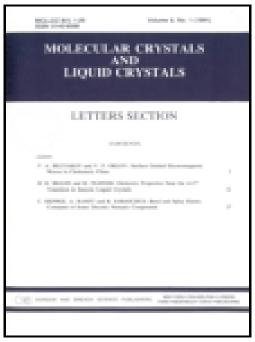


Taylor & Francis
Taylor & Francis Group

Molecular Crystals and Liquid Crystals

ISSN: 1542-1406 (Print) 1563-5287 (Online) Journal homepage: http://www.tandfonline.com/loi/gmcl20

Fabrication and Characterization of Liquid Crystal Waveguides in PDMS Channels for Optofluidic Applications

Rita Asquini, Luca Martini & Antonio d'Alessandro

Mol. Cryst. Liq. Cryst., Vol. 614: pp. 11–19, 2015

ISSN: 1542-1406 print/1563-5287 online
DOI: 10.1080/15421406.2015.1049891

Fabrication and Characterization of Liquid Crystal Waveguides in PDMS Channels for Optofluidic Applications

RITA ASQUINI,* LUCA MARTINI,
AND ANTONIO D'ALESSANDRO

Department of Information Engineering, Electronics and Telecommunications,
Sapienza University of Rome, Rome, Italy

We present our recent experimental results on the fabrication and the characterization of PDMS rectangular channel waveguides infiltrated with a nematic liquid crystal. Optical characterization of waveguide structures with three different widths recently implemented are reported. The particular molecular alignment inside PDMS waveguide allows polarization independent propagation despite liquid crystal anisotropy. Soft material technology based on PDMS used to fabricate liquid crystal channel waveguides is low cost and easy to implement, allowing to obtain any geometry.

Keywords liquid crystals; optofluidic; all-optical devices; PDMS

1. Introduction

The integration on the same chip of microfluidic channels and optical components allows to obtain an optofluidic system with superior functionalities such as reconfigurability, higher sensitivity and better performance [1–4]. Liquid crystals (LC) and LC-composites can be successfully used in the fabrication of photonic devices [5–8] to be employed in several applications including sensors, optical communications and imaging systems. Components in guided-wave microstructures operating at low optical and electrical powers can be engineered and produced exploiting their excellent electro-optic, thermo-optic and nonlinear optical responses [9]. We have investigated different technological processes to make liquid crystal photonic devices based on silica on silicon [10–14] and glass [15–20] in order to obtain new photonic components for optofluidic circuits [21].

By exploiting the optical properties of LC it is possible to add an additional degree of freedom in the fabrication of optofluidic devices.

In this paper we present our recent results on light propagation in polydimethylsiloxane (PDMS) channels with nematic LC infiltrated core (LC:PDMS waveguides). Rectangular waveguide structures with three different widths were recently fabricated and tested. The

*Address correspondence to Rita Asquini, Department of Information Engineering, Electronics and Telecommunications, Sapienza University of Rome, Via Eudossiana, 18-00184 Rome, Italy. E-mail: rita.asquini@uniroma.it

Color versions of one or more of the figures in the article can be found online at www.tandfonline.com/gmcl.

