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Photosensitive post-tuning of chalcogenide photonic crystal waveguides

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***Abstract* — We present experimental results on photosensitive post-tuning the dispersion of a two-dimensional photonic crystal waveguide made from chalcogenide glass. A 5nm shift of the resonant wavelength is reported.**

I. INTRODUCTION

Planar Photonic Crystals (PhC), which consist of a thin high index dielectric slab patterned with a 2D periodic array of air holes, are now recognized as a promising platform for achieving light control in a planar integrated circuit. Their ability to confine light at the wavelength scale has led to the demonstration of unprecedented compact photonic devices for integrated optical circuits [1]. However, in order to achieve desirable functionalities, careful engineering and high accuracy fabrication are required. Due to this, post trimming of the properties of individual components within a PhC is a highly attractive capability, not only to relax fabrication tolerances but also to allow individual components to be optimized for specific environments or applications. In particular, local changes in the refractive index of the crystal could be used to create double-heterostructure type nanocavities [2], or to fine tune a PhC cavity resonance to match a Quantum dot emission wavelength [3].

We demonstrate a novel post-process tuning technique which utilizes the photosensitivity of chalcogenide glass, i.e. the local change of the refractive index and density (volume) of the glass upon exposure to near bandgap light [4], to modify the properties of a PhC. A simple embodiment of this technique involving shifting of the dispersion bands of a PhC waveguide is used to both study the effect of this photosensitivity on the PhC and to provide a proof of concept demonstration.

II. PRINCIPLE

Figure 1 shows the principle of the photosensitive post-tuning experiment. The resonant coupling wavelength from the fiber taper to the modes of the chalcogenide glass PhC waveguide was monitored by measuring the transmission spectrum through the taper with an Optical Spectrum Analyzer (OSA). The dips in the transmission spectrum are associated with coupling to the modes of the PhC waveguide.

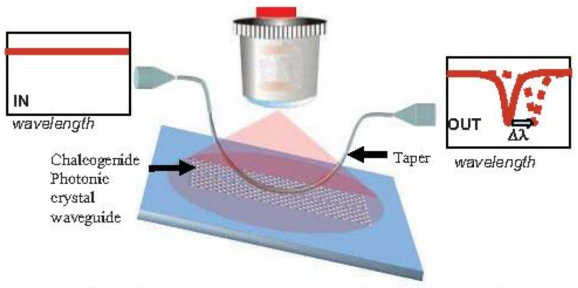

Fig. 1. A schematic diagram showing the principle of the photosensitive post tuning of a chalcogenide photonic crystal waveguide.

The photoinduced change in the PhC was observed by monitoring the shift in wavelength of these dips during the exposure of the PhC sample to 633nm light. The resonant coupling wavelengths are given by the wavelengths at which the dispersion curves of the PhC waveguide and the fiber taper overlap, as shown in figure 2.

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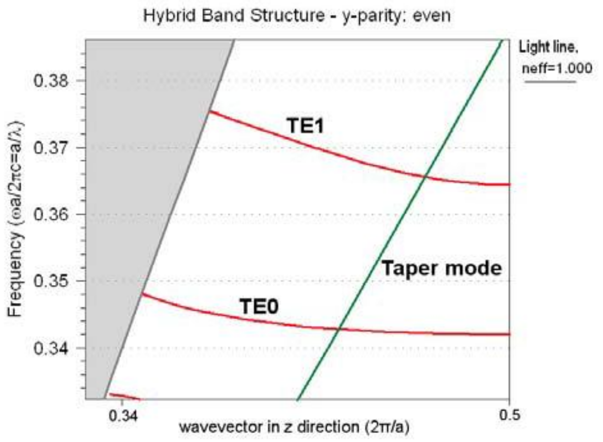

Fig. 2. Calculated band structure of the W1 waveguide used in this work (red) overlaid with the dispersion curve of the tapered fiber in green.

