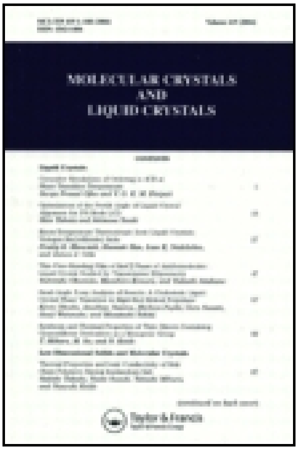

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Integrated Optics Devices Based on Liquid Crystals

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We describe the technology behind a platform for integrated optics based on liquid crystals. Design and technological issues are addressed and effective technological solutions are presented. The physical implementation of optical waveguides characterized by a practical and reproducible process based on preferential etching of crystalline silicon substrates are presented. Devices are manufactured by wet etching a Si substrates first and then by thermally growing thick SiO_2 cladding layer. A nematic liquid crystal is used as core of the waveguiding devices. Experimental results on polarizing properties and single mode propagation of infrared light are presented and discussed.

Keywords: integrated optic polarizers; optical waveguides; packaging; silicon photonics

INTRODUCTION

Thanks to its optical, electronic and mechanical properties, silicon is gaining popularity in photonics. Several reports anticipate this material will play a major role in optoelectronic integration. Developments on

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light emission [1–3], interconnects, [4,5]) and filtering and generic functions [6,7] have already been reported.

The refractive index of silicon in the visible and infrared is between 3.44 and 3.48 in the near infrared for non intentionally doped silicon and virtually no absorption. This is sufficient to achieve very confined structures. Moreover after ion implantation or oxidization a large range of refractive index and conductivity can be achieved, although propagation losses increase with dopant [8].

Silicon oxynitride (SiON) waveguide technologies have also been demonstrated with very low propagation losses below 0.5 dB/cm in the C and L bands (1530–1590 nm) together with the capability of obtaining high index contrast, in the 1.45–2 range [9,10].

On the mechanical point of view, surface and bulk micromachining, and wafer to wafer and wafer to glass bonding offer possibilities of real 3D integration and auto-aligned structures [11].

However the thermo-optic effect is the more viable and elegant means proven so far to provide tuning of integrated optical waveguide components based on silicon and its oxides. Space-division optical switches with MZI configuration based on low loss silica-on-silicon waveguides have been demonstrated, but they require driving powers of the order of 0.4 W [12]. Recently fast polarization independent thermo-optic phase shifters using SiON waveguide technology combined with NiCr/Cr alloy heaters have also been demonstrated. However, even this approach requires driving powers in the range of a few hundreds microwatts [13].

On the other hand, the large inherent birefringence of liquid crystals and their capability to reorient with an external electric field provide an electro-optic response orders of magnitude higher than that exhibited by conventional dielectrics. Consequently, very short coupling lengths can be obtained in switching and routing devices. This may result in very compact and cost effective integrated photonic systems. While liquid crystals can not compete in terms of speed with other technologies on the ground of data and packet switching, they show great potential for reconfigurable optical nodes in high volume cost-sensitive field of telecommunication (i.e. fiber-to-the-home for combined high-speed internet, CATV and telephone services, Local Area optical Networks) and infotainment on public transportation media (i.e. in aircrafts, trains, ferries, buses with audio, video, gaming and internet access through a seat display).

Low power consumption of devices based on liquid crystals can be estimated as follows. Let us consider typical values of average permittivity $\varepsilon_r = 10$ and thickness $d = 4.5\,um$. Therefore capacitance C is $\approx 2\ nF^{*}cm^{-2}$. At 3 V driving voltage and $f = 10\,kHz$ refresh frequency, power dissipation is $\approx 10^{-4}$ $W^{*}cm^{-2}$. In guided optics, the effectively addressed device and system area is only in the close vicinity of narrow waveguides. This area is anticipated well below 1 mm^2. Hence power dissipation is kept in the μW range.

In our approach, we heterogeneously integrate liquid crystals, which have outstanding optical properties, with silicon. Using photonic, micromechanical as well as microfluidic concepts, the basic structures for LC photonic on silicon have been designed and demonstrated.

