

Experimental and theoretical investigation of loss issues in photonic crystal slab waveguide devices.

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ABSTRACT

In this paper we demonstrate ultra-low loss transmission across a photonic crystal super-prism device consisting of 600 lattice periods etched into a slab waveguide at wavelengths both above and below the primary band-gap. By modifying the refractive index of the holes we have reduced overall insertion loss to 4.5 dB across the entire visible region of the spectrum, greatly enhancing transmission and extinction in higher order stop-bands. In addition we show that the remaining loss is predominantly due to impedance mismatch at the boundary between patterned / unpatterned slab waveguide regions and so is no longer proportional to the length of the photonic crystal or the number of lattice periods. This is an important step forward for the realization of functional photonic crystal time delay elements, dispersion compensators and super-prism spectrometer devices. Experimental loss measurements compare extremely well with Finite difference time domain simulations which were used to investigate the effect of etch depth on scattering loss. We find that partial penetration into the underlying buffer region causes massive scattering loss to substrate modes due to loss of waveguiding in the holes.

Keywords: Photonic Crystal, waveguide, loss.

1. INTRODUCTION

Loss is considered to be a limiting factor preventing Photonic Crystals (PCs) from competing in key application areas in integrated optics. The key loss mechanism in waveguiding photonic crystals is up-scattering from the holes. Applications for photonic crystals can be generalized into two categories:

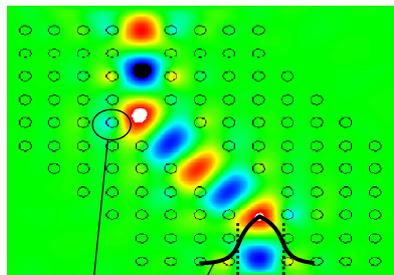
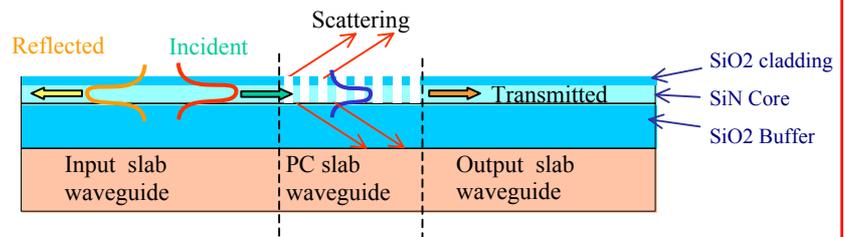


Figure 1: Photonic crystal “line defect” waveguide device, showing associated loss mechanisms



Effective mode index - mismatch causes reflection + scattering loss at boundaries

Figure 2: cross sectional view of photonic crystal “slab waveguide” device showing primary loss mechanisms

The first class of applications include devices such as “line defect”¹ and “CROW” waveguides² which make use of the reflective properties of photonic band gaps (PBGs) to obtain transmission along chains of defect sites at wavelengths lying within the PBG of the surrounding lattice (fig 1). In these applications light is predominantly

localized to high refractive index defect regions bounded by a surrounding photonic crystal lattice. A small proportion of the mode energy is localized within a few rows of holes adjacent to the line defect as an exponentially decaying evanescent field. This system is analogous to a rib waveguide structure with the line defect constituting the waveguide core and the PC the cladding, however the confinement mechanism is no longer by a process of total internal reflection. A small proportion of this evanescent field intersects the spatial regions of the holes as the wave propagates along the line defect waveguide, and is subject to loss. As this proportion can be very small, losses for photonic crystal line defect waveguides are expected to be quite low.

The second class of applications include devices such as Photonic crystal superprisms^{3,4} and optical time-delay elements^{5,6} which make use of the dispersive properties of photonic crystals. These require low loss transmission through the bulk of the photonic crystal across hundreds or even thousands of lattice periods. In these applications light must couple efficiently from an input slab or rib waveguide to dispersive Bloch modes of the photonic crystal at wavelengths outside the photonic band gap (fig 2). The modal properties of light propagating within the bulk of the lattice are no longer analogous to a rib waveguide, and the entire modal power interacts with the porous region and so is potentially subject to scattering loss. In addition there may be a substantial difference in effective mode index at the interface between the photonic crystal and the input rib waveguide leading to further loss due to mode mismatch⁷. Loss reduction and efficient excitation of Bloch modes within these devices is therefore much more challenging.

