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RESEARCH ARTICLE

Liquid crystal applications in photonics

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Abstract We developed new optical switches based on nematic and ferroelectric liquid crystal (LC) cells for photonics applications. Certain new LC switches based on the effect of total internal reflection in nematic LC and deformed helix ferroelectric effect ferroelectric LC with very fast response time were developed. Fast bistable optical switches of the light polarization based on ferroelectric liquid crystal cells were proposed. The switches are characterized by 100 μs switching time and 26 dB crosstalk at the wavelength of 632.8 nm and bistable, i.e., required zero power consumption in the switch state.

High frequency hysteretic free electrically controlled 0–2π phase modulation of light has been proposed using a very short helix pitch (less than 400 nm) deformed helix ferroelectric liquid crystal. The electrically controlled 0–2π hysteretic free phase modulation was achieved at the driving voltage frequency up to 4 kHz and the voltage amplitude of 32 V. The application of fast V-shaped deformed helix ferroelectric ferroelectric LC (DHF-FLC) for new active-matrix liquid crystal display (LCD) and optical data processing devices is envisaged.

Photoalignment technology can be very useful for the new generation of liquid crystal devices as well as in new photovoltaic, optoelectronic and photonic devices based on highly ordered thin organic layers. We have investigated the LC photoalignment in superthin tubes, which are basic elements of switchable photonic crystal/liquid crystal structures and obtained the order parameter comparable with usual homogeneous nematic LC cells. We studied LC alignment on silicon surfaces with submicrometer-sized straight and curved waveguide profiles. The liquid crystal cladding refractive index was then varied according to the applied voltage, and subsequently the microresonator resonance wavelengths were tuned. Based on our initial measurements, the free spectral range (FSR) wavelength shift within the range of 20 nm was obtained, which is comparable with a thermooptic effect. The new voltage controllable Si-based add drop filters are envisaged based on this principle.

Keywords liquid crystals, fiber optical devices, switches, photoalignment, optically rewritable waveguide

1 Introduction

Despite a certain drop in the fiber optical component market within the last three years, the need for reliable passive optical components is still very large and continues to grow. Hong Kong Science and Technology Parks (www.hkstp.org) plans to open a new special building for fiber optics for telecommunications and considers new optical communications technology as one of the key factors to transform Hong Kong into a high tech center. Certain liquid crystal (LC) components, such as LC-based coaxial variable optical attenuators, polarization controllers and phase retarders have already appeared in the market (Manufactures of innovative of fiberoptics components. http://www.lightwaves2020.com). Recently, Vescent Photonics announced the LC waveguides as a new electro-optic technology platform for a variety of applications, such as interferometers, beam steerers, tunable filters and lasers, etc. [1]. This paper will describe certain liquid crystal devices for photonics applications, such as switches and add/drop filters. The photoalignment technology will be also considered as a new approach for the implementation of photonics LC devices.

2 LC switches

Switches for optical fiber optical networks are increasingly important. LC switches show certain advantages in comparison with microelectromechanical system (MEMS) switches [1], commonly used for the same purpose, such as 1) fast switching time, 2) low controlling voltages and power consumption, and 3) higher reliability and working time. However, wavelength dependence of

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the response times and thermal drift of the characteristics of LC switches should be avoided. There are two main techniques that can be used in LC optical switches, working in non-polarized light. In the first one, the non-polarized light from the input fiber is decomposed by polarizing beam splitters (PBSs) on the two orthogonal polarizations, which are then independently rotated by the spatial light modulators (SLMs) and collected on the output fiber, thus transferring the input non-polarized light to the proper output channel [2]. In the second, the voltage controllable diffraction can be used for the optical switch [1]. The LC optical switching can be also arranged by changing the boundary refractive index for the fiber using LC cell [3]. A full cross-switching with a high extinction ratio is possible with ferroelectric LC (FLC) coupling less than 60 μm.

