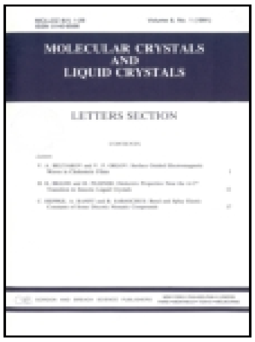

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Design of Optical Directional Couplers Made of Polydimethysiloxane Liquid Crystal Channel Waveguides

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We present numerical simulations of a directional coupler based on three-dimensional waveguides made of a nematic liquid crystal, acting as the waveguide core, infiltrated in polydimethysiloxane channels. Modeling is based on the combination of minimization of Oseen-Frank energy of the liquid crystal molecules with a beam propagation algorithm. Design of the coupler waveguides is optimized to minimize coupling lengths and maximise efficiencies. Such components can be made at low cost on flexible plastic substrates and can be also integrated with optofluidic devices for biomedical applications.

Keywords Optical waveguides; nematic liquid crystals; optofluidics; directional couplers; optoelectronics.

Introduction

Optofluidics based on the optical properties of liquids in microfluidic devices has been gaining a lot of interest recently because of the possibility to make microdevices with advantages in terms of integration and reconfigurability [1]. These features allow for the fabrication of microsystems on chips for several applications including biomedical applications oriented on precocious diagnostics, chemical sensor systems for environmental monitoring, and so on. Moreover the combination between integrated optic and microfluidic devices increase portability and sensitivity. Optofluidic devices can be made by using a reliable and low cost technology based on standard soft photolithography, generally employed to make microfluidic structures in flexible polymeric substrates at reduced costs if compared with traditional glass or semiconductor manufacturing used in integrated optics.

Recently poly(dimethylsiloxane) (PDMS) has been considered an interesting polymer to make microfluidic circuits for its optical transparency, low surface energy, low dielectric constant and Young's modulus, and thermally and optically enabled polymerization [2]. PDMS has been demonstrated to be very effective and reliable for soft lithographic fabrication of many microfluidic and micro-optical devices. An interesting advantage of

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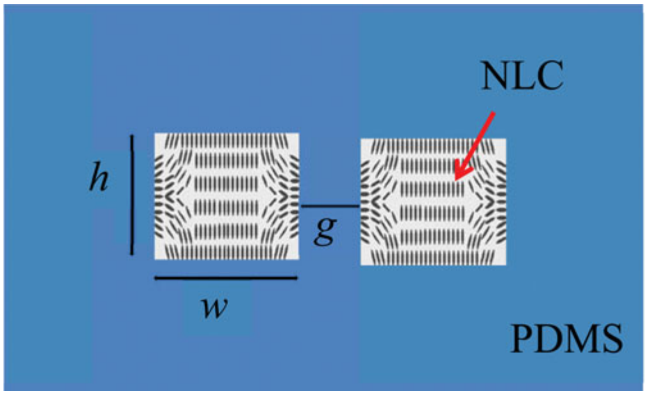

Figure 1. A schematic representation of the cross section of the LC:PDMS waveguide directional coupler. The boundary conditions of the NLC are homeotropic at the surfaces.

PDMS with respect to other materials, such as silicon or glass, is the easy and cheap technological lithographic processing to make patterned geometries on flexible substrates [3]. Furthermore PDMS has been also recently proposed as an interesting material for optical interconnections to replace metallic wired connections in order to reduce heat dissipation and to allow high bit rate interconnections [4]. Reconfigurability can be added to optofluidic devices by using liquid crystals (LC), very well known as very effective electro-optic [5–9] and nonlinear optic devices [10, 11]. Optofluidic channels have been successfully

