Demonstration of superprism effect in silicon pillar 2-D photonic crystal infiltrated with liquid crystals

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Abstract. Superprism-based deflection of an optical beam is observed in a photonic crystal composed of a triangular lattice of pillars infiltrated with a liquid crystal. The device is based on a Silicon-on-insulator substrate and operates in the telecommunications band. The experimental results show a wavelength shift of 0.76 μm/nm, in reasonable agreement with simulations. Temperature-based control of the liquid crystal properties is also shown to modulate the superprism characteristics. © *2011 Society of Photo-Optical Instrumentation Engineers (SPIE).* [DOI: 10.1117/1.3529437]

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1 Introduction

One of the interesting optical properties of photonic crystals (PhCs)[1,2] is the so-called superprism effect,[3–5] producing a strong angular dispersion for frequencies near the edges of the photonic bandgaps. This effect could enable compact, on-chip devices such as multiplexer-demultiplexers[6–8] or ultrafast switches.[9] In particular, a tunable superprism device would be very useful for such applications, and a number of tuning mechanisms have been explored, including electro-optic[10,11] or mechanical[12] control, nonlinear materials,[13,14] or infiltration with liquid crystals.[15–19] In this paper, we investigate planar triangular-lattice PhC structures made of pillars and infiltrated with liquid crystals to realize a tunable superprism effect.

The devices are fabricated using a standard e-beam lithography process on a silicon-on-insulator (SOI) wafer. The structure under study is shown in Fig. 1. It is composed of an input waveguide followed by a PhC region whose orientation is rotated by 15 deg clockwise relative to the input waveguide. A planar output waveguide conducts light to the edge of the device. The PhC is composed of a triangular lattice of pillars with a period of 860 nm, height 340 nm, and diameter 602 nm. The structure is filled with liquid crystals (5CB from Merck) having refractive indices at $\lambda = 1500\,\text{nm}$ of $n_o = 1.51$ and $n_e = 1.63$ at room temperature and $n_i = 1.57$ (isotropic) above 36°C.

2 Modeling and Theory

A theoretical analysis of the PhC structure has been conducted using the MIT Photonic Bands (MPB)[20] software. Isofrequency contours (IFC) for band 5 (TM polarization) are shown in Fig. 2. They highlight two different superimposed effects. At longer wavelengths, a superprism effect is obtained due to the large curvature of the IFC. Moving toward shorter wavelengths, a forbidden band appears, caused by the transition of the incident medium IFC through the Brillouin zone (BZ) boundary.[21] This effect is entirely determined by the period of the structure. Since the incident medium IFC is large compared to the BZ, it is folded multiple times in the BZ. The incident wavevector can lie on any of the foldings depending on the angle of incidence and the frequency. By carefully choosing the angle, the wavevector can be set close to the edge of the BZ. Varying the frequency hence makes the wavevector hop from one folding to another, mimicking the presence of a bandgap. Below this gap, the incident wave matches a second region with super-refracting properties.

From the IFC, we extract the refraction angle at the PhC interface. This angle is presented in Fig. 3 for three values of the liquid crystal refractive index. The two discrete regions where the slope of the curves is greatest indicate a superprism effect for two of the refractive index values. In contrast, for the extraordinary index ($n_e = 1.63$), only one region exhibits a superprism effect.

Two-dimensional finite integral time domain (FITD) simulations with effective index approximation have been performed using CST Microwave Studio. As expected from the MPB simulations, a superprism effect is present as shown in Fig. 4. A displacement of the output spot of $30\,\mu$m is obtained (solid line) corresponding to a displacement rate of $1.2\,\mu$m/nm. Note that the origin of the output spot displacement scale is defined to be the center of the input waveguide. The dashed curve shows the output spot intensity. Large insertion losses, as described in other work,[22,23] are particularly visible. At longer wavelengths, the intensity of the light coupled to the edge of the fourth PhC band is seen to overwhelm the effect of interest. Note that according to MPB, the fourth band lies outside the investigated frequency range. However, beam dispersion at the output of the waveguide and finite size effects can account for the small fraction of light transmitted in the fourth band.

3 Experimental Results

In the experiment, light from a tunable laser (1460–1590 nm) is polarized in a TM mode and injected into the waveguide through a lensed fiber (see Fig. 5). The detection is performed

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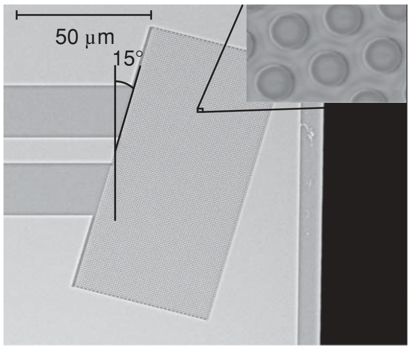

Fig. 1 SEM picture of the superprism device fabricated on a SOI wafer. Incident light arrives from the left in the ridge waveguide, then encounters the PhC structure rotated by 15 with respect to the waveguide axis.

