SILICON-ON-INSULATOR OPTICAL WAVEGUIDES WITH LIQUID CRYSTAL CLADDING FOR SWITCHING AND TUNING

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Abstract *We demonstrate refractive index modulation in SOI waveguides with a liquid crystal top cladding. The effective refractive index of the waveguide can be controlled by applying a voltage over the liquid crystal.*

Introduction

The tendency to shrink the size of photonic components has prompted the use of high refractive index contrasts in photonic waveguides. High-contrast material systems like silicon-on-insulator (SOI) allow for waveguides with smaller cores and shorter bends. However, in order to implement active functions we need an electro-optic effect much stronger than that of semiconductors or carrier-induced effects. Alternatively, because in these narrow, high-contrast waveguides a significant fraction of the light is carried in the cladding, it is possible to tune the waveguide's effective index through the cladding, by replacing it with a liquid crystal. When this is done on a very frequency-selective component, like a Bragg grating [1] or an interferometer, tuneable wavelength-selective elements can be made.

Liquid crystals (LC) have a strong anisotropy with an extraordinary refractive index along the molecule axis that is much higher than the ordinary refractive index. They also tend to align with an external electric field. We have applied a top cladding of liquid crystal on an SOI waveguide and observed changes in effective index when a voltage was applied over the LC.

Silicon-on-insulator waveguides

Silicon-on-insulator consists of a silicon top layer, with an index of 3.45, which has a very strong contrast with the surrounding air and the silica cladding (n=1.45). In our case, the top core is 220nm thick, and the buried oxide cladding 1μm. We fabricated a number of waveguides of various widths using 248nm deep UV lithography and deep etching [2].

The effective index of these SOI waveguides is very dependent on the waveguide width. Also, for narrow waveguides (photonic wires) a larger fraction of the light will be carried outside the core. Therefore, when we surround the waveguide with LC, we expect a stronger effect for narrow waveguides.

Liquid Crystal

In a nematic liquid crystal the molecules tend to orient themselves parallel with each other, but the position of the molecules can vary freely. The orientational order of the long molecules leads to a strong anisotropy in the electrical and optical constants. We simulated the effect of the anisotropy on the effective index of SOI waveguides with different widths. As a cladding we used the nematic liquid crystal E7, with a refractive index which can vary between 1.49 and 1.69 [3]. Figure 1 shows that an effective index change of 0.15 is possible for 300nm wide photonic wires. To achieve this change we assumed that the LC reorients itself completely when a voltage is applied. However, the behaviour of LC near the surface depends strongly on the material characteristics and the geometry. By default, LC aligns itself parallel with the surface, and even with an electric field a thin boundary layer will keep this alignment.

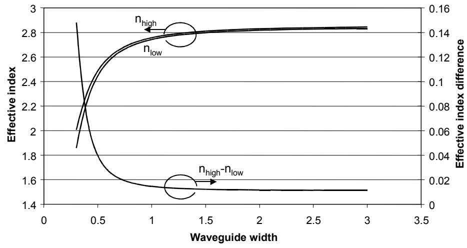

Figure 1: Simulated effective index of an SOI waveguide with a top cladding with either the ordinary or extraordinary index of E7 liquid crystal.

Figure 2 shows the orientation of an E7 liquid crystal near the edge of a 3μm wide SOI waveguide. The voltage is applied between the substrate and a top contact. While the bulk of the LC aligns to this external electric field, the boundary layers partially keep their original state. This makes the behaviour of the liquid crystal hard to model. On the top contact the alignment of the liquid crystal is controlled using a coating with a directional rubbing. However, on the substrate and the waveguide, the LC can have a different orientation, especially in structures where the sidewalls are not perfectly smooth.

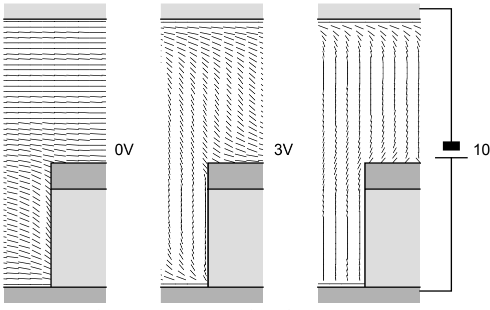

Figure 2: Orientation of LC molecules near the edge of a waveguide for different voltages.