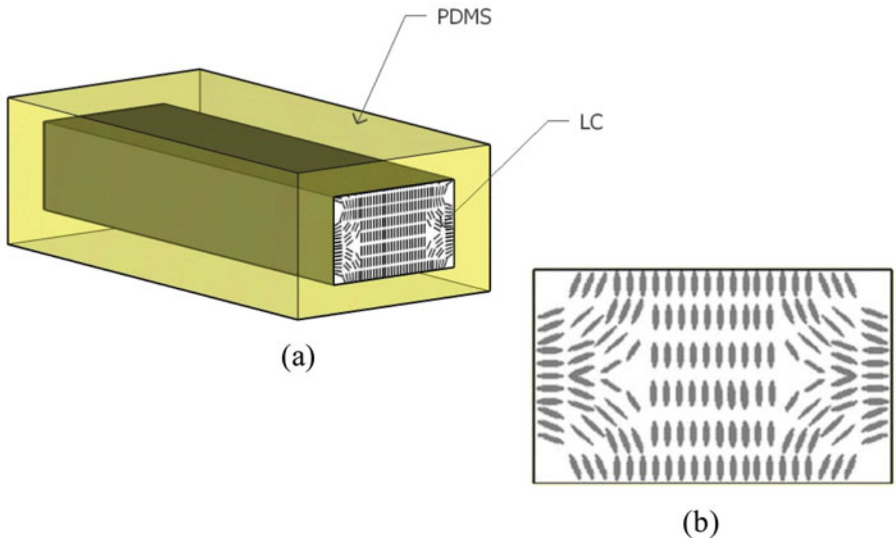


Figure 1. Sketch of a polydimethylsiloxane (PDMS) channel infiltrated with LC core (LC:PDMS waveguide) (a) and schematic of a cross section showing LC homeotropical molecular orientation (b).

technological steps to make LC:PDMS waveguides are reported in details. Modelling and experimental results demonstrate polarization independent light transmission.

2. Modelling and Liquid Crystal Alignment

The structure of a LC:PDMS waveguide is reported in Fig. 1(a). It consists of a rectangular PDMS channel filled with a nematic LC (NLC). Because PDMS surface is hydrophobic respect to the NLC, LC molecules are homeotropically oriented on the borders of the channel, i.e. are perpendicular to the PDMS channel walls, as sketched in Fig. 1(b).

A preliminary modelling was carried out at the wavelength of 1550 nm through a finite element method by minimizing the total free energy to obtain the orientation of the LC molecular director and the index profile inside the channel [11, 22]. The refractive index profile of the LC:PDMS waveguide core was evaluated for a channel 8 μm width and 5 μm height, filled with the NLC E7. Refractive indices used in the modelling were 1.5 and 1.689 for the LC ordinary and extraordinary index, respectively, and 1.3997 for the PDMS refractive index. Simulations indicate that total transmission is equivalent both for TE and TM polarizations.

3. Fabrication Process of Liquid Crystal PDMS Waveguides

To study the optical properties of LC:PDMS waveguides, we designed and made 3 sets of waveguides whose widths were 8, 10 and 15 μm, respectively. Each set consisted in 5 micro-channels, with a length of 9 mm. The fabrication process was based on casting and molding techniques. The mold to create micro-channels was obtained through soft photolitography with SU-8 2005 negative photoresist (from MicroChem), while for the fabrication of the entire device, PDMS (Sylgard 184 Dow Corning) was used. The whole production process was optimized by us to achieve our purpose and is described in the following.

3.1 Mold Preparation

The sets of waveguide channels were designed by using a computer drawing tool and transferred on a chrome mask by electron-beam lithography. The mask was used in contact photolithography process to yield a master composed of a positive relief of photoresist SU-8 2005 on a 2.5 × 2.5 cm silicon crystalline wafer (Fig. 2 (a)). The main reason for the choice of the mold substrate is based on the superior adhesion strength of silicon with respect to glass (38 Mpa vs 35 Mpa) granted by SU-8 2005. Prior photolithography, the native oxide layer of the wafer was removed by immersion in a 2% HF solution for approximately 1 minute. To obtain the required 5 μm thickness structures, the SU-8, dispensed directly on the wafer, was first processed with optimized spin coating program (first ramp 500 rpm for 5 seconds with acceleration of 500 rpm/s, second ramp 3000 rpm for 30 seconds still with 500 rpm/s acceleration), and after soft baked on level hotplates with thermal control (1 minute at 65°C and 2 minutes at 95°C). UV illumination at 360 nm wavelength was used in the contact photolithography process and best results were obtained with an exposure energy of 250 mJ/cm^2. A post exposure bake process was performed using again the hotplates (1 minute at 65°C and 1 minute at 95°C). After cooling, the mold was immersed in the SU-8 developer, agitated for 1 minute to remove the SU-8 resist in the areas not exposed to UV light and finally cleaned with isopropyl alcohol.