Loss in photonic crystal slab waveguide devices arise from several affects: Firstly, imperfections in fabrication give rise to roughness of the walls of the holes, causing partial scattering of the waveguide mode into the substrate and surroundings. Secondly, refraction occurs at the boundaries of the structured elements causing light to diverge strongly in the vertical direction. Refracted light propagating across a hole experiences no confinement in the vertical direction as there are no further dielectric boundaries and so a small percentage of the modal energy escapes as radiation loss. As the waveguide structure is generally non symmetric in refractive index profile, (consisting of a substrate layer with a higher refractive index than air, unless it is an undercut air-bridge structure), most loss occurs due to scattering into the substrate⁸. Divergence within the hole regions was first acknowledged by Krauss et al⁹, who suggested that minimizing hole width would help to reduce vertical scattering loss. This principle has been widely adopted for the demonstration of waveguiding photonic crystal structures.

Our solution to this problem is rather different. By introducing a third material into the holes such that $n_{\text{core}} > n_{\text{rods}} \sigma n_{\text{cladding}} \& n_{\text{buffer}}$ greater confinement can be provided for an optical signal passing through the guide. Light localized within the holes then experiences a dielectric boundary in the vertical direction, which under suitable geometrical conditions enables waveguiding to be maintained within the spatial regions of the holes. The higher refractive index of the holes therefore reduces the tendency for light to leak into the buffer layer and reduces divergence at the boundaries of the hole walls^{10,11}.

2. EXPERIMENT 1: Index fluid filled holes.

To confirm this theory a photonic crystal device with holes etched through the cladding and core layer was fabricated. The slab waveguide consisted of a silicon substrate with a 2.2 μm thick SiO₂ buffer layer formed by thermal oxidation, a 180nm thick SiN core layer deposited by LPCVD and a 600nm thick SiO₂ top cladding deposited by PECVD. This was then patterned by direct write e-beam lithography and etched by RIE to form an array of air voids. Devices were then cleaved by a LOOMIS scribe and dice machine to provide high quality facets.

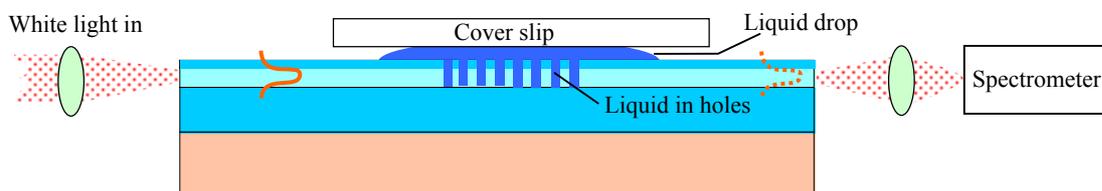


Figure 3: cross sectional view of experimental arrangement for "liquid filled" holes

Broadband transmission spectra were acquired for the two principal symmetry directions on a device consisting of 60 rows of holes arranged in a triangular lattice using a broadband laser source. A drop of calibrated refractive index matching fluid ($n=1.4$) was then deposited onto the porous region, and the device sealed with a cover slip (fig 3) to

prevent evaporation. Spectra were then re-acquired. All spectra were normalized to the transmission spectra of an unpatterned region of slab waveguide located directly adjacent to the patterned area thus removing loss due to input coupling to the slab waveguide facet.