Fabrication of the liquid crystal cell

Because a voltage needs to be applied to the liquid crystal, it needs to be enclosed between electrical contacts. The silicon substrate of the optical waveguides acts as the bottom contact. The top contact is a glass plate with an evaporated gold layer. On the gold layer a polyimide alignment layer is spun. Rubbing creates a pattern in the polyimide, to which the liquid crystal molecules align themselves. There, the liquid crystal molecules are parallel to the glass interface and orthogonal to the axis of the waveguide.

The glass plate is then attached to the SOI sample with two parallel stripes of glue. In this glue, small 1.6μm spheres are suspended. This way, the spacing between the glass plate and the optical waveguides is uniform. The glue is then cured with UV light. The cell is designed in such a way that the incoupling facets of the SOI waveguides are accessible, and the bottom side of the glass plate can be contacted.

Finally, the cell is filled with liquid crystal. The liquid crystal and the cell are first heated to 20ºC above the LC's isotropic state (63ºC). Then, the cell is inverted and a drop of LC is deposited on the glass plate near the edge of the SOI sample. The LC is then drawn in by capillary forces. The cell with the LC is slowly cooled so a single-domain state can form.

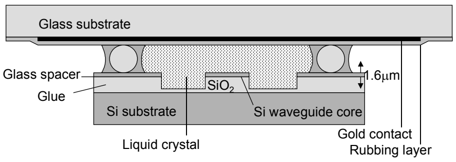

Figure 3: Liquid crystal cell with SOI waveguide.

Measurements

The samples are characterised by measuring the transmission through the waveguides. We coupled light with a wavelength around 1.55μm from a tuneable laser into the SOI waveguides with a lensed optical fibre. The transmitted light is collected on a power detector using an objective. The liquid crystal cell was driven with a voltage source.

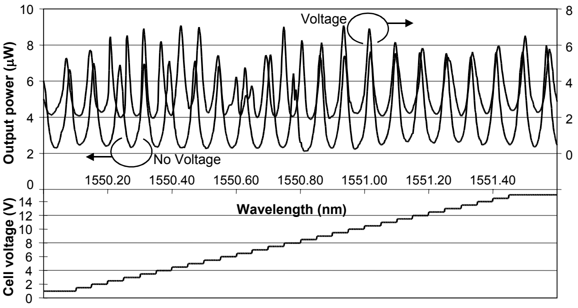

Figure 4: Transmission spectrum without voltage and with stepwise increasing voltage over the cell.

Because the cleaved facets of the SOI waveguides reflect about 35% of the light, a Fabry-Pérot cavity is formed, giving a comb-like transmission spectrum. As the position and spacing of the fringes depend on the optical cavity length, we can observe the change in effective index of the waveguide by the movement of the fringes when a voltage is applied to the cell.

Figure 4 shows the transmission spectrum of a cell modulated with a stepwise increasing voltage. The spectrum is compared to that of the unmodulated cell. During the wavelength sweep, the voltage is increased. We see additional shifts with each step.

The wavelength shift is not linear with the voltage over the cell. As shown in Figure 5, a threshold is needed to move the LC away from its rest state, while for high voltages, the crystal is fully aligned with the electric field, and the effect saturates. This is in good agreement with the theoretical models.

Knowing the length of the cavity and the area covered with LC we can deduce the change in effective index. For the saturation voltage the effective index of the 3μm wide waveguide increases with 0.002 (over the active section). This effect is still considerably smaller than the theoretical prediction in Figure 1, which illustrates that surface effects play a major role.

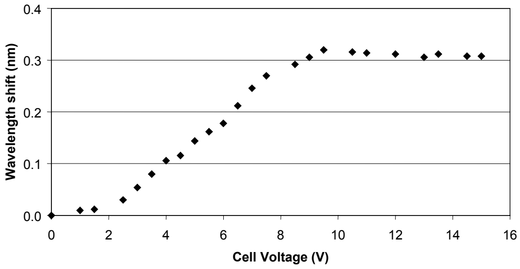

Figure 5: Wavelength shift (absolute value) of Fabry-Pérot fringes as a function of cell voltage.

Conclusions and perspectives

We have demonstrated a high-contrast silicon-on-insulator optical waveguide with liquid crystal cladding. By applying a voltage over the LC, we observed an effective index change of 0.002 for a 3μm wide waveguide. With improved modulation the prospects of this technique for switching and tuning are promising. More experiments with ring-resonators and mach-zehnder circuits are planned.

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