III. EXPERIMENTAL METHOD

The photonic crystal sample used in this work consisted of a triangular lattice of air holes in a 300nm thick slab of AMTIR-1 ($Ge_{33}As_{12}Se_{55}$) chalcogenide glass suspended in air. The sample used in this work is shown in figure 3, in which the hole pitch was 550nm and the hole radius was 165nm. Fabrication of the sample was achieved by first depositing a thin film of the glass by pulsed laser deposition and then patterning this film by means of electron beam lithography and chemically assisted ion beam etching. The silica fiber taper used in this work was estimated to have a diameter of 1.3 microns and was formed into a loop in order to localize the interaction between the taper and the PhC waveguide.

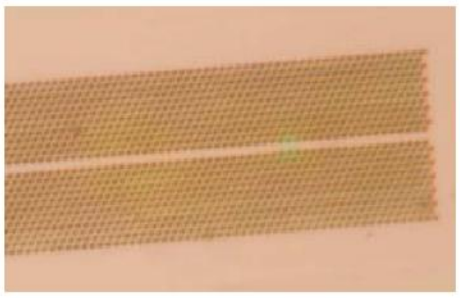

Fig. 3 Optical microscope image of the W1 PhC waveguide sample used in this work.

The photosensitive post trimming experiment was performed by first bringing the fiber taper into contact with the PhC waveguide so that coupling between the taper and the waveguide was achieved. Then the entire sample was exposed to light at a uniform intensity of 1.3W/cm^2 and a wavelength of 633nm. The transmission spectra of the fiber taper, which indicated the resonant coupling wavelengths, was recorded at 1 minute intervals throughout the exposure and was also monitored for several days after the exposure was finished. The exposing light was supplied by a HeNe laser and was linearly polarized, although the dependence on the polarization of the exposing light was not studied. The wavelength of 633nm was chosen as this is close to the electronic bandgap energy of the AMTIR-1 glass.

IV. RESULTS

Figure 4 shows the transmission spectrum of the fiber-taper due to coupling to the fundamental PhC waveguide mode for different exposure times. The resonance associated with coupling to the TE_0 mode was observed to shift to longer wavelengths with increasing exposure. In addition, we observed an increase in the coupling strength with exposure.

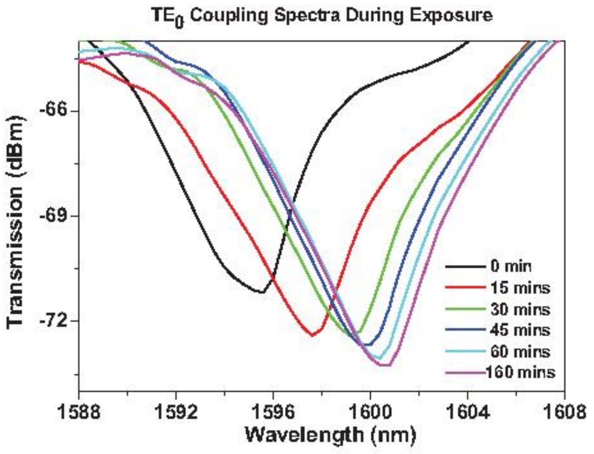

Fig. 4. Photosensitive tuning of the TE_0 mode during the exposure. The resonance dip is plotted for a range of times during the exposure.

Figure 5 shows a plot of the resonant wavelength versus exposure fluence, which clearly displays saturation behaviour at higher fluences. The circles in the graph are experimental data points whilst the curve is an empirical fit to an exponential curve. The maximum wavelength shift was 5.2nm ±0.4nm whilst the maximum increase in the resonance depth was ~ 2dB.

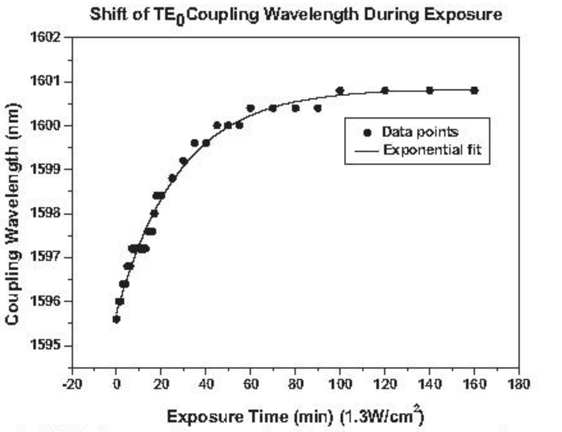

Fig. 5. Shift in coupling wavelength versus exposure fluence at 633nm of the PhC TE0 waveguide mode.