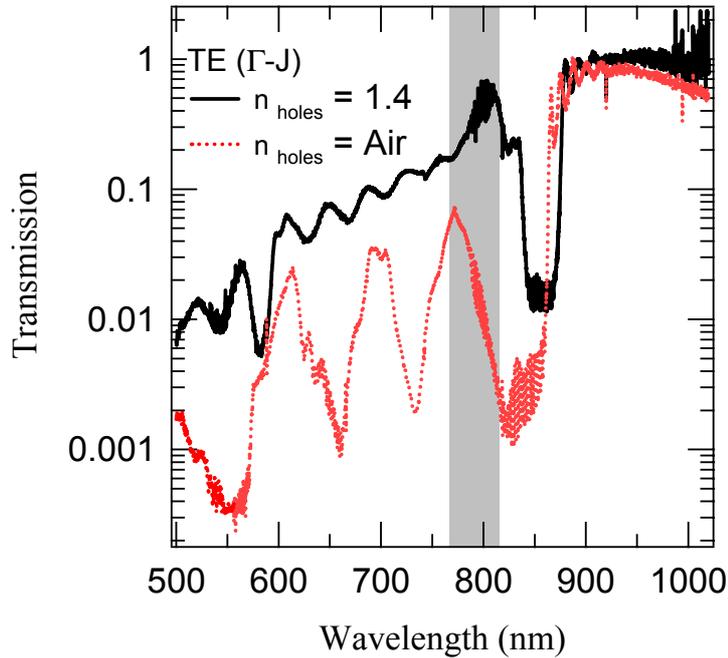


Figure 4: Transmission spectra (Γ -J symmetry direction) comparing air and $n=1.4$ fluid filled holes. Shaded area highlights region of high loss at the lower band edge.

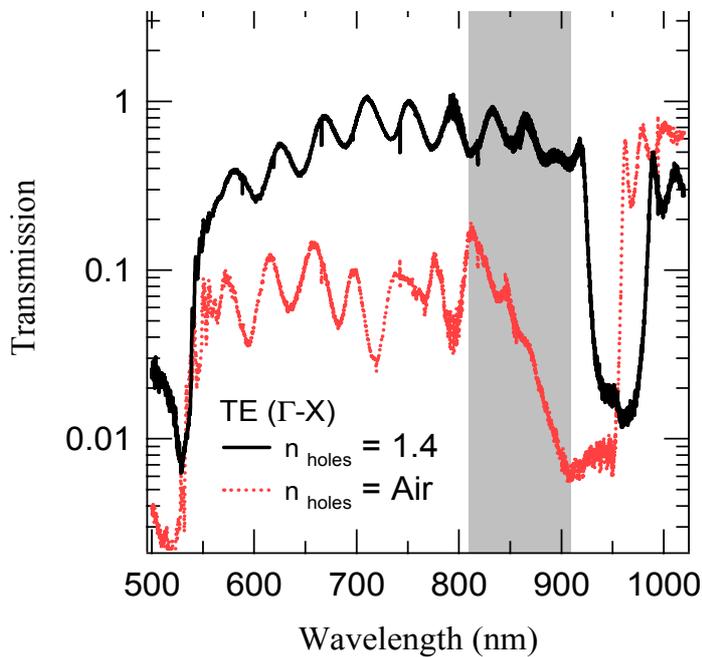


Figure 5: Transmission spectra (Γ -X direction) comparing air and $n=1.4$ fluid filled holes. Shaded area highlights region of high loss at the lower band edge.

Spectra for the Γ -J direction (Fig 4) show near unity transmission at wavelengths above the upper band edge tailing off slightly towards longer wavelengths with little difference between traces for filled / unfilled holes. Below the band-gap spectra for filled / unfilled holes both traces follow a classic scattering curve with a clear offset in amplitude.

Primary band gaps are observed for the Γ -X direction (fig 5) over $\lambda = 811$ -988 nm with corresponding extinction ratios of 14.6dB ($n=1.4$) and 18.6dB ($n=1$), and for the Γ -J direction (fig 4) over the range $\lambda = 771 - 879$ nm with extinction ratios of 17.5dB ($n=1.4$), 26dB ($n=1$).

Periodic ripples on the spectra are attributed to interference (beating) between waves partially reflected from the boundaries (effectively Fabry-Perot modes) of the patterned region, confirming an effective mode-index mismatch between the patterned PC slab waveguide region and the un-patterned input and output slab waveguide regions.

The amplitude offset between filled / unfilled spectra indicates a reduction in loss. This was quantified by measuring the average amplitude offset between the Fabry-Perot fringes over $\lambda = 550 - 800$ nm. Loss was found to be reduced by an average of 4.3dB for the Γ -X direction, and 9.6dB for the Γ -J direction over this wavelength range. At wavelengths close to the lower band edge (shaded region of graphs) loss was reduced by 19dB for both symmetry directions.

At first sight the apparent reduction in loss observed at the lower band-edge could be attributed to an expected reduction in bandgap width due to the reduced refractive index contrast between the holes and the waveguide core material.

