we report on the performance of three telecommunication devices operating at 1550 nm, namely a switch or optical power modulator, a variable attenuator, and a rotatable waveplate. All three devices employ either the bistable ferroelectric or the analogue electroclinic effect shown by the chiral smectic organosiloxane liquid crystal presented in [2].

2. FERROELECTRIC AND ELECTROCLINIC RESPONSE

The SmC* phase exhibits ferroelectric properties [3]. We consider here a planar aligned sample with an electric field $\boldsymbol{E}$ applied perpendicular to the confining cell surface. In this case the director $\boldsymbol{n}$ lies perpendicular to $\boldsymbol{E}$ and makes an angle of $\pm\theta$ with the smectic layer normal depending only on the polarity of $\boldsymbol{E}$. The response time τ, however, is a function of the magnitude of $\boldsymbol{E}$, i.e. $\tau \propto 1/|\boldsymbol{E}|$.

In the SmA* phase the director response is described by the electroclinic effect [4]. For the same cell geometry as above $\boldsymbol{n}$ rotates continuously through an angle $\pm\theta$ in the plane of the cell surface as a function of $\boldsymbol{E}$. For small electric fields and away from the SmC*–SmA* phase transition θ is a linear function of $\boldsymbol{E}$. The response time of the electroclinic effect is independent of $\boldsymbol{E}$.

Between crossed polarisers the re-orientation of $\boldsymbol{n}$ as a function of $\boldsymbol{E}$ leads to a modulation of the transmitted optical power according to

$$P_{\text{out}} = P_{\text{in}} \sin^2(2\alpha)\sin^2(\Phi/2), \tag{1}$$

where α is the director orientation with respect to the input polariser. The retardance Φ of the liquid crystal cell is given by

$$\Phi = 2\pi\frac{d\Delta n}{\lambda}, \tag{2}$$

where Δn is the birefringence of the liquid crystal, d is the cell thickness, and λ is the wavelength of the light.

The largest intensity modulations in the SmC* or SmA* phase occur when the sample is oriented such that $\alpha = 0^\circ$ for the maximum available electric field of one polarity, e.g. $\boldsymbol{E}^+$. In this orientation the transmission becomes minimal, $P_{\min}$. The maximum transmission $P_{\max}$ of the device is reached when applying the maximum field with opposite polarity, $\boldsymbol{E}^-$, upon which $\boldsymbol{n}$ rotates through an angle 2θ. The extinction ratio $P_{\min}/P_{\max}$, or contrast ratio in terms of display applications, becomes largest if $2\theta = 45^\circ$ and $\Phi = \pi \equiv \lambda/2$.

3. EXPERIMENTAL ARRANGEMENT

A device demonstrator was fabricated using a $d = 3.76\,\mu\text{m}$ thick glass cell with anti-parallel rubbed polyimide alignment layers and ITO electrodes. Planar alignment of the liquid crystal was achieved by shear alignment during cooling from the isotropic into the SmA* phase. The phase transition temperatures where measured under a polarising microscope giving the following phase diagram: sub-ambient SmC* 43 SmC* + SmA* 50 SmA* 70 I.

The experimental arrangement for testing the devices at $\lambda = 1550\,\text{nm}$ is shown in Figure 1. Light from a tunable semiconductor laser was coupled into single mode fibre. A 50 mm long free-space section (OFR fibre bench) consisting of a collimator and a collection lens was connected in-line with the fibre optic network. A pair of rotatable polarisers was inserted into the free space section. Their individual extinction ratio was 30 dB, i.e. 1:1000. A polarisation controller was employed to maximise the transmitted optical power through the first polariser. Finally

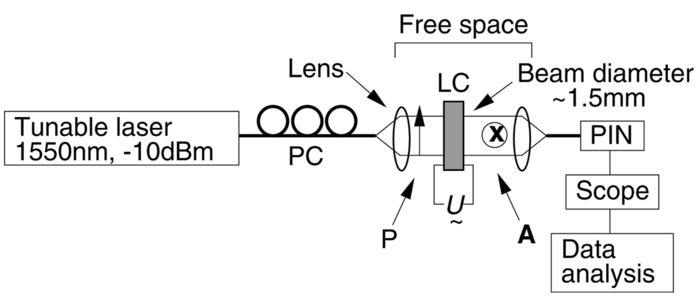

FIGURE 1 Optical setup to characterise liquid crystal cells at 1550 nm. PC = polarisation controller, P = polariser, A = analyser, PIN = photodetector. Sample thickness here 3.76 μm.