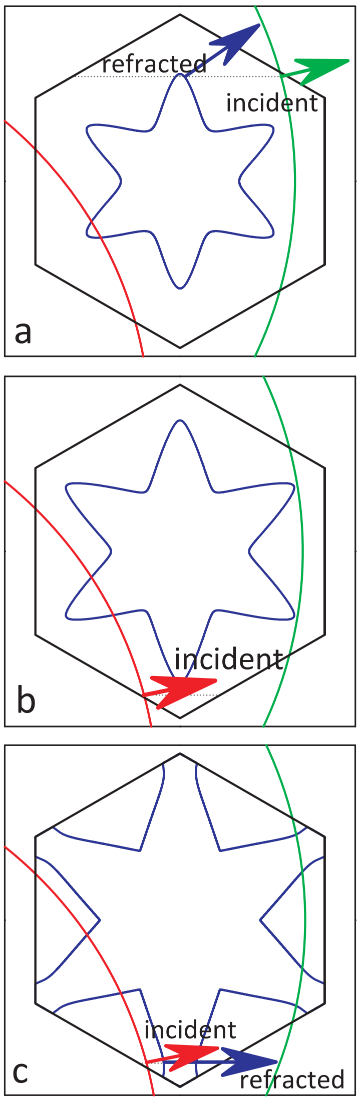

Fig. 2 Isofrequency contours at three different wavelengths; a) $\lambda = 1522$ nm (superprism regime), b) $\lambda = 1494$ nm (forbidden band), c) $\lambda = 1463$ nm (superprism regime). The red and green curves represent two translated copies of the IFC in the incident medium.

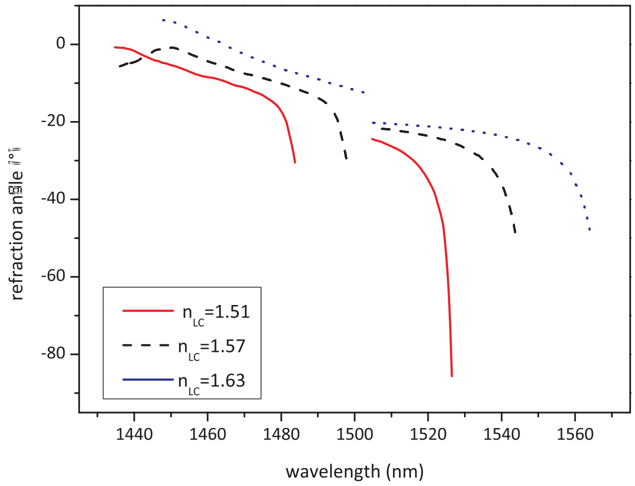

Fig. 3 Refraction angle at the waveguide-PhC interface for three refractive indices of the liquid crystals, computed using MPB. With $n_o = 1.51$, $n_i = 1.57$, and $n_e = 1.63$ the ordinary, isotropic, and extraordinary refractive indices of the liquid crystal at $\lambda = 1500$ nm.

by imaging the output edge using an InGaAs infrared camera (Polytec model SU320MS-1.7RT) positioned in front of the planar output waveguide. Another IR camera is mounted above the sample in order to precisely align the injection into the planar waveguide. The device is designed to work with liquid crystal surrounding the structure, so, a droplet of liquid crystal is deposited on the PhC.

The experimental result (see Fig. 6) shows two distinct regions where a superprism effect is observed (emphasized by the red lines). Note that in Fig. 7 the origin of the output spot displacement is arbitrary. The region included between $\lambda = 1493$ nm and $\lambda = 1515$ nm exhibits a displacement rate of $0.55\,\mu$m/nm. The greatest displacement, equal to $20.5\,\mu$m, is measured between $\lambda = 1541$ nm and $\lambda = 1568$ nm and corresponds to a displacement rate of $0.76\,\mu$m/nm, which corresponds to a deviation of 0.6°/nm. As a comparison, a conventional prism has a deviation around 0.006°/nm and a diffraction grating 0.1°/nm.[24,25]

The measured values are smaller than the ones predicted by the FITD model. This difference could arise from the dif-