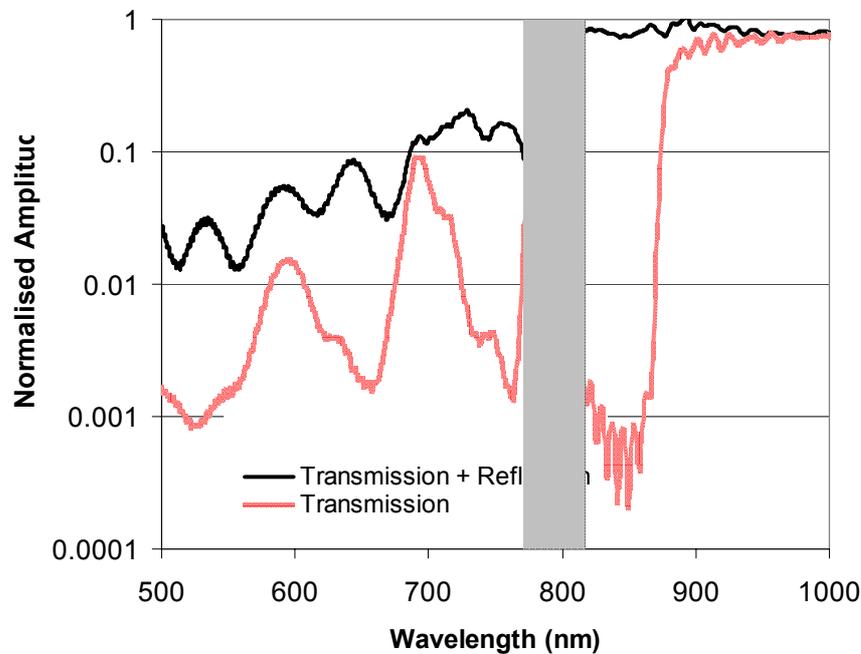


Figure 6: Theoretical transmission spectra for air filled device (Γ -J direction). Shading indicates region of high loss at lower band-edge. Deviation from unity for black trace indicates loss.

To investigate this effect more thoroughly, cross-sectional profiles of the patterned slab waveguide structures were modeled using Finite Difference Time Domain analysis. In the simulation, both transmission and reflection spectra were acquired simultaneously (very difficult to do experimentally). It is well known that an “ideal” photonic crystal should reflect all light within the wavelength range of the photonic band gap without loss, whereas all wavelengths outside the bandgap should be transmitted without loss, hence by summing transmission and reflection together, scattering and insertion loss can be visualized as a function of wavelength as the level of deviation from unity.

Fig 6 shows the theoretical transmission spectra for unfilled holes. As was the case in the experiment this was normalized to an un-patterned slab waveguide with identical cross sectional profile and length, hence effects due to intrinsic material absorption and waveguide dispersion have effectively been removed from the plot. As was the case for the experiment, near unity transmission is observed at wavelengths above the upper band edge and some distance into the band gap. At wavelengths closer to the lower band-edge (shaded region of the plot) loss increases dramatically, confirming the fact that light which should couple from the input waveguide to the PC device at the lower band edge does in fact scatter out of the device. This loss manifests itself as a “blurring” of the lower band edge.

It now becomes clear that the experimental data presented in figs 4 and 5 do indeed show greatly reduced loss and enhanced coupling for modes lying close to the lower band gap edge. Bloch Modes at the lower (wavelength) band edge of a PBG are commonly known as “air band” modes since simulations have shown that they have a large field component localized to the spatial regions of the holes. Bloch modes at the higher (wavelength) band edge of a PBG are known as “dielectric band” modes since they are known to be predominantly localized to the spatial region of the dielectric material between the holes. Our experimental and theoretical results therefore confirm our prediction that loss for modes predominantly localised to the spatial regions of the holes can be reduced significantly by providing confinement in the vertical direction in the spatial regions of the holes and is not simply attributed to a reduction in band gap size due to reduced dielectric contrast.

This result has extremely important implications for applications which make use of the dispersive properties of these modes such as super-prisms and optical time delay elements where the performance of the device in a practical application is directly limited by insertion loss.

3. EXPERIMENT 2: Silica filled holes.

Although the optimal geometric arrangement is to ensure that $n_{\text{rods}} > n_{\text{cladding}}$, the added complexity of fabrication of such structures may in practice make their implementation impractical or very costly. An alternative solution is to fill the holes with the cladding material. This improves confinement somewhat by reducing divergence whilst still providing vertical confinement in the regions of the holes, however leakage to substrate modes may still occur hence this is far from the theoretical ideal.

