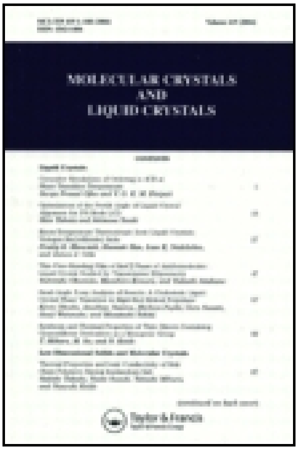

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Realization of a Liquid Crystal Electrically Controlled Optical Waveguide on Micromachined Silicon

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Realization of a Liquid Crystal Electrically Controlled Optical Waveguide on Micromachined Silicon

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In this paper we report the major fabrication steps and preliminary electro-optical characterization of a novel integrated liquid crystal optical waveguide on silicon substrate. The optical waveguide is made of a SiO_2/Si V-groove with a triangular cross-section filled with nematic liquid crystal E7. The optical propagation in the channel waveguide is controlled by an external voltage which induces a refractive index variation by means of molecular director reorientation. For TM polarized light at a wavelength of 1.55 μm, a threshold voltage of only about 2 V and an extinction ratio higher than 35 dB were measured with 6.5 V applied.

Keywords: electro-optic effect; liquid crystals; optical waveguides; silicon photonics

INTRODUCTION

Silicon photonics has been gaining great attention demonstrating that silicon is an excellent material to build high performing integrated optic devices [1,2]. A common silicon platform can be used to integrate electronics and photonics on a single chip, mainly because silicon is transparent to the optical communication wavelengths of 1.3 μm and 1.5 μm and the mature silicon VLSI processing can be exploited. Another important advantage of silicon is that its native oxide SiO_2 can be exploited both as an electrical insulator and as a low-loss optical buffer layer. In addition technological breakthroughs have recently led to light emission on a silicon substrate [3,4]. The possibility to realize low cost

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photonics systems on chip with increased bandwidth for optical interconnects seems to be just around the corner.

Liquid crystals (LC) have been extensively studied and engineered for photonics applications because of their huge electro-optical effect and their transparency especially in the NIR [5]. The possibility of encapsulating LC in micromachined silicon channels thus opens the way to make active integrated optic devices operating at low driving power, because of the efficient LC electro-optic effect. This approach can be an interesting alternative to more power consuming active photonic devices on silicon, like those currently adopted based on thermo-optic effect or current injection mechanisms. In previous papers we have demonstrated the possibility to fabricate nematic liquid crystal (NLC) channel waveguides in oxidised silicon grooves [6]. In the previous passive devices, TM-like propagation was supported by a 10 μm wide waveguide with E7 NLC oriented along the propagation direction showing the TE-like polarization suppressed by more than 25 dB.

In this paper we report the fabrication and preliminary characterization of a novel integrated LC active device working as optical gate. The device is composed by a silicon V-groove filled with E7 LC, acting as voltage-controlled channel waveguide. Optical propagation can be enabled or inhibited according to the applied voltage, by exploiting the LC electro-optic effect and modifying the refractive index distribution of the waveguide core.

DEVICE STRUCTURE AND FABRICATION

A sketch of the device structure is shown in Figure 1 representing the LC waveguide cross-section (Fig. 1a) and the longitudinal section along the propagation direction (Fig. 1b). The waveguide has a triangular cross-section, typical of silicon micromachining. The silicon groove was oxidized, yielding a SiO_2 cladding layer. It was filled with an E7 NLC core and covered by an ITO (indium tin oxide) coated top glass substrate. In this device silicon is used as counter-electrode, allowing a driving electric field between the substrate and the ITO layer of the glass cover. The details of the fabrication are given in the following.