The following electro-optical effects in liquid crystals can be used in optical switching.

1) Electroclinic effect in smectic LCs. The switching time of 5 ms was reported for the controlling voltages of 30 V [2]. The effect has a weak dependence on the light wavelength. However, the switching must be provided in a double cell configuration (one cell does not allow ninety degree rotation of the light polarization).

2) Deformed helix ferroelectric (DHF) effect in FLCs. The switching time, less than 10 μs at the controlling voltage of 20 V can be provided, which is temperature independent over the broad temperature range [4,5]. The DHF LC cells are the basis for fast responding modulators and optical filters, which are applicable in fiber optical communication systems. High operation speed is achieved for DHF-FLC at low driving voltages. This takes place because a slight distortion of the helix near the equilibrium state results in a considerable change in the transmission. The DHF effect is also less sensitive to the surface treatment and more tolerant to the cell gap inhomogeneity. The DHF effect allows the implementation of a "natural", i.e., dependent on voltage amplitude, grey scale both linear and quadratic in voltage [5].

High frequency hysteretic free electrically controlled 0–2π phase modulation of light has been proposed using a very short helix pitch (less than 400 nm) deformed helix ferroelectric liquid crystal. The electrically controlled 0–2π hysteretic free phase modulation was achieved at the driving voltage frequency up to 4 kHz and the voltage amplitude of 32 V. The 0–2π phase modulation in DHF-FLC cell is accompanied with a weak (around 3%) light intensity modulation, which can be considerably decreased using a series connection of DHF-FLC cells. The application of fast V-shaped DHF-FLC for new active-matrix liquid crystal display (LCD) and optical data processing devices is envisaged (Figs. 1 and 2) [5].

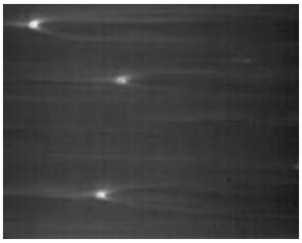


Fig. 1 Optical quality of DHF-FLC structure at 50 μm cell [5]

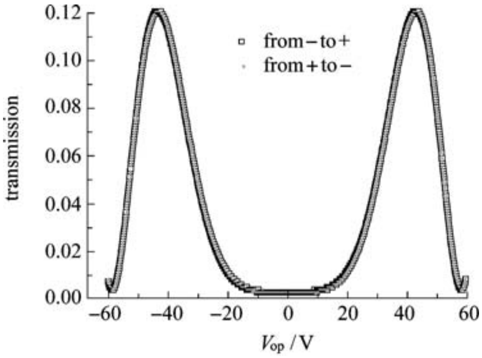


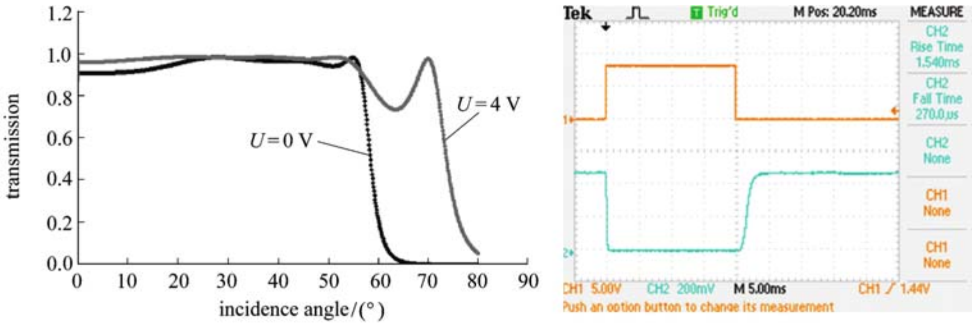
Fig. 2 V-shaped switching of DHF-FLC for 4 kHz frequency [5]

3) Volume-stabilized (VS) FLC mode. In this case, the FLC helix pitch may be infinite and plays no role. The V-shaped curve is obtained by i) using FLC with a high spontaneous polarization to produce multi-stable switching of two domain structures [6] and ii) polymer stabilization of FLC structure [7].