the liquid crystal cell, mounted on a heating stage, was positioned between the polarisers inside the free space section. It should be noted that the heating stage was not thermally isolated from the environment, so the actual temperature of the liquid crystal could have been a couple of degrees lower than the reading from the internal thermocouple of the stage. The diameter of the collimated beam within the free space section was about 1.5 mm. The optical power after the free space section was measured with a fibre coupled photodetector whose minimum detectable power was 10 pW. An optical power of 14 μW was incident on the liquid crystal sample. AC electric fields up to $\boldsymbol{E} = \pm 23\,\mathrm{V}/\mu\mathrm{m}$ with square and triangular waveforms at a frequency of 10 Hz were applied to the device. The transmitted power measured by the photodetector was recorded on a digital oscilloscope. In order to achieve a large extinction ratio $P_{\mathrm{min}}/\mathrm{P}_{\mathrm{max}}$ the sample was oriented such that for maximum positive electric field, i.e. $\boldsymbol{E}^{+} = 23\,\mathrm{V}/\mu\mathrm{m}$, the director was aligned with the polariser.

4. RESULTS AND DISCUSSION

4.1. Birefringence and Rotatable Waveplate

Figure 2 shows the director orientation as a function of applied electric field $\boldsymbol{E}$ in the SmC* and SmA* phases. A maximum tilt angle $\theta = 27^{\circ}$ was observed in the SmC* phase. The temperature region for which the electroclinic response was linear for small $\boldsymbol{E}$ was 58–65°C. The maximum induced tilt angle in the SmA* phase for $\boldsymbol{E} = 23\,\mathrm{V}/\mu\mathrm{m}$ was $\theta = 19^{\circ}$.

We determined the birefringence Δn of the liquid crystal at 1550 nm by measuring the transmitted power through crossed and parallel polarisers with the director oriented at 45° with respect to the fixed first polariser. The retardance of the cell is related to these optical powers by [5]

$$\frac{P_{\perp}}{P_{\parallel}} = \tan^{2}\left(\frac{\Phi}{2}\right), \tag{3}$$

where $P_{\perp}$ and $P_{\parallel}$ are the transmitted powers for crossed and parallel polarisers. With the cell thickness $d = 3.76\,\mu\mathrm{m}$ Equation (2) can then be used to calculate Δn, which is shown in Figure 3 as a function of temperature. Within the two mesophases the birefringence is independent of temperature. However, a clear Δn change can be observed at the SmC*–SmA* phase transition. We assume that strong intermolecular forces help maintain the long range order of the liquid crystal molecules within each mesophase.

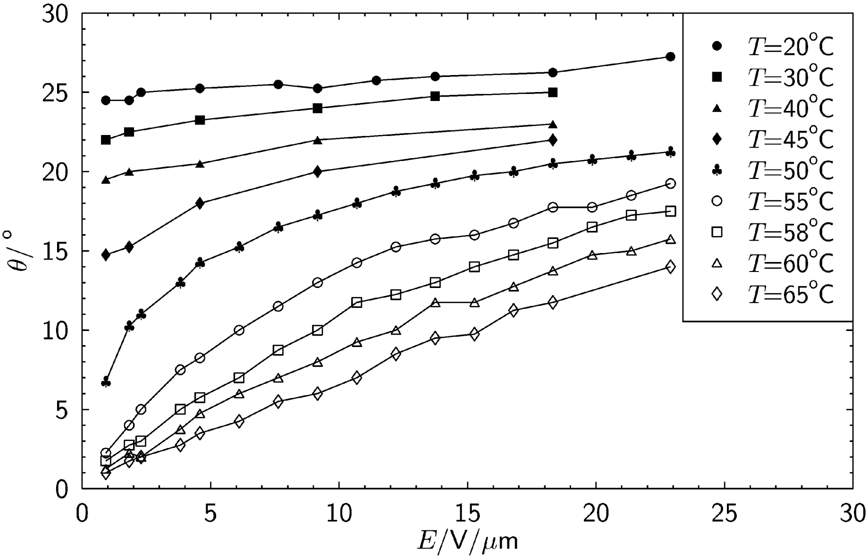

FIGURE 2 Tilt angle θ as function of applied electric field $\boldsymbol{E}$, as measured under polarising microscope. Ferroelectric response for $T \leq \sim 45$°C, electroclinic response for $T \geq \sim 50$°C.