The cover glass is an ITO-coated borosilicate glass D263 provided by Diamond Coatings with a thickness of 500 μm. The ITO is about 100 nm thick and has a resistivity of 80 Ω/square. Nylon6 (0.5% wt./vol in trichloroethanol) was spin-deposited onto the cover glass. The spinning parameters were: 4000 rpm for 40 s, resulting in a Nylon6 layer about 50 nm-thick. The glass plate was then baked

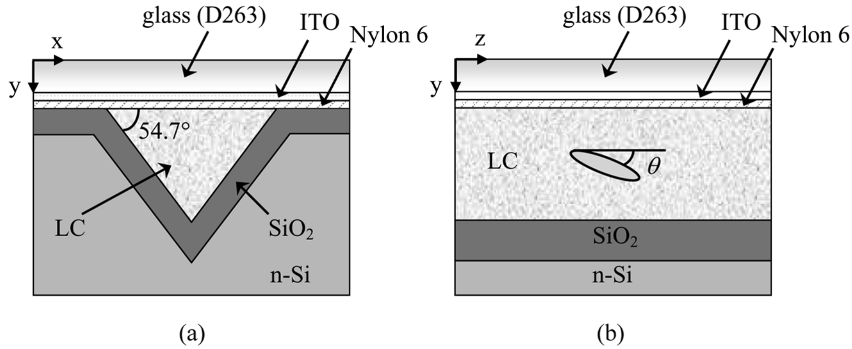

FIGURE 1 Structure of a LC channel waveguide on silicon with a V-groove cross section.

at 90°C for 30 min, softly rubbed using a velvet cloth and hard-baked at 160°C for 4 hours in air. Such procedure promotes planar homogeneous alignment of the E7.

The groove was obtained starting from a (100) silicon wafer of standard thickness 380 μm. A thin silicon dioxide layer of about 300 nm was grown by dry thermal oxidation of the wafer and was used as a mask for the following Si-etching. A post-exposure cured photoresist was used to pattern the grooves obtained by UV exposure through a lithographic mask. Then silica was etched in an aqueous solution of buffered HF (BHF), and after resist removal silicon was finally etched in a KOH solution at 80°C. The groove cross section obtained with the previous steps has a triangular shape due to the preferential etching along the (111) silicon crystallographic orientation. The triangular cross section of the V-groove is characterized by a width d and depth p where:

$$p = d\frac{\tan \alpha}{2} \cong d\frac{\sqrt{2}}{2}$$

being $\alpha = 54.7^\circ$ the angle to the base with respect to the wafer plane (111). While the width d of the groove depends on the mask aperture in the photolithographic process, the waveguide maximum depth p is precisely defined by silicon etching. After Si-etching, the substrate was cleaned by removing the photoresist.

The following step consisted of the thermal growth of a silicon dioxide (SiO_2) cladding, up to a thickness of 1.5 μm along the [1 0 0] direction and 2 μm along [1 1 1]. Silicon dioxide grows by 44% in the silicon wafer and the remaining 56% in air above the silicon level.

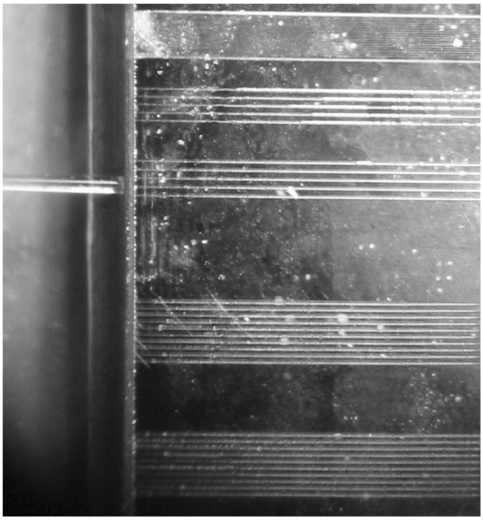

FIGURE 2 Snapshot of LC optical waveguides coupled with a fiber.

Then the silicon wafer and the glass cover were assembled, taking care of aligning the rubbing direction with the groove axis. Such an alignment promotes a LC molecular orientation along the groove (i.e., along the optical propagation). The glass cover was glued to silicon with the NOA 61 UV-curable adhesive and the cell was filled according to the procedure described in [7].

The refractive indices at $\lambda = 1550$ nm relevant for the optical structure are 1.516 for the glass cover, 1.45 for SiO_2, an extraordinary refractive index $n_e = 1.69$ and an ordinary refractive $n_o = 1.50$ for E7.

A picture of LC optical channel waveguides is reported in Figure 2 where it is possible to see different sets of LC channel waveguides ranging from 4 to 15 μm. Moreover, on the left-hand side of Figure 2, it is possible to notice the input fiber butt-coupled to a 15 μm channel waveguide for optical characterization.