4) The LC switches can use the effect of total internal reflection in nematic LC [8] or selective reflection effect in cholesteric LC [9]. The total internal reflection switch operates only for one light polarization (TE mode) and the most promising is vertical aligned nematic (VAN) configuration [8]. The switching time of 1 ms can be easily obtained in this case for the switching pulse amplitude of 5 V (Fig. 3) [8].

5) Bistable nematic switches are also possible, using bistable nematic twisted (BTN) cells [10]. In the latter case, the switching power is reduced, as the LC cell keeps the switched state without voltage. Recently, a bistable ferroelectric LC optical switch was demonstrated [11]. Both bistability and fast FLC switching were shown with a typical response time of 100 μs from TE to TM state and vice versa. The switches are characterized by 100 μs switching time and 26 dB crosstalk at the wavelength of 632.8 nm and bistable, i.e., required zero power consumption in the switch state. A very low power consumption device with a rather satisfactory optical quality was developed as a result (Figs. 4 and 5).

6) The bypass optical switch based on two nematic liquid crystal cells with a switching time less than 200 μs was demonstrated using two temperature-stabilized nematic LC birefringent cells [12]. Two subsequent nematic liquid crystal (NLC) cells with crossed optical axes compensate the relaxation of NLC birefringence if turned off simultaneously. Thus, the switching speed of the



(a)

(b)

Fig. 3 Total internal reflection (TIR) in nematic LC [8]. (a) Calculations of TIR transmission versus light incidence angle for two voltages $U=0$ V and $U=4$ V; (b) experimental data of switching dynamics of TE mode in VAN configuration

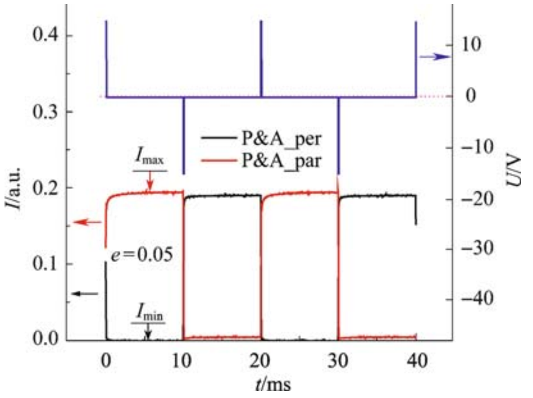


Fig. 4 Electro-optical response of a bistable ferroelectric LC optical switch (blue line: voltage applied to 1.7 μm FLC cell; black line: electro-optical response of the cell placed between two crossed polarizers; red line: electro-optical response of the cell placed between two parallel polarizers; parameter e is ellipticity of the light passing through the cell in memorized states after positive driving voltage pulse)

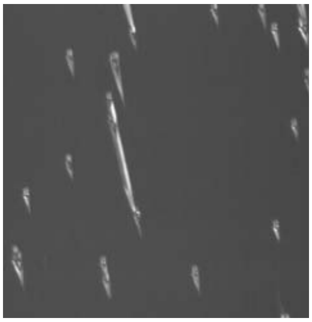


Fig. 5 Quality of 1.7 μm FLC cell alignment (FLC cell is placed between crossed polarizers; micro-photo dimension is 140 μm×140 μm)

two-cell switch can be as fast as NLC cell turn-on times. The cells can be specified to a certain fiber wavelength by adjusting the cell gap thickness.