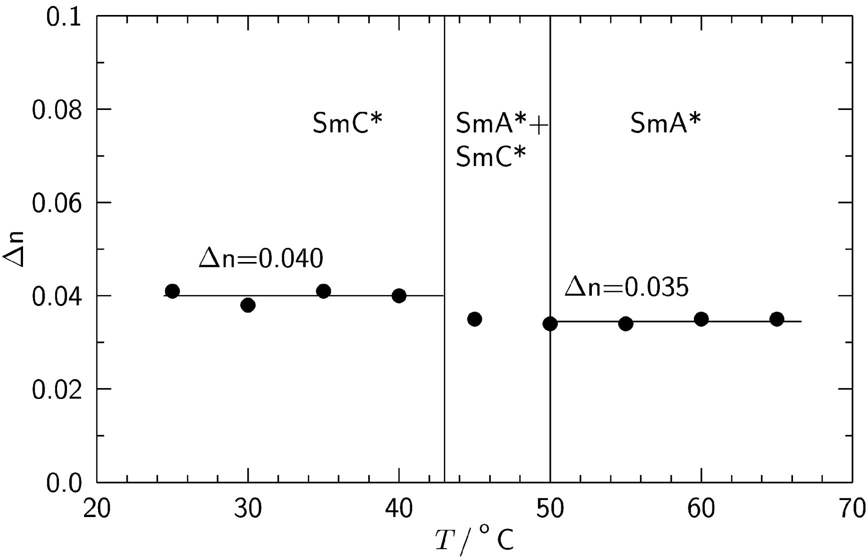

FIGURE 3 Birefringence Δn at 1550 nm as a function of temperature.

The retardance of the cell determined from (3) was $\Phi \sim \lambda/12$ and $\sim\lambda/10$ in the SmA* and SmC* phase, respectively. For continuously rotatable $\lambda/2$ or $\lambda/4$ waveplates in the SmA* phase cell thicknesses of 22 μm or 11 μm are required, respectively. We expect that liquid crystal alignment can be maintained over such cell gaps. The optic axis of the waveplate could be continuously rotated through 2θ, i.e. by a maximum of 38°, see Figure 2.

4.2. Optical Switch and Modulator

In the SmC* phase the liquid crystal was employed as a binary optical power switch or modulator between crossed polarisers. The cell was oriented such that the director was parallel to the input polariser for $\boldsymbol{E}^+$ in order to obtain the maximum extinction ratio between the on and the off state. Since θ is temperature dependent the cell was re-oriented by about 1–2° at each temperature setting. Figure 4 shows the applied electric field and the obtained optical power modulation for different temperatures in the SmC* phase. The extinction ratio between the on and off state was as large as 38 dB or 6300:1. This extinction ratio is generally acceptable for telecommunication applications. The switching angle 2θ decreases with increasing temperature leading to a reduction of the extinction ratio in accordance with (1)

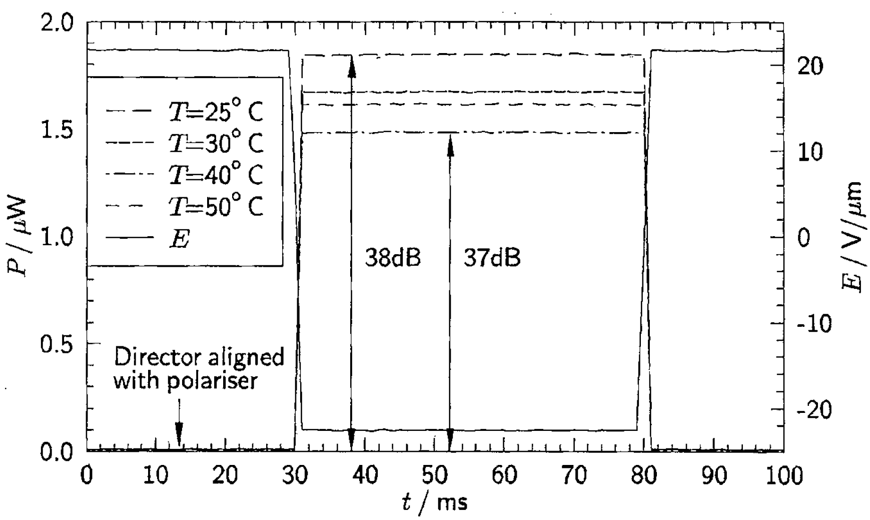

FIGURE 4 Response of optical switch in ferroelectric SmC* phase subject to square wave. Response time ~100 μs.

for $\alpha = [0^\circ, 2\theta]$. Increasing the cell thickness to 22 μm such that the cell becomes a $\lambda/2$ waveplate would increase the maximum transmitted power P_{max}. This would result in an increased extinction ratio and a reduction of optical loss.