Following on from the “liquid filled holes” experiments, methods of filling the holes with silica were investigated. These included PECVD and “spin on glass” (SOG) coating. Slab waveguides consisting of a 2200nm thick SiO_2 buffer layer and a 180nm SiN core layer were grown as described earlier, but this time arrays of holes were patterned and etched directly into the core layer. The resultant porous waveguide core was then overcoated with a 600nm thick SiO_2 cladding layer by PECVD or SOG to produce the cross sectional structure depicted by fig 7.

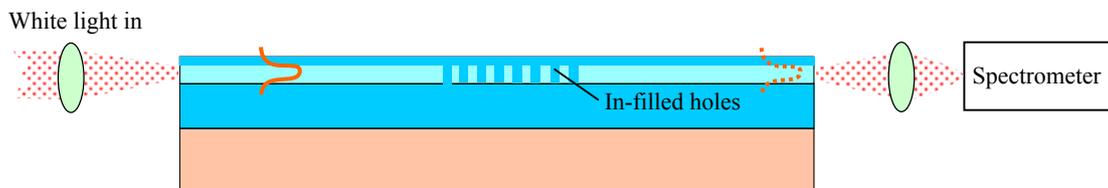


Figure 7: cross sectional view of experimental arrangement for “silica filled “ holes

The SOG process proved to be less effective for filling the holes, tending to produce a “capped” structure of air holes. Fig 8 shows an example SEM cross-section for one of these devices. PECVD was found to be far more effective in filling holes (Fig 9) but suffers from problems due to “necking off” at the top of the holes for holes of diameter $< 200\text{nm}$ resulting in an air void at the center.

An experimental comparison was made between a device with liquid-filled holes ($n=1.4$) and one overcoated with SiO_2 by PECVD. Spectra for devices consisting of 600 rows of holes arranged on a rectangular lattice with an aspect ratio of 1:1.5 and a pitch of 310nm (measured along the minor axis of the rectangle), and nominal hole diameter of 180nm, are shown in figure 10. Four different directions of propagation were investigated.

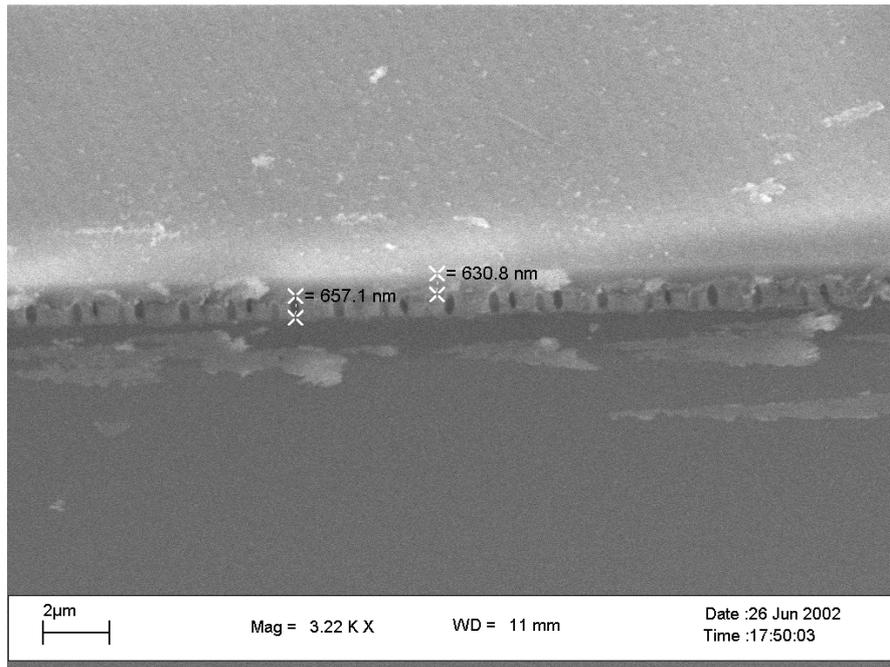


Figure 8: Cross sectional SEM of spin on glass (SOG) coated PC structure. Holes are clearly unfilled by this method, resulting in a capped air cavity structure.