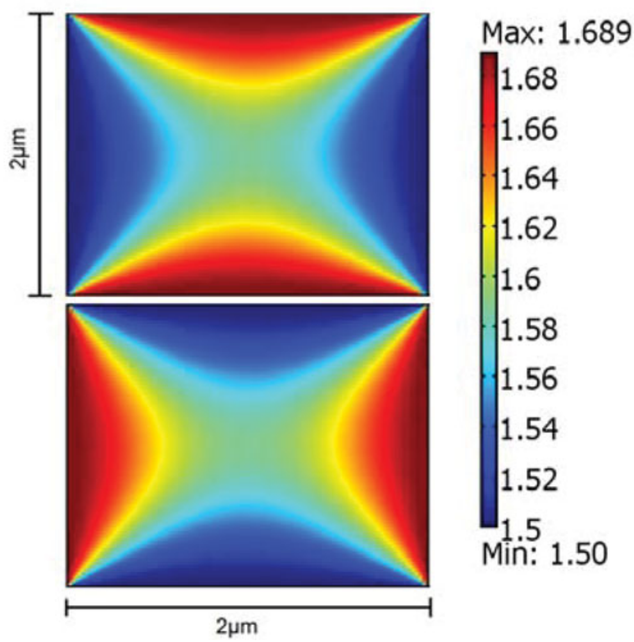

Figure 2. NLC refractive index profile in a single PDMS channel of the directional coupler for TM input light (top) and TE input light (bottom).

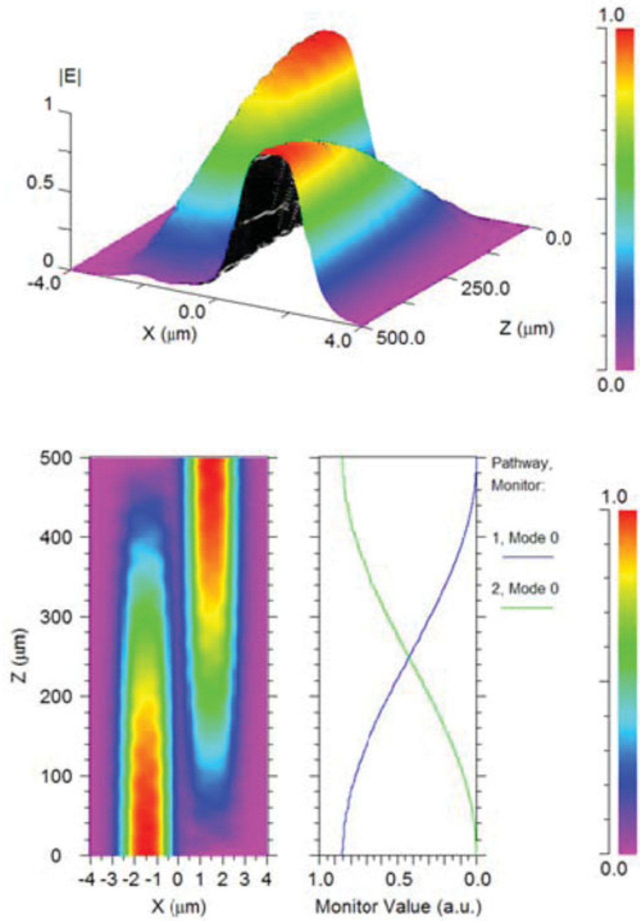

Figure 3. Coupling between two LC:PDMS square waveguides with a side of 2 μm separated by a gap g = 1 μm: three-dimensional (top) and bi-dimensional (bottom) view of the optical electric field evolution.

proposed by infiltrating liquid crystals (LC) in PDMS to demonstrate both simple optical waveguides (LC:PDMS waveguides) and the variation in the diffraction pattern of an array of microfluidic channels acting as a grating [12]. Furthermore straight LC:PDMS optical waveguides are able to transmit light with intensity, which is independent on the state of polarization, despite of LC typical optical anisotropy [13].

In order to make functional photonic devices like integrated optical switches, ring resonators, multi/demultiplexers, it is required to optimize guided wave directional couplers as basic building blocks. Integrated optical couplers were already demonstrated by using LC in combination with either ion-exchanged glass [14–17] polymers [18] or silica on silicon channel waveguides [19]. In this paper we present the design and the simulations of a new kind of directional coupler based on channel LC:PDMS waveguides. Coupling length versus separation distance between the coupled waveguides is studied in order to optimize the design of compact sub-millimeter devices.