7) LC switch can be made to control light beams in a plane of LC layers [13]. It was shown experimentally that the direction of the light beam can be considerably changed by refraction and reflection of light at the sharp boundaries between the regions with different LC orientations [13]. LC switching can be controlled by an electric field. Certain ways were proposed for optimization insertion loss and crosstalk of the 1×2 switcher for real photonic applications. Using different indium tin oxide (ITO) templates, it is possible to create $N\times M$ switch and other different optical processing data elements, e.g., attenuators. There are a number of ways to optimize such types of LC devices including application of fast operating ferroelectric liquid crystal layers, which can provide the operation times in a microsecond range.

3 Liquid crystal photo-alignment technology for photonics applications

Photo-alignment possesses obvious advantages in comparison with the usual "rubbing" treatment of the substrates of LCD cells. Possible benefits for using this technique in photonics LC devices include [14]:

1) New advanced applications of LC in fiber communications, optical data processing, holography and other fields, where the traditional rubbing LC alignment is not possible due to the sophisticated geometry of the LC cell and/or high spatial resolution of the processing system;

2) Ability for efficient LC alignment on curved and flexible substrates;

3) Manufacturing of new optical elements for LC technology, such as patterned polarizers and phase retarders, tunable optical filters, variable optical attenuators, etc.

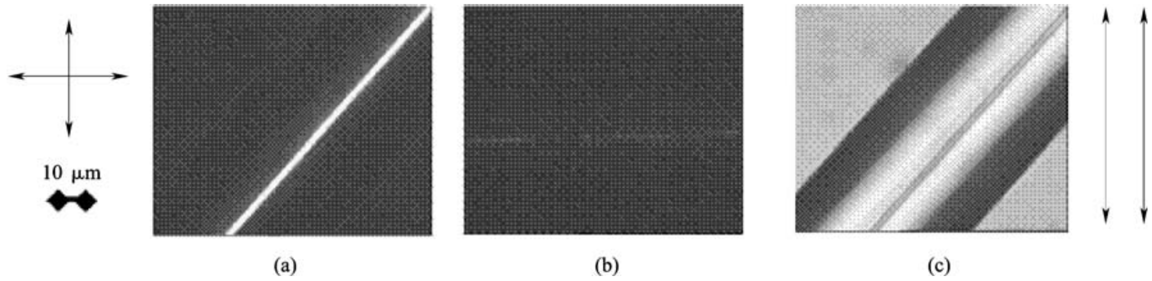
The photo-aligning materials developed by us are based on photo-polymerized and cross-linked dye photosensitive layers that enable [14] 1) a high order parameter of more than 0.8; 2) excellent alignment quality of nematic and ferroelectric LC materials in various modes; 3) temperature and ultra violet (UV) stability due to the polymerization and cross-linking effect in dye layers; 4) perfect adhesion and anchoring energy comparable with rubbed polyimide (PI) layers; 5) excellent sensitivity with a minimum exposure energy; and 6) ability to align LC materials in curved surfaces and photonic holes.

Photonic crystal fiber is a glass or polymer fiber with an array of microscopic air holes running along the length of the fiber. The waveguide properties of such a fiber can be controlled by introducing an additional material into the air holes [15–17]. LC is suitable for that purpose because its refractive index can be easily tuned by an electric field or temperature. The technique of photo-configurable alignment of LC in glass micro-tubes and in photonic crystal fiber has been developed (Fig. 6) [18]. Good homogeneous alignment was detected with polarized microscopy and Fourier transform infrared (FTIR) spectroscopy methods. The presented technique of alignment is based on properly developed photoaligning azo-dye material and is promising as a non-contact method for LC orientation in complex photonic crystal structures [18]. Figure 6 presents the glass tube of inner diameter 4 μm treated with the photoaligning sulfonic azo-layer (SD1) and filled with uniform nematic LC orientation without point defects or linear disclinations. The order parameter S of LC has been obtained from FTIR spectroscopy data and has demonstrated good alignment quality ($S = 0.63$ [18]). The presented technique can be used as a non-contact method of LC alignment in complex photonic crystal structures.