3.2 Fabrication of the PDMS Channels and LC Filling

The liquid PDMS was obtained in a non-cross-linked form under the trade name SYLGARD 184 (Dow Corning), as a two-part resin and cross linker mixed at room temperature in a 10:1 ratio by weight. Such obtained liquid was used to shape three PDMS sets of channels to be filled with the NLC by using proper reservoirs. The waveguide fabrication was achieved by pouring the PDMS directly on the SU-8 mold, which was previously placed in a holder consisting in a 2.5 × 2.5 cm box, allowing from 3 to 4 mm thickness for the PDMS (Fig. 2(b)). A similar operation was necessary to create the reservoirs and in this case PDMS was poured on a cleaned silicon substrate, laid on the base of a holder box, whose scope was to provide a smooth surface for PDMS which could be easily removed. A specific mold was placed in the PDMS to be shaped as a tank. A PDMS film was obtained by pouring the liquid PDMS on a glass surface carefully cleaned and then spinned by using the first ramp at 500 rpm for 10 seconds with acceleration of 500 rpm/s, the second ramp at 2000 rpm for 30 seconds again with a 500 rpm/s acceleration. In order to avoid air entrapment in the PDMS channels, the prepared samples were placed under vacuum for 30 minutes. The samples were baked in oven at 80°C, taking care to warm separately each part before assembling and subsequently casting them together while completing the baking. In detail we heated together the different PDMS parts for approximately 15 minutes, starting with the two holders containing the waveguides and then the reservoirs, and placing the PDMS film in the oven after 8 minutes, since the thickness of the latter component needs a shorter baking time. The overall baking time of the parts was calibrated in order to keep the PDMS sufficiently stiff to avoid deformations during the final device preparation but at the same time fairly sticky to allow the parts to be removed from the holders and to be assembled. The micro-channel structure was then simply peeled from the SU-8 mold (Fig. 2 (c)), and the exceeding PDMS which didn't fit the SU-8 pattern was sharply cut away using