In this article we present the foundation of the manufacturing of integrated optics devices based on silicon and liquid crystal. Also the example of an integrated optics polarizer will be given.

FABRICATION OF MICROMACHINED PHOTONIC STRUCTURES

When (100) silicon wafer is immersed in KOH solution, the etching rate of flat (100) and oblique (111) planes are in the 100 s to 1 ratio range [14] depending upon temperature and concentration. This leads

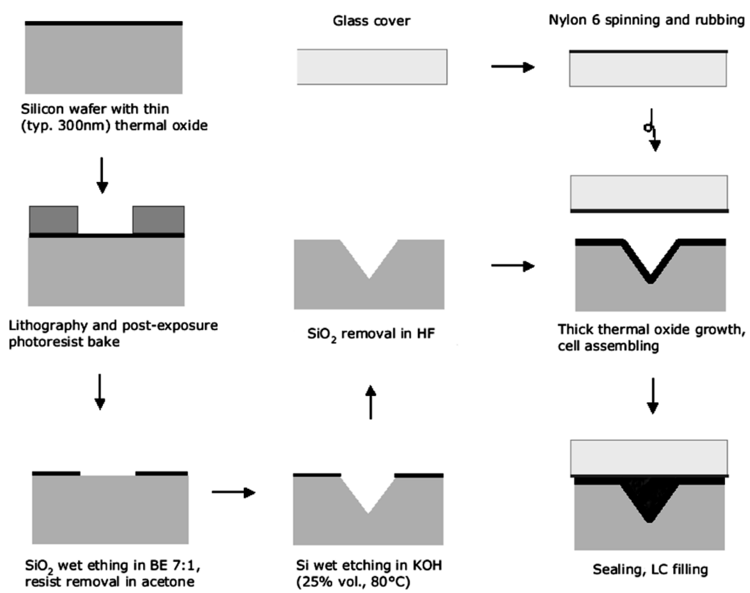

FIGURE 1 Technological steps for the fabrication of a LC filled waveguide on silicon.

to the formation of grooves, whose cross section is inscribed in a triangle of base d and depth p, where:

$$p = d\frac{\tan 54.7^\circ}{2} \cong d\frac{\sqrt{2}}{2}$$

The process is exemplified in Figure 1. By controlling the etching time, either triangular or trapezoidal shapes are obtained. Especially in the latter case, as no etch stop material is present, lower roughness is obtained when isopropanol is added to the KOH solution [15] and nitrogen bubbling is used. After the etching, the wafer can be cleaned in HF or H_2O:H_2O_2:HCl (3:2:2). Then an approximately 2 μm thick SiO_2 cladding layer is thermally grown. Only the cover glass cover is coated with a mechanically rubbed nylon 6 film. After cell assembling, the grooves are filled under vacuum and at 70°C by the nematic liquid crystal E7.

Figure 2 shows an image a V-groove after the final thick oxidization acquired with an atomic force microscope in contact mode. It shows that some irregularity might occur, but the angles of the sidewalls well approximate the theoretical value. Minor differences with respect to the theoretical value are related to possible minor misalignment of the mask with respect to the crystallographic planes and to the finite etch rate of the (100) plane. It is worth noting that the sharp edge of the triangular groove is well conserved even after oxidization. The measured RMS roughness is a few 10 s of nm.

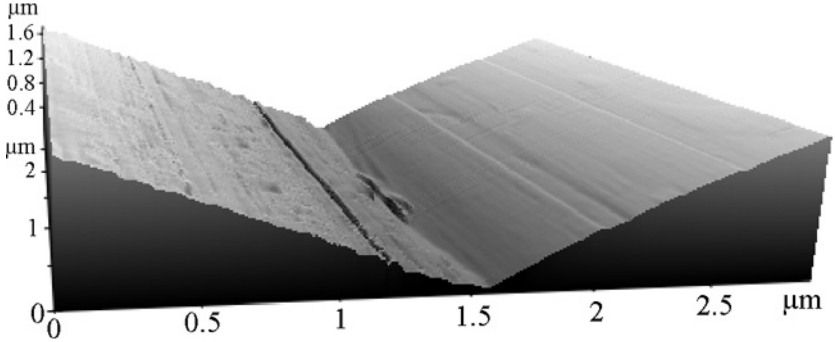

FIGURE 2 V-shaped profile acquired by Atomic Force Microscopy. Scanning is approximately along the axis of the groove. No filtering nor post-acquisition processing is applied. Some inhomogeneity are related to minor misalignment in the photomask with respect the silicon crystal main axis.