The uniform azo-dye photoalignment on the profiled three-dimensional (3D) surface (substrate with bulk relief) was demonstrated [19]. The three-step exposure process for uniform surface alignment was developed. Patterned exposure of azo-materials is a very useful procedure for LC photonic devices as a high quality LC alignment on profiled surfaces can be obtained.

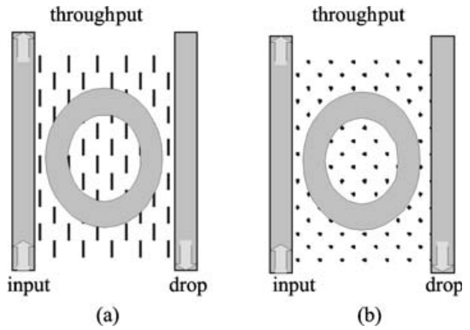
LC alignment on submicrometer-sized rib waveguides on silicon chips was studied [14,19]. The experiments using nematic liquid crystal cladding on silicon waveguides and microrings coated with photoalignment layer, and covered with a vertically aligned polyimide rubbed glass, revealed a defect-free hybrid aligned liquid crystal cell on silicon substrate (Figs. 7 and 8). An electrically tunable micro-resonator using photoaligned liquid crystal as cladding layers, where a photoalignment layer on the device surface defined the orientation of the liquid crystal molecules, and the transmission property of the waveguide-coupled micro-resonator electrically tuned by varying the cladding refractive index under an applied electric field in the vertical direction was demonstrated [14,19].

The liquid crystal cladding refractive index is then varied according to the applied voltage, and subsequently the microresonator resonance wavelengths were tuned. Based on our initial measurements, the free spectral range (FSR) wavelength shift within the range of 20 nm was obtained, which is comparable with a thermooptic effect.



(a) (b) (c)

Fig. 6 Photo-alignment in micro-tube [18]. (a) Angle between polarizer and tubes axis is 45° (crossed polarizers); (b) angle between polarizer and tubes axis is 0° (crossed polarizers); (c) angle between polarizer and tubes axis is 45° (parallel polarizers)



(a) (b)

Fig. 7 LC configurations on photoaligned cladding azo-dye layer. (a) Planar; (b) homeotropic

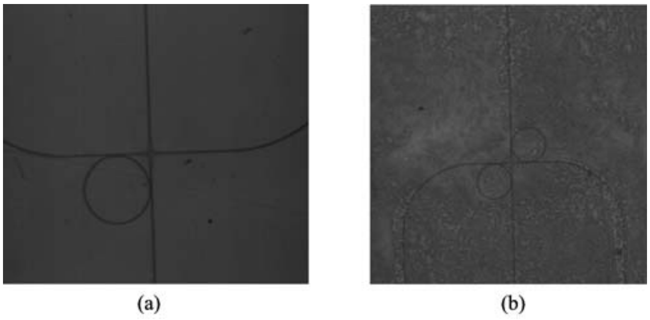

(a) (b)

Fig. 8 LC alignment on microring [14]. (a) With photoalignment layer; (b) without photoalignment layer (this is clear that the LC structure on the right produces a non-uniform LC alignment with a high scattering effect)

The new voltage controllable Si-based add drop filters are envisaged based on this principle.

It is easy to show that LC photoalignment can provide a perfect quality of LC alignment without any scattering effect (Fig. 8) [14].

4 Conclusions

Further work in the field of passive liquid crystal elements for fiber optical communication systems is needed. High-quality LC switches, variable optical attenuators, voltage controllable filters based on Si photonics devices, polarization controllers and rotators have to be developed. New working prototypes ready for packaging are highly desirable. Use of photonic crystals and photo-alignment technique makes it possible to develop new LC fiber components. There exist certain problems in wavelength dependence such as too large losses, thermal drift, and high crosstalk. New LC materials for the infrared (IR) region used for fiber optical communications have to be tested. Specific LC materials with a high birefringence and low rotational viscosity have to be developed for the IR region.

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