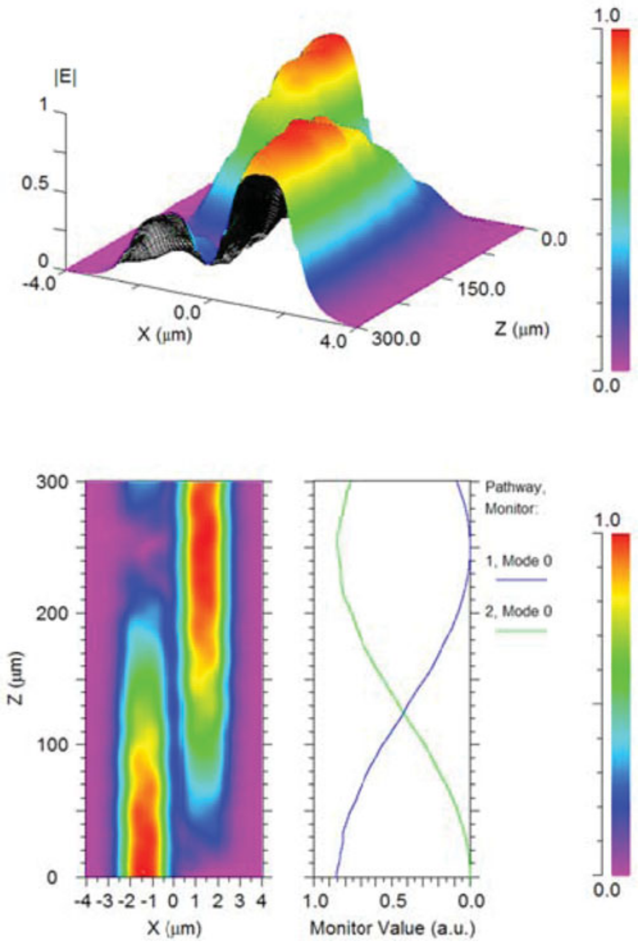

Figure 4. Coupling between two LC:PDMS square waveguides with a side of 2 μm separated by a gap g = 0.75 μm: three-dimensional (top) and bi-dimensional (bottom) view of the optical electric field evolution.

LC:PDMS Directional Coupler Modeling

A directional coupler can be obtained by filling two channels in a PDMS substrate with a nematic liquid crystal by using the well-known technique based on casting and molding. Fig. 1 sketches the cross section a directional coupler made by two LC:PDMS waveguides with width w and height h, separated by a gap g. The nematic LC (NLC) molecules are typically aligned homeotropically with respect to the surfaces as found experimentally.

In order to study the behavior of the directional coupler the refractive index profile was calculated in the cross section of the waveguides from the distribution of the molecular director. The LC director orientation was obtained by means of the minimization of the Oseen–Frank energy related to the elastic properties of the LC molecules by solving a partial derivative Euler-Lagrange differential equation by means of 2D finite elements implemented in Comsol Multiphysics®. The calculations were carried out for square waveguides with w = h = 2 μm at the wavelength of 1550 nm. A NLC extraordinary refractive index equal to 1.689 along the molecular longitudinal axis, and the ordinary index equal to 1.5