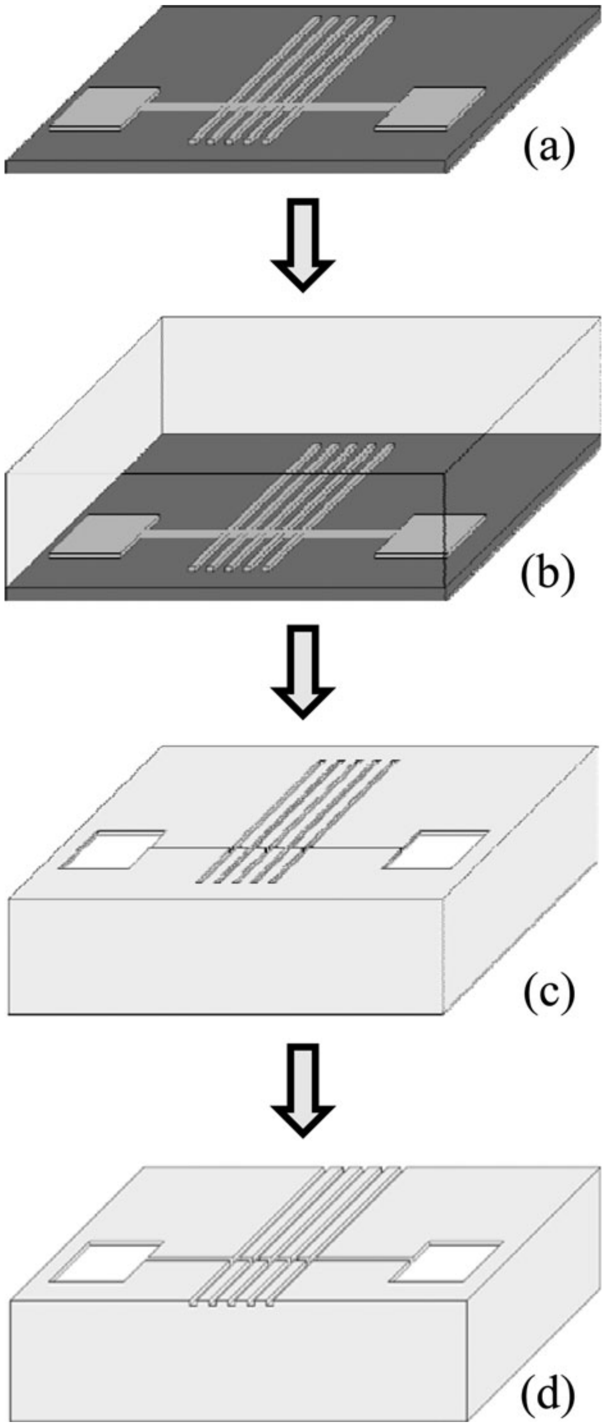


Figure 2. Fabrication process of LC:PDMS waveguides: (a) SU-8 patterned mold (light gray) on silicon substrate (dark gray); (b) PDMS is poured on the mold to duplicate channel network; (c) the mold is peeled from the PDMS replica; (d) edge of the PDMS replica are sharp cut and channels are opened.

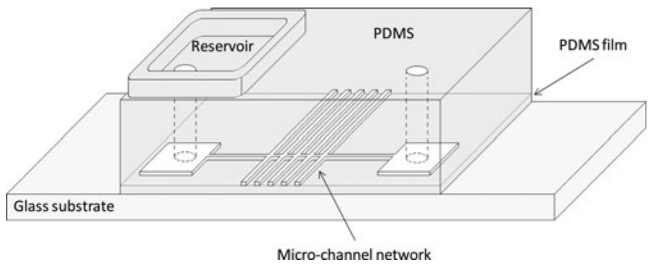


Figure 3. Assembled device; for picture clarity only a simplified network of 5 waveguides is represented.

a razor blade, bringing the PDMS walls to the end of the micro-channels (Fig. 2(d)). The three parts were then assembled together (Fig. 3) and baking was completed by baking the final samples in the oven at 80°C for 60 minutes. After casting the three parts in one single sample, the fabrication process was ended by drilling a hole to connect the reservoir to the the micro-channels sets.

The micro-channels were filled by capillarity with the NLC E7 in its isotropic phase at 80°C in a vacuum oven and then cooled down at room temperature. No alignment layer was needed to obtain molecular orientation, due to the LC and PDMS surfaces hydrophobic interaction.

Figure 4 depicts some of the main steps of the fabrication process which were carried out.

