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Tuning SOI filter structures with liquid crystals

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Liquid crystals offer the possibility to add tuning functionality to silicon-on-insulator filter structures. When liquid crystals are used as a cladding layer on the chip, we can change the filter characteristics with an externally applied voltage. The rod-shaped molecules of the liquid crystal reorient along the fieldlines which influences the effective index of the waveguide mode. We have fabricated several tunable components (ring resonators and Mach-Zehnder interferometers) operating according to this principle. Next to the experimental results, we will present our simulations and theoretical calculations which offer an explanation of the tuning mechanism.

Introduction

As optical communication is advancing rapidly, the need grows for components that can filter a small wavelength band from a broad spectrum. Ring resonators can perform this task and are already often used in (de-)multiplexers. In reconfigurable optical networks these components need to be tunable which can be achieved with e.g. heating/cooling or carrier injection. In this paper we will study the tuning capabilities of optical filters with a liquid crystal (LC) cladding. Next to ring resonators we will also discuss our work on Mach-Zehnder interferometers (MZIs).

In the past decade, silicon-on-insulator (SOI) has become the most important material system for photonic ICs. Silicon has very low losses for light in the wavelength range used in telecommunication, the high index contrast allows for very small components and the fabrication is based on the well-known techniques used for CMOS [1]. There are also downsides to silicon for photonics. As it is a material with an indirect bandgap, it is nearly impossible to conceive efficient light sources based on silicon. However, techniques such as heterogeneous integration can get around this problem. A second issue is wavelength tuning of SOI components like optical filters. Often used methods are heating/cooling or carrier injection. Heating is a rather slow tuning method. Moreover, it is limited in tuning range which is also something carrier injection struggles with.

Nematic liquid crystals (LCs) consist typically of rod-shaped molecules sharing a preferential orientation defined by the director. Therefore its refractive index is anisotropic. This means that light travelling in different directions through the liquid crystal will see different refractive indices. When an electric field is present, the director will reorient itself along the fieldlines. This effect is very useful when the liquid crystal is applied as a cladding on waveguides. Depending on the presence and direction of an electric field the light in the waveguide will see a different refractive index in the cladding and the mode will have a different effective index. This gives us the possibility to tune the characteristics of optical filters with an externally applied electric field.

In this paper we will discuss SOI filter structures designed for TE polarised light clad with nematic LC. In the next section we will explain the fabrication of the cells. The third section will show the experimental results. In the last section we will clarify the tuning mechanism.

Cell overview

The optical filters are fabricated in a 220nm thick Si layer, which forms the top of the SOI chips. A $2\mu m$ thick layer of SiO_2 isolates the devices from the Si substrate. UV-curable glue mixed with silica spacers is used to attach a glass plate to the chip. The cell is then filled with 5CB (a commonly used nematic LC). A schematic cross section of the cells is displayed in Figure 1 (A). There are two additional layers on the glass plate. The first is a layer of ITO which can be used as an electrical contact. The second is an alignment layer (usually nylon or polyimide) which, when rubbed, forces the LC director to align parallel to the rubbing direction. On the surface of the chip there is no alignment layer and it is not well known how the director behaves on such a surface. We designed test structures to investigate this problem. They can be seen in the inset of Figure 1 (B). A waveguide is flanked by two series of Si rectangles forming a grating. The chip is clad with 5CB and a glass plate with a polyimide alignment layer is attached to it. The LC on the surface of the glass plate is aligned parallel to the direction of the waveguide. From our experience we know that 5CB aligns in a planar fashion to Si or SiO_2. Figure 1 (B) shows the image acquired with a polarisation microscope with crossed polarisers. The polariser is parallel to the preferential direction defined by the alignment layer. In the black regions, the LC director causes no change of the polarisation as it retains the same orientation from glass plate to chip surface. The bright parallel lines correspond to the rectangles next to the waveguide. The waveguide itself also appears dark. The lines are bright because the LC is twisted to align with the grating sections perpendicular to the waveguide. This is a strong indication of the ability of the director to follow the silicon structure down to nanometer scale (see also [2]). We can say that the director orientation in our cells is parallel to the direction defined by the alignment layer except on the surface of the chip where it follows the ribs of intersecting surfaces. When a voltage is applied between the ITO layer on the glass plate and the substrate the director will reorient to a vertical orientation, along the electric fieldlines.

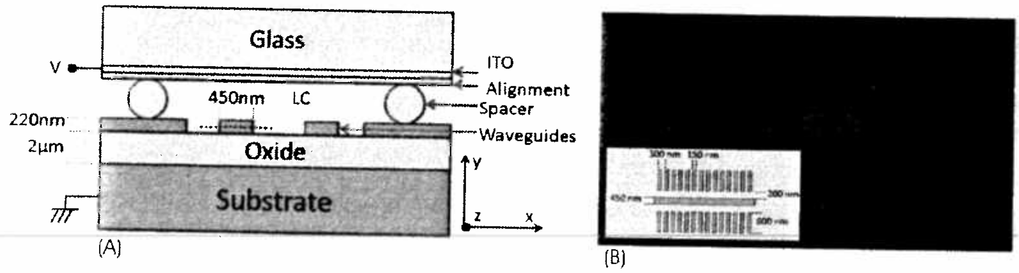

Figure 1: (A) Schematic cross section of the cell; (B) Polarisation microscope image of LC aligned to waveguide and grating - Inset shows details of the structure.