WORKING PRINCIPLE

In this device the transmission of optical power from the waveguide input to the output along z is controlled by an applied voltage, as schematically shown in Figure 3. The applied voltage permits to control the LC tilt angle and consequently the average refractive index of the LC waveguide core. At $V = 0$, the LC molecules lie in the rest position, therefore the transverse refractive index tensor has all

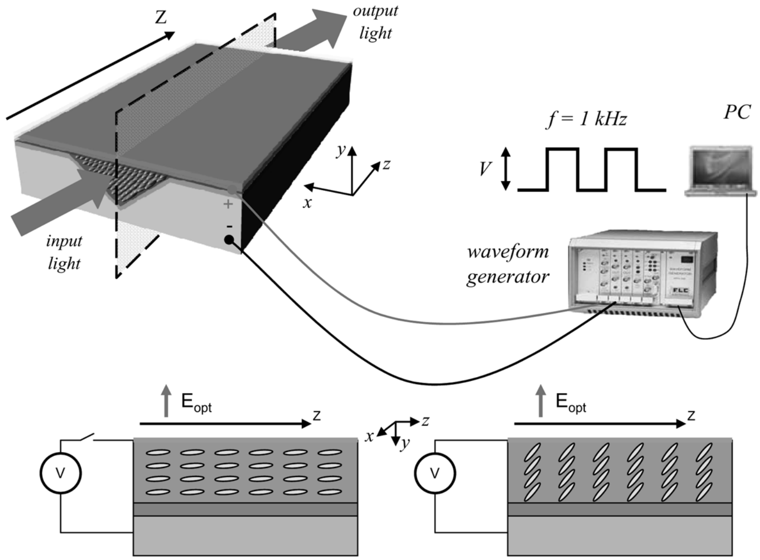

FIGURE 3 Device working principle.

components equal to the ordinary refractive index n_o, which is lower than the cover index in our case. In this case light coupling to cover radiating modes will result. At saturation voltage, all the molecules are ideally along the vertical out-of-plane direction. The corresponding refractive index seen by a TM polarization is the extraordinary index n_e, which is larger than the cover index. In this case a light beam confined in the core will result. Therefore a threshold voltage is expected below which there is no guided mode. In this way it is possible to control the optical confinement enabling or not the light propagation and the device acts as a voltage-controlled optical gate. Furthermore we expect that applying an external voltage, the refractive index in the LC waveguide core can be increased, thus enabling guided propagation for single mode to multimode propagation.

DEVICE CHARACTERIZATION

Figure 4 shows the optical set-up used to investigate the optical propagation through the LC waveguides and in particular to quantify the threshold voltage below which there is no guided propagation. Input and output facets of the waveguides were sawn in order to couple light by butt-coupling technique. The laser source is an external-cavity tuneable laser emitting wavelengths ranging from 1510 to 1590 nm.

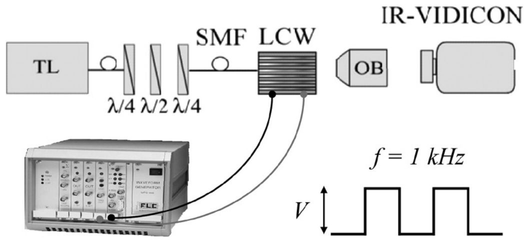

FIGURE 4 Optical measurement set-up to characterize the optical gate.

A pigtailed polarization controller was connected to a single mode optical fiber, terminated with a cleaved facet to couple light to the LC optical channel waveguides.

The polarization controller consists in a sequence of three miniature waveplates $\lambda/4$-$\lambda/2$-$\lambda/4$ placed between two aligned fiber collimators. Each waveplate is mounted on a graduated goniometer, which permits to set the polarization of the input light without power variation. In particular the state of polarization of light is calibrated at the output of the cleaved input fiber. The optical waveguide output is collected by a 10X microscope objective and focussed on an IR vidicon camera for inspection.

The characterization presented in this paper is related to a 15 μm wide LC channel waveguide but similar behaviour has been found for the waveguides of different widths.

A square wave voltage with a frequency of 1 kHz it is used to drive the LC and by continuously varying its amplitude we measured a threshold voltage of about 2 V.