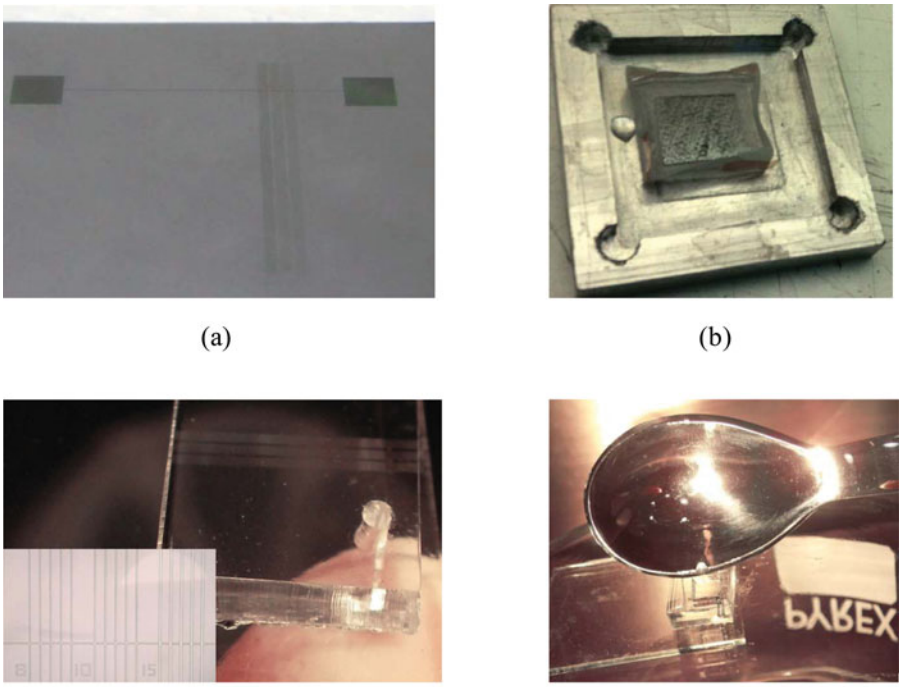
4. LC:PDMS Waveguide Characterization

In Fig. 5(a) the picture of one sample with some filled waveguides is presented, while Fig. 5(b) shows the array of 5 filled micro-channels observed under a polarized microscope between crossed polarizers. Because of the homeotropic alignment between PDMS surface and LC molecules, an optical delay on the edge makes the micro-channels bright along the edges and dark in the middle where the molecules are aligned perpendicularly to the horizontal plane.

A preliminary propagation test using an helium-neon laser at 632.8 nm on the LC:PDMS channel made (Fig. 6(a)) was performed. The red laser beam propagating through the waveguide is reported in the picture of Fig. 6(b) where in the insert there is a polarized microscope image between crossed polarizers of three filled channels.

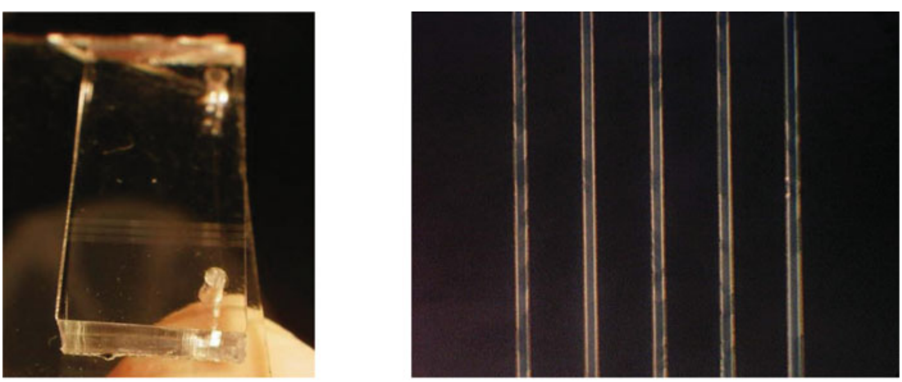
LC:PDMS waveguides characterization was carried out at the infrared wavelength of 1550 nm.

The characterization set up included a fiber-pigtailed solid state DFB laser source at 1550 nm connected to a three retarder plate polarization controller (Fig. 7). The latter was used to calibrate and to control light polarization at the waveguide input. Furthermore the set-up included two single-mode fibers whose bare ends were butt-coupled to the input and output facets respectively of the LC:PDMS waveguides, and a power meter, whose photodetector was equipped with an FC connector, was used to receive the output signal from the output optical fiber (Fig. 7). Fiber to waveguide butt-coupling was optimized by using nano-positioners with a piezoelectric drive. Using a polarization analyzer after the input fiber and before the sample, calibration of the input linear polarization was achieved by regulating the orientation of the three plates of the polarization controller. Light intensity transmitted in the micro-channel was measured by using the power meter.