PACKAGING OF INTEGRATED OPTICS DEVICES BASED ON LIQUID CRYSTALS

In most optical applications of liquid crystals light propagates mainly perpendicular to the substrates; in these cases the sealing of the device is not critical for the optical performance. In integrated optics applications (where the propagation is in the plane of the wafer), we also have to deal with at least two additional facets for the light input and output. Some initial work exists in waveguiding structures made of liquid crystal as a core. While low losses where found in very narrow capillaries [16], works on simple glass planar waveguiding structures demonstrated losses above 20 dB/cm [17]. However very few address the issue of direct coupling. So far these make use of extra glass plates placed perpendicularly [18,19]. Planar liquid crystal devices with polymer waveguides can be prism-coupled [20]. Alternatively liquid crystal devices can use ion-exchange waveguides in which light can be easily coupled in [21]. However packaging and the achievement of a good interface fibre-waveguide in general have been so far obstacles to the development of LC for integrated optics. Direct coupling, also known as butt-coupling, is based on matching the mode profiles of the fibre and of the waveguide. This is a simple, practical coupling and scalable to mass production. In the case of liquid crystals additional sealing should be added at the input or output interfaces. The specifications of such sealings are: (i) small roughness, (ii) refractive index about 1.5, (iii) no disturbance of the LC director alignment and (iv) no ion injection in the LC. Although issue (iv) is common to the LC display industry where light travels only through the glass plate, the others issue are unique to guided optics. We have devised a simple and practical method to achieve effective interface that shows good compatibility with nematic liquid crystals [22]. This is summarized as follows:

a) Preparation of the substrate and cover: spin-coating of Nylon 6 as alignment layer, rubbing with a velvet cloth to obtain a planar homogeneous alignment.
b) Assembling the cell: the spacers are positioned only in the 4 corners.
c) Insertion of the UV-curable polymer on two faces only, the input and output sides. We carefully dispense the polymer (NOA 61) at the borders of the cell by standard glue dispensing syringes or pipettes. By capillarity the polymer diffuses homogeneously inside the cell; we wait until the polymer front penetrates a few hundreds of microns inside the cell.
d) UV-exposure: this step crosslinks and freezes the polymer. By controlling the temperature and the delay before exposure, we obtain

quite a reproducible interface. The polymer behaves as glue and sealant. More importantly here it also smoothes out effects of any residual roughness of the interface and director non-uniformity, thanks its refractive index is close to the average refractive index of the LC.

e) Liquid Crystal (E7) insertion on one of the free edge.
f) Sealing of the free edges.
g) Sawing the input and output with a conventional water-cooled rotating blade substrate dicer. Optical loss per facet is typically lower than 1.5 dB [23]. If lower loss is expected, as the device is perfectly sealed, lapping and polishing can also be easily performed.

The low scattering interface is illustrated in Figure 3 for a uniform sample device *without* any waveguiding structure.

The technique is to be combined with micromachined microfluidic photonic structures as exemplified in Figure 4. Further perpendicular channels for filling the thin waveguing channels are needed. Simulations reveal that scattering losses introduced by the filling channels are negligible if their width is kept within 20 μm.