Experimental results

The optical characterisation is done by sending light vertically into the waveguides through grating couplers. The working principle of grating couplers is based on diffraction of light and their use makes it easy to align optical fibers to the nanophotonic waveguides [3]. We measure the output spectrum of different filter structures for different values of the applied voltage. In Figure 2 (A) we track the resonance wavelength of an SOI ring resonator (radius 4μm) for voltages up to 30V. We get a blueshift of about 0.6 nm, which is better than the values found in literature [4]. We see that there is a certain voltage required for the tuning to start. This is the treshold-voltage at which the elastic forces holding the molecules are overcome. At higher voltages we see a saturation effect, meaning that the molecules have turned to a completely vertical orientation. In the inset of Figure 2 (A) the output spectra for 0V and 30V can be seen. Figure 2 (B) shows the tuning of an asymmetric MZI. The minima, where the light from the two arms interferes destructively, shift about 3 nm towards the blue side of the spectrum.

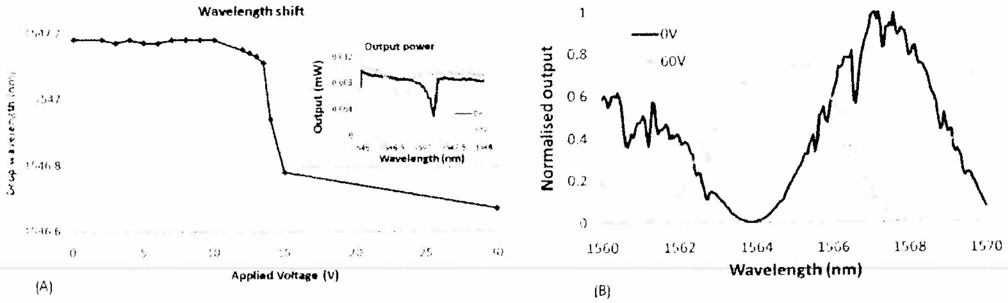

Figure 2: (A) Tuning curve of a ring resonator with LC cladding - Inset shows the output spectra; (B) Output of a MZI with LC cladding (0V and 60V).

Explanation of the tuning mechanism

As stated before, on the surface of the chip, the director of the LC will be parallel to the waveguides. When a voltage is applied it will reorient vertically. We use two simulation tools to study and verify the behaviour of these waveguides. For the calculation of the LC orientation, we use a variable order calculation [5] based on the minimisation of the Landau-de Gennes free energy functional [6]. This model is implemented in a finite-element scheme. With this tool, it is possible to model the behaviour of LC near small structures like our waveguides. We use a finite element mode solver to calculate the modes in optical waveguides with LC top cladding. This solver is based on the solution of the variational form of the curl-curl equations of the electric field [7] and is able to take into account the full anisotropy of the LC. Combining those two tools allows us to calculate the effective index of the TE mode of an SOI waveguide with a 2μm cladding of 5CB. From this we can e.g. calculate the wavelength shift in a ring resonator. A blueshift of the resonant wavelength with increasing voltage is found, in agreement with our experiment (see Figure 3 (A)). At a critical value of the applied voltage a Freedericksz transition occurs resulting in a distortion of the LC director field. This threshold effect is observed, as well as a saturation effect for higher voltages. This is in good agreement with the experimental results. We can understand the blueshift by taking a look at the individual electric field components. The field profiles along a horizontal cut through the cross section (dotted line in Figure 1 (A)) are shown in Figure 3 (B). We see that next to the x-component a considerable part of the z-component of the electric field is located in the LC cladding. The y-component is very small and we will neglect it. As the LC switches from an orientation along the z-axis to a position along the y-axis, the x-component of the electric field will not contribute to a change in n_{eff}. Theoretical calculations confirm this. The z-component will see a decreasing value of the dielectric constant and will cause a decrease in n_{eff}. This will result in a blueshift of the resonance. We note that for different values of the device thickness and the anchoring strength the magnitude of the shift and the threshold voltage change, which explains the differences between the simulations and experiments.

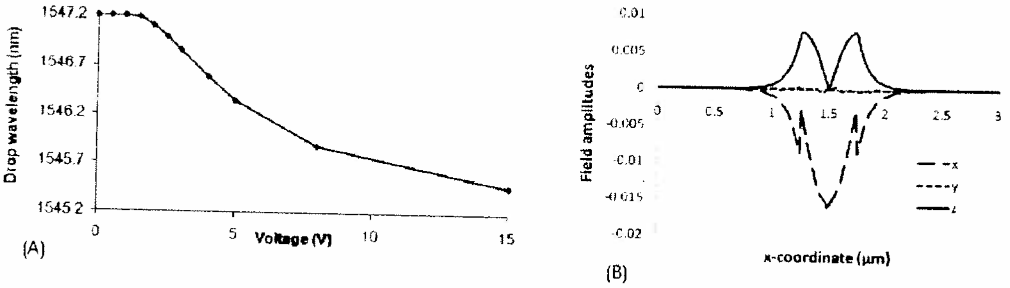

Figure 3: (A) Simulated tuning curve for a ring resonator with LC cladding; (B) Profiles of the electric field components along a horizontal cut through the waveguide.

Conclusion

We have demonstrated tuning of SOI ring resonators and Mach-Zehnder interferometers with a top cladding of liquid crystal. Moreover we have explained the tuning mechanism and verified the experimental results by means of simulations.

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