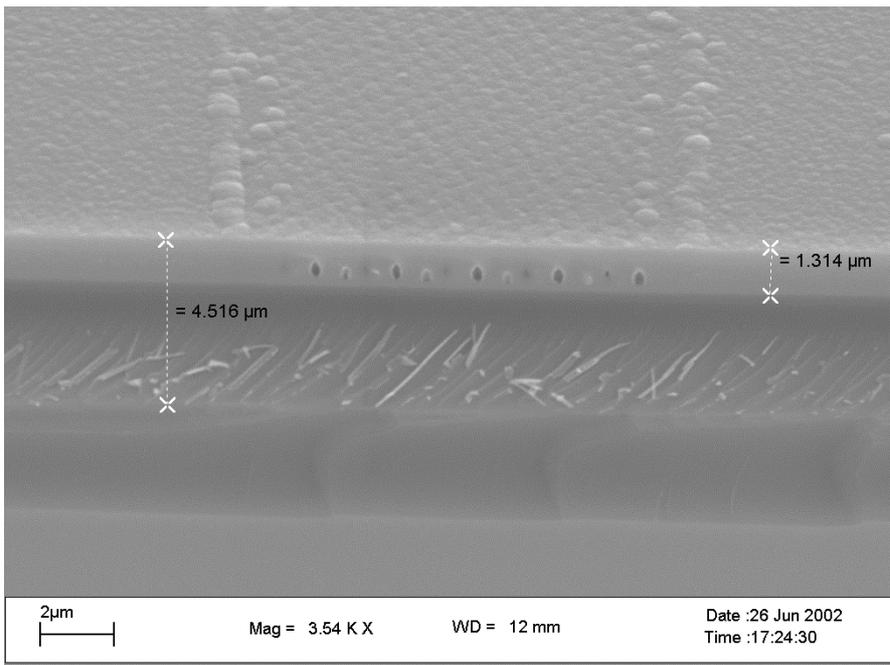


Figure 9: Cross sectional SEM of PECVD Silica coated PC structure. In this device (hole diameter 180nm) holes are partially filled by silica due to a “necking off process” during growth. Although air voids can be seen at the centre of the holes, the side walls of the holes are coated.