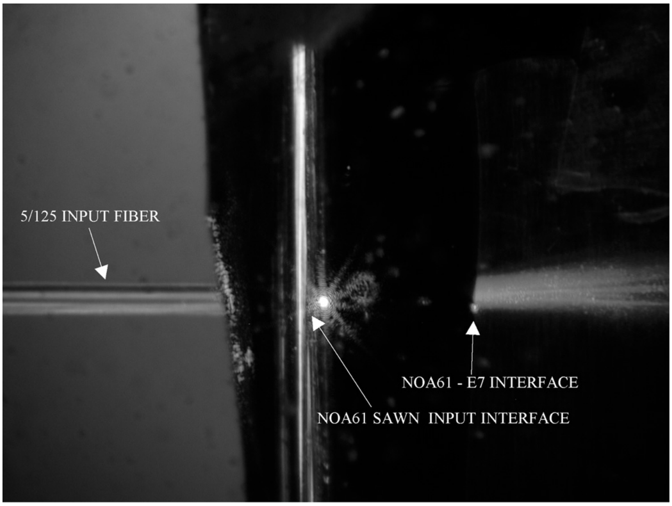

FIGURE 3 Light is launched from the left-hand side by a standard 5/125 fibre in NOA61 and reaches E7: it scatters in E7 (right side). No scattering is observable in NOA61 while negligible scattering is seen the interface. The irregular left glass edge is due to incomplete cut and it is far out of the plane of the propagation. Edges are neither lapped nor polished.

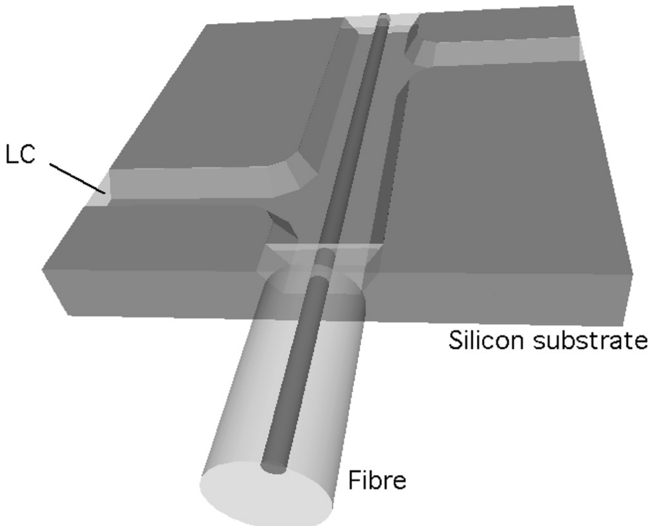

FIGURE 4 Schematic illustration of a micromachined microfluidic photonic structure suitable for LC filling. The structure is sealed with a top cover glass (not shown). Butt coupling is performed through the sharp sealing edge.

EFFECT OF MOLECULAR DIRECTOR DISTRIBUTION

In LC-filled grooves, the waveguide core is a made of LC. Therefore its refractive index depends on the molecular orientation. To test the optical behavior, we have launched a linearly-polarized light, at wavelength 1.5 μm, in a 10 μm wide triangular LC waveguide. We have observed that the output intensity varies according to the polarization orientation and is suppressed by more than 25 dB. Thus as a first approximation we modeled the LC waveguide as a uniform birefringent medium.

After modal analysis, it results that propagation is only compatible with an effective pretilt in the 15° to 24° range [24]. This is quite higher than the 1.3° pretilt we usually obtained for E7 in antiparallel glass cells when evaluated with the crystal rotation method [25].

After optical and AFM inspection, we argue that such a high pretilt might be due to the asymmetry in the structure. The rubbing only on the coated glass plate, differences in the materials surrounding the LC (thermally grown SiO_2 and nylon), and the very confining unconventional grooved geometry may play some role and induce a higher pretilt on the edges of the groove.

CONCLUSIONS

We have presented technological solutions for a liquid crystal on silicon integrated optics platform. A standard silicon micromachining process based on wet etching is used. A clever packaging technique that provides low losses and is suitable for mass production is presented. We have demonstrated that a LC-filled waveguide behaves as an integrated optic polarizer, letting only TM polarization through. In very preliminary devices, without edge facets optimised as described above, extinction ratio of TE polarization is more than 25 dB. First investigations reveal that LC alignment is not determined by rubbing only. This opens up scientific questions on the confinement of LC with more than two boundary conditions in micromachined microfluidic structures.

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