(a) (b) (c) (d)

Figure 4. Step fabrication of PDMS waveguide: (a) Mold fabrication: the substrate used is silicon wafer; geometries are made through photolitografic process of SU-8 2005. (b) Channels fabrication: liquid PDMS is poured on the mold and baked in oven at 80°C for 15 min, along with a glass on which there is a PDMS film of 50 μm. (c) Device assembly: PDMS with channels and a glass slide with a PDMS film are sticked together and baked in oven at 80°C for 1 hour. (d) Liquid crystal filling: channels filling is made in oven under vacuum conditions at 80°C, at which LC is in isotropic phase.



(a) (b)

Figure 5. A produced prototype with sets of E7 nematic LC straight waveguides (a) and a polarizing microscope image of LC homeotropic alignment in PDMS channels (b).

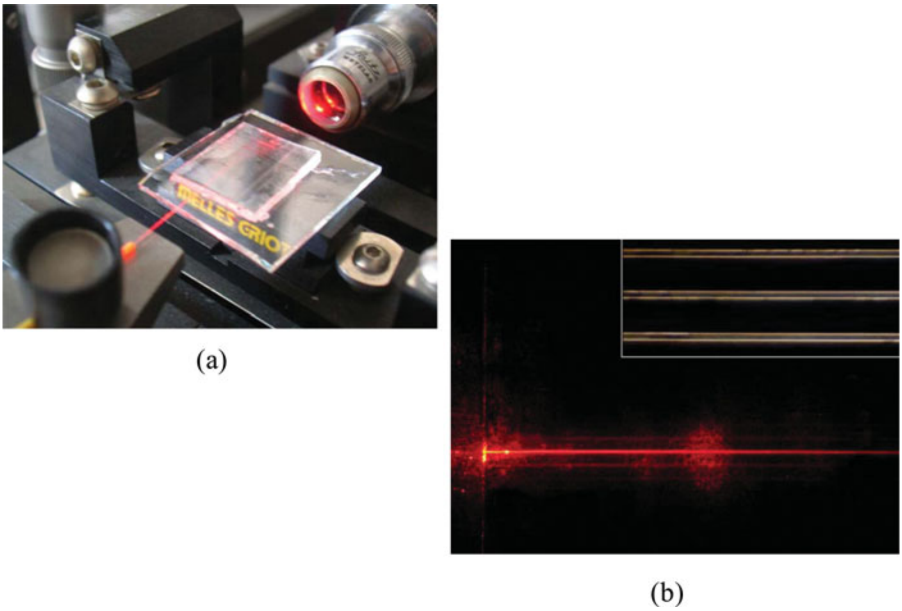


Figure 6. Propagation test with 632.8 nm wavelength: (a) picture of a LC:PDMS prototype during characterization; (b) laser beam propagating through a waveguide and three filled channels taken with a polarized microscope between crossed polarizers (in the inset).