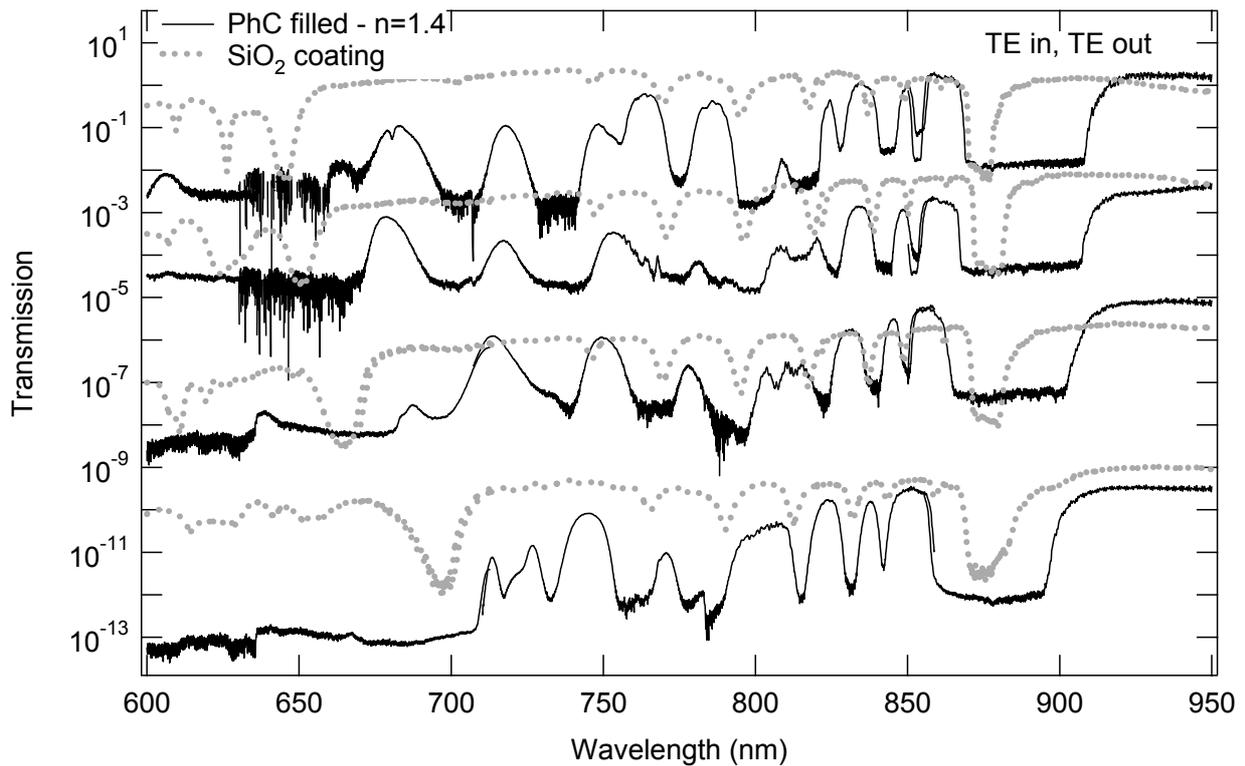


Figure 10: Transmission spectra for liquid filled holes and SiO₂ overcoated samples.

Solid traces show spectra for a liquid filled device. Both edges of the primary band-gaps are extremely well defined with an extinction ratio better than 20dB in the band-gap. In addition, there are several well defined dips in transmission corresponding to dispersive features of the photonic band-structure. The position of these features shift only slightly with direction of propagation. Overall transmission reduces significantly as wavelength gets smaller and at wavelengths below 675nm the liquid filled spectra become extremely lossy.

Dashed traces show spectra for SiO₂ over-coated samples. Again the edges of the primary band gap are very well defined, but its width is somewhat reduced due to a reduction in Δn between the holes and the core material. As was the case for the liquid filled samples, dispersive dips are observed at wavelengths below the lower band edge, in roughly the same positions, however they are more sharply defined and transmission returns to near unity inbetween.

The most significant feature of the SiO₂ over-coated spectra is the fact that the overall transmission amplitude remains near unity over the entire wavelength range of the scan. In fact the loss for the over-coated sample was found to increase by just 0.07dB across the entire wavelength range 680-900nm. Strong dips are also observed over the wavelength range 600-700nm. These change position rapidly with direction of propagation, and thus correspond to higher order mini-stop bands of the photonic crystal. These features are not apparent at all in the liquid filled spectra due to high losses at those short wavelengths.

The differential in loss between the liquid filled and SiO₂ overcoated sample was again quantified by comparing the amplitude of several peaks across the wavelength range 600-850nm. Loss was found to be reduced by an average of 16dB across this entire wavelength range, varying from 10dB at 785nm to 20dB at 600nm.

Overall insertion loss (excluding facet coupling loss) for the overcoated Photonic crystal device was measured to be just 4.5dB. The majority of this insertion loss can be attributed to a miss-match in effective mode index between the input and output slab waveguide regions and the photonic crystal region, hence loss does not in this case scale significantly with number of rows. This result has extremely important implications for the realisation of commercially viable super-prism and time delay components, whose performance is largely limited by a trade off between total

number of rows of lattice periods and insertion loss. Furthermore, as these applications do not necessarily require the existence of a photonic band gap, but merely require the existence of strongly dispersive features, our novel loss reduction mechanism allows higher order dispersion bands to be utilised for these applications. This greatly reduces fabrication tolerance since required lattice pitch scales directly with dispersion band number.

4. AFFECT OF ETCH DEPTH

Finally, we investigate the influence of etch depth on loss. Figure 11 shows theoretical transmission spectra for a photonic crystal device etched some distance into a slab waveguide structure identical to that investigated in section 3 (600nm top cladding layer 180nm core layer, 2.2 μm buffer layer) as a function of etch depth. In this case the photonic crystal consists of a triangular lattice with holes of index $n=1.3$. As a reference, spectra for holes etched through the cladding layer to the core / cladding interface only are plotted. In this case transmission remains at unity (as would be expected from a normalised spectra) except close to the edges of the photonic band gap where the influence of perturbations of the cladding becomes more significant.