The optical field image was acquired with a frame grabber and then processed. Figure 5 reports the image of the output near-field for 0 V and for 6.5 V. It can be observed a good optical confinement when a voltage of 6.5 V is applied. In a zoom image of the output spot at 6.5 V it is possible to recognize the triangular shape of the cross section of the waveguide. Moreover by enlarging the image of the output beam and analyzing the optical field profile it is possible to see different side lobes, which indicate that propagation is multimode.

The intensity profile of the light spot is reported in Figure 6. The spot profile was obtained after converting the snapshot from the IR camera in numerical format. Furthermore we measured the extinction ratio defined as the ratio between the output optical power transmitted at 6.5 V and the power transmitted when no voltage is applied and we found that it is over 35 dB, which is comparable to the state of the art optical switches.

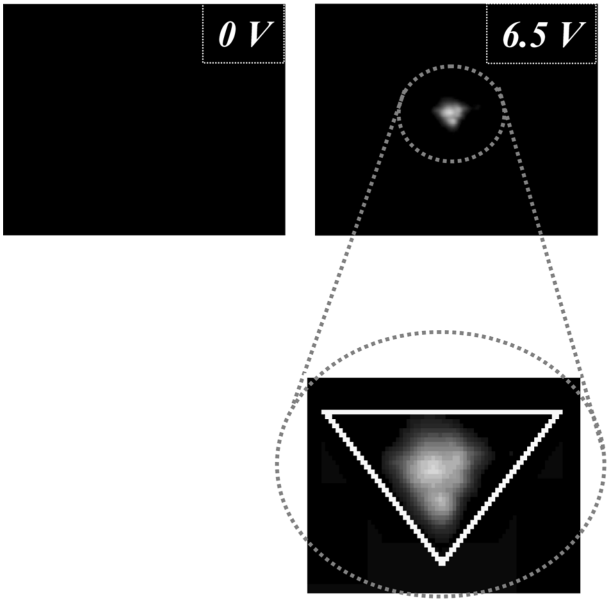

FIGURE 5 Output near field captured by the IR-vidicon camera for 0 V and 6.5 V with the zoom showing multimode propagation.

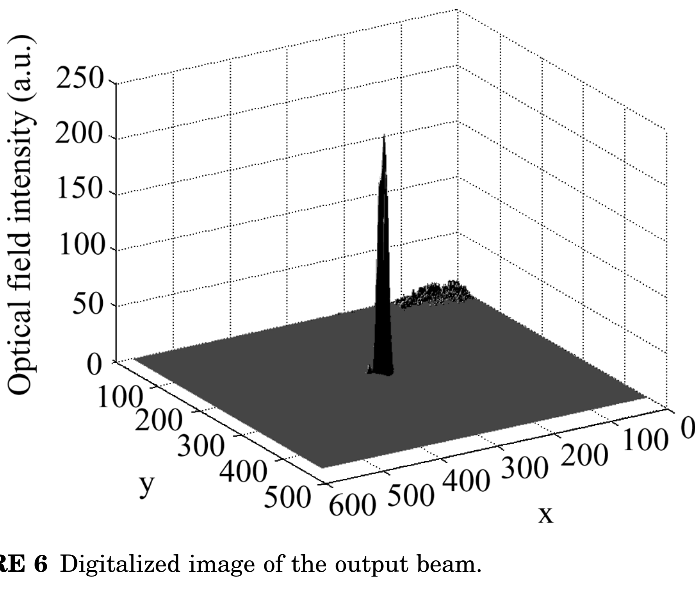

FIGURE 6 Digitalized image of the output beam.

CONCLUSIONS

A novel, electrically controlled liquid crystal optical waveguide on silicon substrate has been experimentally demonstrated. The device consists of a SiO_2/Si V-groove filled with nematic liquid crystal E7. Light propagation occurs along the LC channel longitudinal axis and can be controlled by the application of an external voltage. We have demonstrated that the optical waveguide operates in an off-state mode for zero voltage and in an on-state mode for voltages larger than a threshold voltage. At a wavelength of 1.55 μm, for TM light polarization, the device shows a threshold voltage of only about 2 V and an extinction ratio between the two operation modes higher than 35 dB for 6.5 V applied voltage.

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