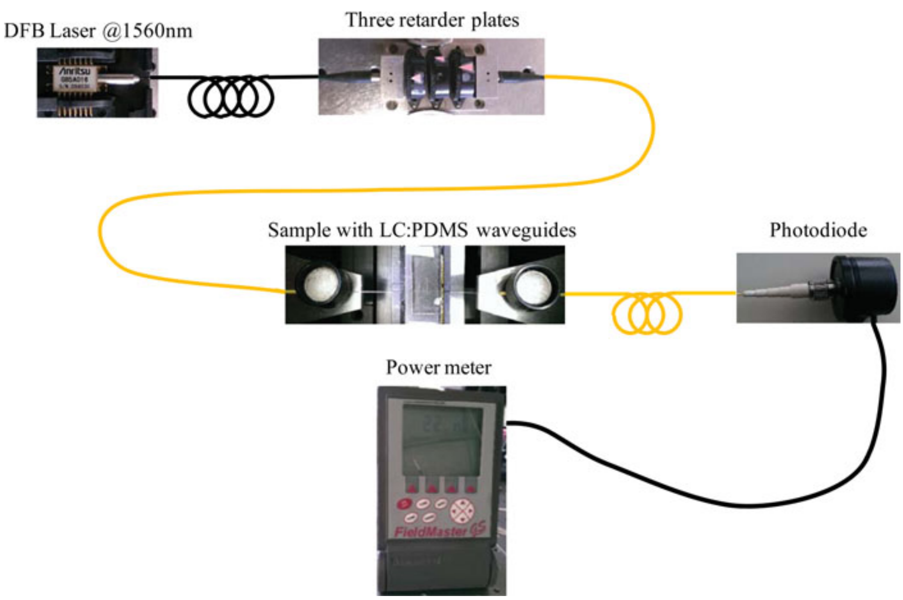


Figure 7. Experimental set-up used for optical characterization of the LC:PDMS waveguides.

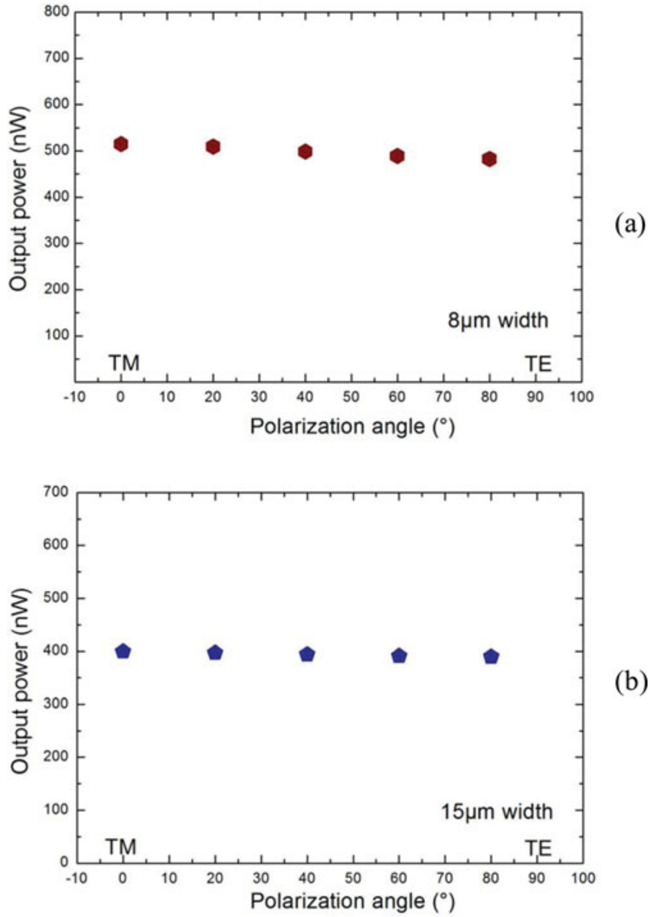


Figure 8. Measured light transmission at 1550 nm versus polarization in LC:PDMS 9 mm long waveguides for 8 μm (a) and 15 μm (b) width. The plots show that a polarization independent light transmission was achieved, despite the typical LC optical anisotropy.

Output power from the LC:PDMS waveguides was measured for different light polarizations at the waveguide input from 0° (TM input light) to 90° (TE input light). Fig. 8 shows that a polarization independent light transmission on a 9 mm length waveguides of 8 μm (Fig. 8(a)) and 15 μm (Fig. 8(b)) width was achieved, despite the typical LC optical anisotropy. A transmission variation of only 0.3 dB was observed due to the LC molecules orientation.

On our sample the propagation losses were estimated about 8 dB/cm. The lack of neat input and output faces were responsible of such high losses. The channels were left open after LC filling, producing scattering inside the waveguides for at least 2 mm on each side due to the irregular orientation of the LC molecules. A significant loss reduction is expected by using PDMS input and output short coupling waveguides [23].

5. Conclusions

A novel technology process has been assessed to fabricate LC core waveguides in PDMS channels. We found that light transmission is polarization insensitive. Moreover no optical retardation is induced during propagation, therefore light polarization is preserved along the waveguide. These features make the proposed LC waveguide structure an interesting basic building block for low cost photonic devices for optical interconnections or for integration with microfluidic circuits in lab on chip and sensing applications.