The exact cause of the observed increase in coupling strength is still under investigation but it is likely to be related to a modification of the waveguide mode field profile resulting from changes in the waveguide dispersion curve. In principle, one would expect that in modifying the group index of the PhC waveguide mode, the overlap with the taper mode, and hence the coupling strength, could change. The shift in the coupling wavelength of the higher order waveguide mode follows the same trend as for the fundamental mode and during the exposure there was no relative shift between the two modes, i.e. the wavelength difference remained constant to within the resolution of the OSA.

Preliminary investigations into the photosensitivity of unpatterened AMTIR-1 films [5] at 633nm have shown a decrease in the material refractive index and a volume expansion. These results are consistent with previous work by Zakery *et al.* [6], who reported a refractive index decrease in AMTIR-1 due to exposure, and Igo *et al.* [7], who reported photoexpansion in a range of As-Se-Ge glasses. For the PhC waveguide, a refractive index decrease results in a shift of the waveguide modes to shorter wavelengths. Our calculations indicate that a wavelength shift of ~5nm is obtained with an index change of 0.01, and that this change occurs linearly in the region of interest. Conversely, expansion of the PhC causes a shift towards longer wavelengths, a ~5nm wavelength shift of the TE_0 mode is obtained for 0.31% material expansion. Thus we attribute the observed wavelength shift to a combination of these two competing effects. However, the material expansion has the bigger effect in this case leading to the observed resonance shift to longer wavelengths. Work is in progress to resolve the magnitude of each contribution to the resonance shift.

For many potential applications, the ability to tune the resonance towards longer wavelengths in a controlled manner is particularly relevant. For instance, the double heterostructure cavity suggested by Noda *et al.* [8] relies on precise engineering of the lattice constants along a line defect. Light is confined to the central region (larger lattice constant) due to the differences between the mode-gap frequencies along this line defect. In the same way, it should be possible to create a double heterostructure cavity by exposing a small region of a W1 in chalcogenide photonic crystal. Based on band structure calculations, a 5nm shift is equivalent to the band shift that would be induced by an increase in the refractive index of ~ 0.01. Results reported in [2] show that this should lead to a cavity Q ~30000. In order to reach the maximum Q predicted theoretically, a ~ 20nm shift would be required. Future studies into different techniques or different chalcogenide glass compositions may increase the tuning range.

Another area where the photosensitivity of chalcogenide glass could prove to be highly practical is single quantum dot devices based on cavity QED, such as a single photon source. This technique offers a way to align the cavity resonant wavelength with the QD emission wavelength – an important challenge since enhancing the QD SE rate via the Purcell factor of the cavity mode requires critical spectral matching between the single QD and the cavity mode. The ability to tune the cavity resonant wavelength, via a photosensitive chalcogenide cladding applied on top of the PhC device for instance, in order to match it to the QD emission appears highly promising.

V. CONCLUSIONS

We present the first experimental demonstration of photosensitive post-tuning of a planar photonic crystal device. We use the material photosensitivity of $Ge_{33}As_{12}Se_{55}$ (AMTIR-1) chalcogenide glass to 633nm light in order to modify the resonant coupling wavelength of a W1 photonic crystal waveguide by up to ~ 5nm towards longer wavelengths. The wavelength shift showed a saturating exponential growth trend with increasing exposure, and this suggests that a high degree of control over the photosensitive tuning process should be possible. This work demonstrates that this post-processing technique is highly promising for applications where fine post-tuning of existing structures is required, such as for single photon source applications or for directly photo-writing resonant cavity structures.

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