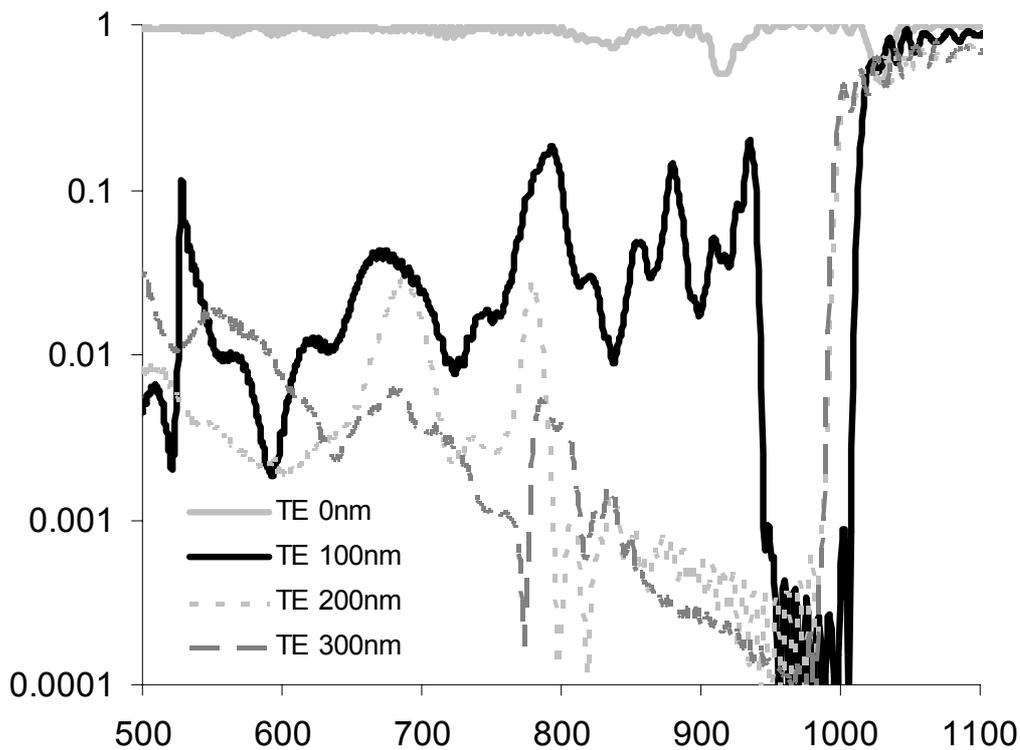


Figure 11: Affect of etch depth from on loss. Depth measured from core / top cladding boundary. Core thickness 180nm.

Etching down approximately 50% through the core layer (100nm) results in the formation of a strong primary photonic band gap with an extinction ratio of approximately 40dB inside the bandgap, and several weaker dispersive features at shorter wavelengths. As discussed in the previous sections of this paper, loss increases as wavelength decreases.

Etching beyond the core / buffer interface the situation changes very significantly. The lower edge of the photonic band gap nearly completely disappears, with very high losses over a wavelength range greater than 150nm below the lower band gap edge. Further increase in etch depth changes (eg 300nm) loss very little more. This phenomena can be attributed to scattering to underlying substrate modes.

Provided the holes do not breach the core / buffer boundary, the effective index of the guided Bloch modes in the spatial vicinity of the holes remains very slightly above that of the underlying buffer layer and so light remains well confined to the core layer. Etching beyond a certain critical depth reduces the effective index of the guided mode in the spatial region of the hole below that of the underlying buffer layer and light becomes coupled to substrate modes inducing high losses.

5. CONCLUSIONS

In conclusion, we have demonstrated a significant milestone in the reduction of scattering loss in photonic crystal slab waveguide devices. Loss was reduced by 4 – 9 dB over the spectral range 500-1000nm by incorporating index matched fluid in the holes of an otherwise lossy photonic crystal device. Loss was reduced by a further 10-20dB over the same wavelength range by filling the holes with SiO₂ by PECVD. Insertion loss of the resultant photonic crystal region was measured to be just 4.5dB, most of which was shown to be attributed to coupling loss. Loss was found to increase by just 0.07dB over the entire visible spectra. This is to our knowledge the first detailed practical or theoretical investigation of broadband loss in photonic crystal slab waveguides, and the first practical realisation of a photonic crystal device capable of using higher order photonic band gaps in applications such as super-prisms and optical time delay elements.

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