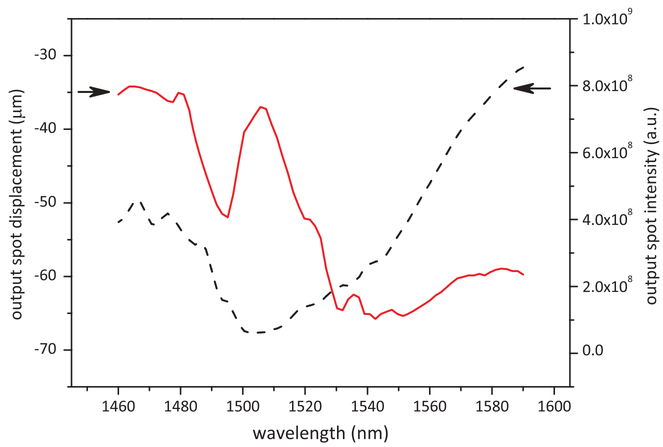

Fig. 4 Two-dimensional simulation of the structure showing an anomalous dispersion (red curve) and the related intensity of the output spot (black dashed curve).

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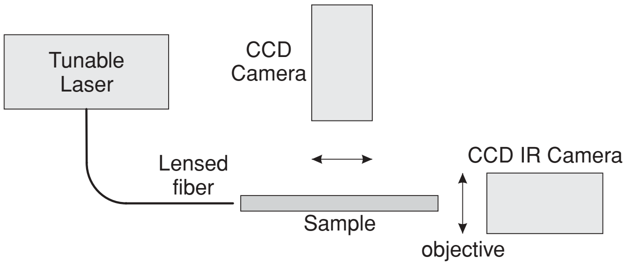

Fig. 5 Scheme of the experimental setup.

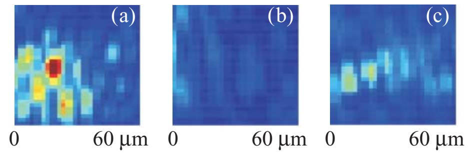

Fig. 7 Temperature-based modulation of the superprism device: output light spot at room temperature (a) initially, (b) after heating to 45°C, and (c) after returning to room temperature. Note that in (b) no output spot is observed due to the change in the liquid crystal index of refraction.

ficulty of detecting the adjacent sharp dip and peak observed in Fig. 7. We also observe a red shift of the area of interest between the simulations and the experiment that could be due to imperfect alignment of the liquid crystal with respect to the pillars. Nevertheless, the superprism effect is presented for the first time for a PhC made of silicon pillars infiltrated by liquid crystal.

The superprism properties can be modulated using temperature, due to the fact that the optical properties of the liquid crystal change from anisotropic to isotropic at 36°C. In this experiment, a Pelletier element is used to heat the device and liquid crystal from room temperature to 45°C. Figure 7 shows the images, obtained by the in-plane camera, of the spot refracted by the PhC at a wavelength of $\lambda = 1510\,\text{nm}$. Figures 7(a) and 7(c) show the spots before and after heating, whereas Fig. 7(b) shows the same area with the liquid crystal in the anisotropic state. [The intensity variation between the spots shown in Figs. 7(a) and 7(c) is most likely explained by the automatic calibration of the infrared camera.] The disappearance of the spot at the higher temperature is due to the extreme sensitivity of the superprism effect to the surrounding refractive index. This slow temperature-based modulation could be enhanced by instead using the electro-optic properties of the liquid crystal. Moreover, the liquid crystal infiltration adds functionality that makes this structure promising for future generations of very compact optical systems.

4 Conclusion

We have simulated, fabricated, and characterized a device exhibiting a superprism effect in a two dimensional PhC composed of silicon pillars infiltrated by liquid crystal. We achieve a 0.76 μm shift per nm of injected wavelength in the near infrared. An improved time response and control of the orientation of the liquid crystal could be achieved through electro-optic modulation. Further improvements could be based on manufacturing by interference lithography, which would allow efficient production at very low cost.

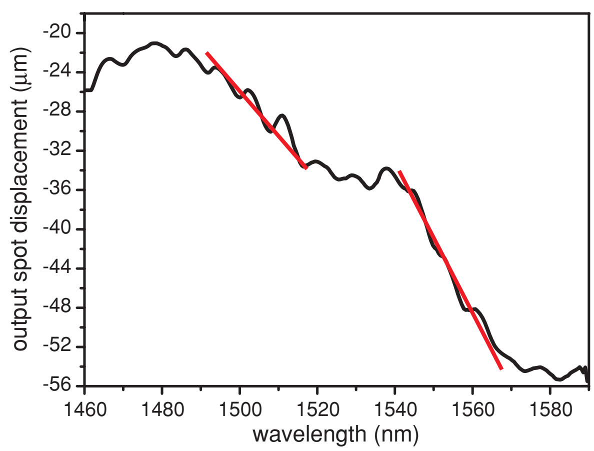

Fig. 6 Experimental result demonstrating a superprism effect in the infrared range using silicon pillars surrounded by liquid crystal. The red lines show the regions where the effect is obtained.

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