The response time of the liquid crystal cell was about 100 μs, providing fast enough switching times for circuit switching and bandwidth provisioning in optical telecommunication networks. A practical device could, for example, be made in the form of a spatial light modulator filled with this organosiloxane liquid crystal [6].

4.3. Variable Attenuator

In the SmA* phase we used the analogue response of the electroclinic effect to realise a variable attenuator between crossed polarisers. Again the director was aligned parallel to the input polariser for $\boldsymbol{E}^+$. Figure 5 shows the transmitted power as a function of applied electric field for various temperatures in the SmA* phase. The combination of smaller θ and reduced Δn in the SmA* phase led to a smaller power modulation compared to the switch in the SmC* phase. However, the variable attenuation range of ~36 dB is useful for telecommunication applications such as channel equalisation [7]. The optical

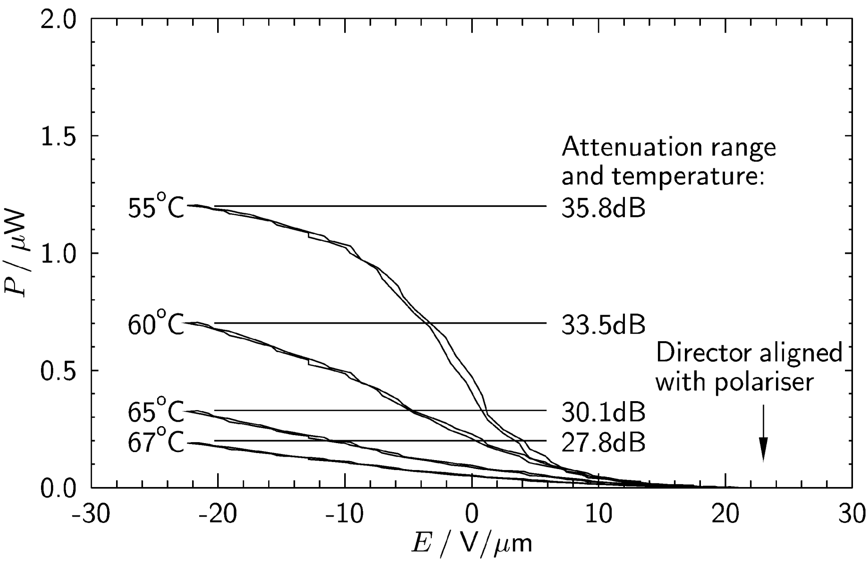

FIGURE 5 Response of variable attenuator in electroclinic SmA* phase as a function of electric field.

response is non-linear since the device was operated away from its small linear regime in order to maximise the attenuation range.

A drawback of this device is its large optical loss which is caused by two factors. Firstly the switching angle 2θ of the electroclinic effect is generally $< 45^\circ$. Secondly, as for the optical switch in the SmC* phase the retardance of the cell is smaller than $\lambda/2$.

5. CONCLUSION

We have employed a chiral smectic organosiloxane liquid crystal to demonstrate three devices for telecommunication applications at 1550 nm: a fast switch with up to 38 dB extinction ratio and a switching time of around 100 µs, a variable attenuator with a maximum attenuation range of 36 dB, and a $\lambda/12$ waveplate continuously rotatable through a maximum of 38°. The maximum driving voltage for the 3.76 µm thick cell was 85 V corresponding to an electric field of 23 V/µm. While extinction ratio and attenuation range are suitable for telecommunication applications, the optical loss of the device needs to be decreased. A straight forward way would be to increase the cell thickness to obtain a retardance of $\lambda/2$. This would require correspondingly higher drive voltages. Alternatively a liquid crystal with larger Δn at 1550 nm could be employed. An increase of the electroclinic rotation angle to 45° would also be desirable.

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