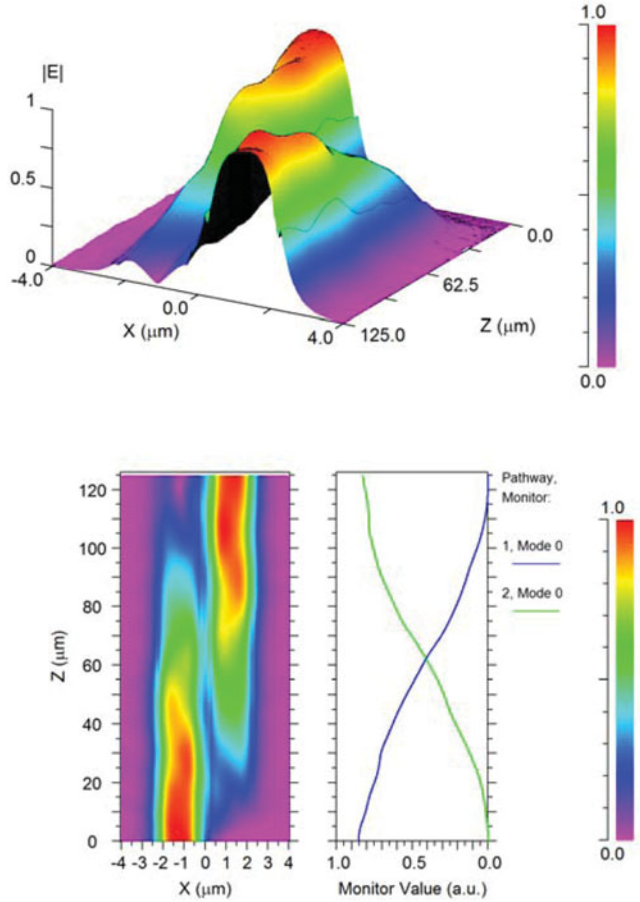

Figure 5. Coupling between two LC:PDMS square waveguides with a side of 2 μm separated by a gap g = 0.5 μm: three-dimensional (top) and bi-dimensional (bottom) view of the optical electric field evolution.

perpendicular to the molecular axis were used and a PDMS index of 1.406 was considered in the calculations. Fig. 2 shows the computed contour maps of the refractive index seen both by TM polarized input light (top) and by TE input light (bottom) in the LC:PDMS square waveguide. As expected the refractive index is maximum on the vertical side for TE input light and on the horizontal side for TM input light.

The computed refractive index was implemented in a beam propagation algorithm to design directional couplers with optimized performance in terms of short coupling length and maximum extinction ratio.

Simulation Results and Discussion

A finite difference based vectorial beam propagation algorithm was used to study propagation of light in a set of directional couplers obtained by varying the waveguide gap.

Figure 3 shows the performance of a directional coupler made of two LC:PDMS waveguides with a 2×2 μm^2 cross section with a separation gap of 1 μm. Complete

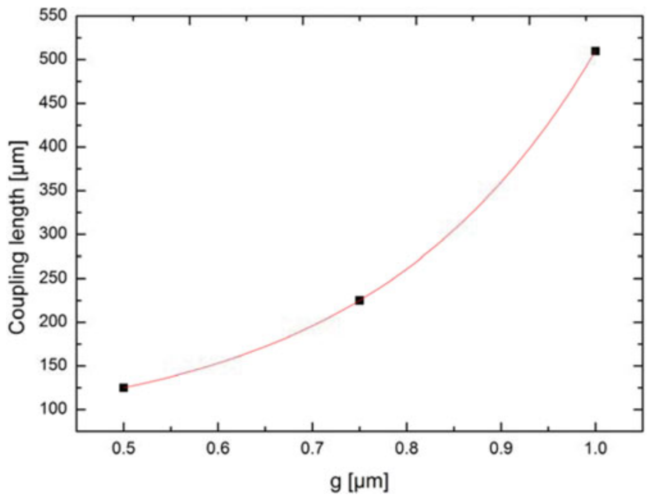

Figure 6. Plot of coupling length versus separation gap between two LC:PDMS square waveguides with a side of 2 μm.

exchange of optical power between the two waveguides occurs at a distance which is as short as 500 μm. Figure 4 shows that a shorter coupling length of 240 μm can be obtained as expected by reducing the waveguide gap to 0.75 μm.

The simulations for a minimum gap separation of just 0.5 μm at limit of a technologically feasible separation distance between the two waveguides are shown in Fig. 5. In this case a minimum coupling length of 120 μm is obtained.

The results reported in Figs. 3, 4 and 5 obtained for TE polarization input light are summarized in Fig. 6, where the plot of the coupling lengths versus the coupler gap is reported. As expected the coupling length increases as the gap increases, although remaining below 500 μm, which implies that very compact directional couplers can be made. Similar results are obtained for TM input polarization as expected because the symmetry of the waveguide.

Conclusions

We have performed simulations of a directional coupler made of LC:PDMS microchannels with a squared section with a 2 μm side length and homeotropic boundary conditions of the LC at each wall inside the PDMS channels. Our simulations are based on the combination of Oseen-Frank free energy minimization of the NLC inside the PDMS channels and the BPM algorithm. The free energy minimization provides the molecular director orientation distribution which determines the refractive index profile. The directional coupler design implemented in the BPM with the calculated NLC refractive index profile allows to study the evolution of light in the directional coupler versus the separation gap between the two waveguides. A coupling length for the maximum power transfer from one waveguide to another can be reduced to 120 μm for a gap of 0.5 μm, which allows to make very compact integrated optical devices.

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