References

[1] Fan, X., & White, I.M. (2011). *Nature Photonics*, *5*, 591.

[2] Schmidt, H., & Hawkins, A. R. (2011). *Nature Photon.*, *5*, 598.

[3] Monat, C., Domachuk, P., & Eggleton, B. J. (2007). *Nature Photon.*, *1*, 106.

[4] Psaltis, D., Quake, S. R., & Yang, C. H. (2006). *Nature*, *442*, 381.

[5] d'Alessandro A., & Asquini, R. (2003). *Mol. Cryst. Liq. Cryst.*, *398*, 207.

[6] d'Alessandro, A., Asquini, R., Bellini, R. P., Donisi, D., & Beccherelli, R. (2004). *Liquid Crystals VIII: Proc. of SPIE, 7775*, SPIE: Bellingham, WA, 123.

[7] Beeckman, J., Neyts, K., & Vanbrabant P. J. M. (2011). *Opt. Eng.*, *50*, 081202.

[8] Asquini, R., Gilardi, G., d'Alessandro A., & Assanto, G. (2011). *Opt. Eng.*, *50*, 071108.

[9] Asquini, R., & d'Alessandro, A. (2013). *Mol. Cryst. Liq. Cryst.*, *572*, 13.

[10] d'Alessandro, A., Asquini, R., Trotta, M., Gilardi, G., Beccherelli, R., & Khoo, I. C. (2010). *Appl. Phys. Lett.*, *97*, 093302.

[11] d'Alessandro, A., Bellini, B., Donisi, D., Beccherelli, R., & Asquini, R. (2006). *IEEE Journal of Quantum Electronics*, *42*, 1084.

[12] Asquini, R., Donisi, D., Trotta, M., d'Alessandro, A., Bellini, B., Gilardi, G., & Beccherelli, R. (2009). *Mol. Cryst. Liq. Cryst.*, *500*, 23.

[13] Donisi, D., Bellini, B., Beccherelli, R., Asquini, R., Gilardi, G., Trotta, M., & d'Alessandro, A. (2010). *IEEE Journal of Quantum Electronics*, *46*, 762.

[14] Trotta, M., Asquini, R., d'Alessandro, A., & Beccherelli, R. (2011). *Mol. Cryst. Liq. Cryst.*, *549*, 100.

[15] Asquini, R., & d'Alessandro, A., (2002). *Mol. Cryst. Liq. Cryst.*, *375*, 243.

[16] Fratalocchi, A., Asquini R., & Assanto, G. (2005). *Opt. Express*, *13*, 32.

[17] Asquini, R., Fratalocchi, A., d'Alessandro, A., & G. Assanto (2005). *Applied Optics*, *44*, 4136.

[18] d'Alessandro, A., Donisi, D., De Sio, L., Beccherelli, R., Asquini, R., Caputo, R., & Umeton, C. (2008). *Opt. Express*, *16*, 9254.

[19] Donisi, D., Asquini, R., d'Alessandro, A., & Assanto, G. (2009). *Opt. Express*, *17*, 5251.

[20] Gilardi, G., Asquini, R., d'Alessandro A., & Assanto, G. (2010). *Opt. Express*, *18*, 11524.

[21] Zografopoulos, D. C., Asquini, R., Kriezis, E. E., d'Alessandro, A., & Beccherelli, R. (2012). *Lab Chip*, *12*, 3598.

[22] Asquini, R., Martini, L., Gilardi, G., Beccherelli, R., & d'Alessandro, A. (2014). IEEE Photonics Conference (IPC), San Diego, CA, USA, 12–16 Oct. 2014, 36.

[23] Bellini, B., d'Alessandro, A., & Beccherelli, R. (2007). *Optical Materials*, *29*, 1019.