



Cryan, M. J., M., H., R., V., M., R., Craddock, I. J., Yu, S., ... Rorison, J. M. (2003). Modelling and measurement of 2D photonic crystals with tapered hole profiles. In 2003 International Conference on Transparent Optical Networks - ICTON 2003. (Vol. 1, pp. 344 - 347). Institute of Electrical and Electronics Engineers (IEEE). 10.1109/ICTON.2003.1264651

Link to published version (if available):
[10.1109/ICTON.2003.1264651](https://doi.org/10.1109/ICTON.2003.1264651)

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Modelling and Measurement of 2D Photonic Crystals with Tapered Hole Profiles

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ABSTRACT

2 and 3D Finite Difference Time Domain (FDTD) simulations and measurements of a hexagonal lattice 2D photonic crystal with holes having taper angles in the region of 3 to 7 degrees are performed. The results show a smoothing of band edges and increased losses. Reasonably good agreement between measured and modelled results is obtained.

Keywords: Photonic Crystals, 3D-FDTD

1. INTRODUCTION

Two dimensional Photonic Crystals (PCs) can be fabricated by a number of methods [1]. These include Chemically Assisted Ion Beam Etching (CAIBE), Electron-Cyclotron Resonance-Reactive Ion Etching (ECR-RIE) and Inductively Coupled Plasma (ICP) Etching. Recently another approach has been investigated which uses Focused Ion Beam Etching (FIBE) [2]. This is a rapid, maskless etching technique which allows post processing of semiconductor devices [3]. Whilst it has the advantage of very fast turnaround times, the hole verticality is less good than other approaches with typical hole angles in InP in the range of three to seven degrees. Currently more advanced methods involving FIBE are being investigated to overcome this problem. In order to characterise currently fabricated devices it is important to understand the effects of hole angle on PC based devices. In fact angled holes may prove useful in applications such TE/TM mode conversion. Also as PC based devices begin to approach real applications it is important to understand the impact of fabrication induced effects such as random hole position, radius and hole taper angle. To this end 3D FDTD modelling and measurements are used to study the effect of hole taper angle.

2. MODELLING

FDTD is a fullwave method which allows arbitrary combinations of high index contrast dielectrics and as such is ideally suited to the study of PC based devices. The FDTD code used in this work is a mature in-house code which has been used to study losses in PC waveguides [4]. The structure to be studied is shown in plan view in figure 1. It consists of a hexagonal lattice of air holes etched into a 3 layer slab guide. The PC has a lattice constant of 364nm and a radius to lattice constant ratio (r/a) at the core of the waveguide of 0.22. Propagation is in the gamma-M direction. The waveguide consists of an upper cladding of 400nm, refractive index=3.17, a central core of 240nm, refractive index=3.46 and a lower cladding layer of 1000nm, refractive index=3.17. Input and output ridge waveguides are used to couple power into the structure. Two different ridge widths are used, firstly a narrow width for coupling to PC waveguides and secondly a wider ridge for modelling purposes. It should be noted that since the structure is symmetrical and being excited symmetrically only half the structure need be simulated and an electric wall can be placed at the centre of the structure when TE excitation is being used. Initially a quasi-2D version of the 3D code was used to study the structure – in order to decrease runtimes [5]. Translight [6], a Transfer Matrix Method code was used to validate these initial simulations, the results are shown in figure 3.

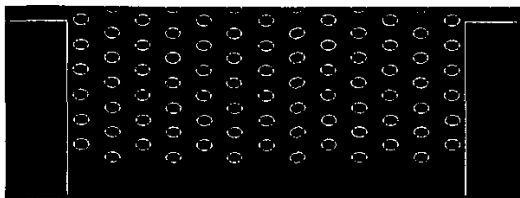


Figure 1 Plan view of Photonic Crystal structure, narrow ridge guides.

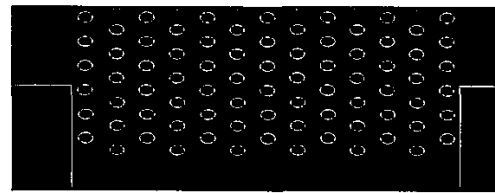


Figure 2. Plan view of Photonic Crystal structure, wide ridge guides.

Figure 3 shows quite good agreement in the case of wide ridge guide and less good with the narrow guide. This is as expected since Translight assumes an infinite plane wave to be incident on the structure. The narrow guide results show that increased losses result, here most likely due to diffraction from the narrow guide, however, for PC waveguide applications narrow guides are required for good coupling.

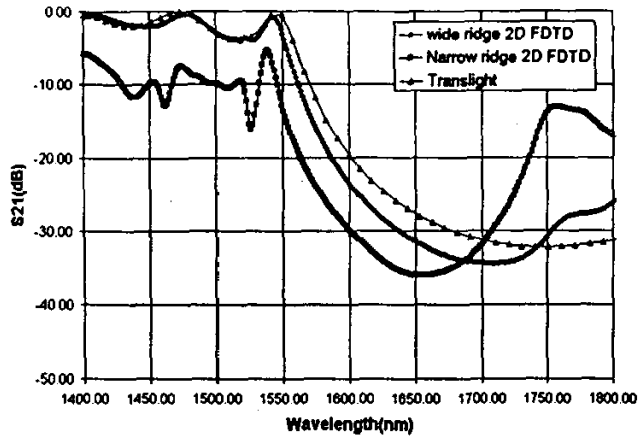


Figure 3. Transmission coefficient for structures in figures 1 and 2 compared with translight, $r/a = 0.22$.

Having validated the 2D code, the 3D structure can now be studied. Here the structure is excited with the fundamental TE mode of the input waveguide, derived from a 2D FDTD mode solver. Figure 4 shows a vertical cross section through the structure with tapered holes and figure 5 shows an individual hole showing how it is constructed from a set of cylinders. A number of simulations are performed, firstly, vertical holes with no taper and tapered holes with angles of 3 and 7 degrees.

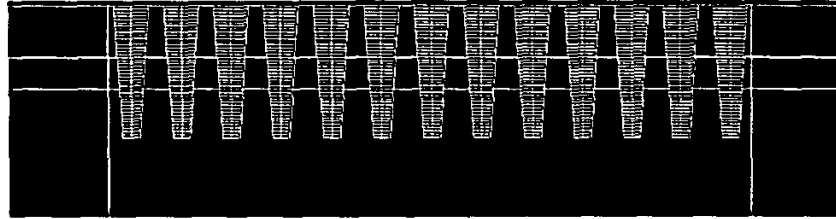


Figure 4. Vertical cross section through PC structure with tapered holes.

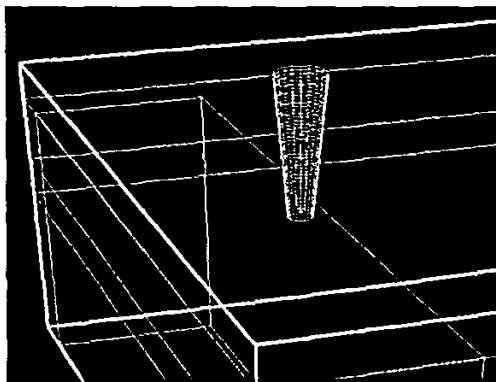


Figure 5. 3D view of isolated hole.

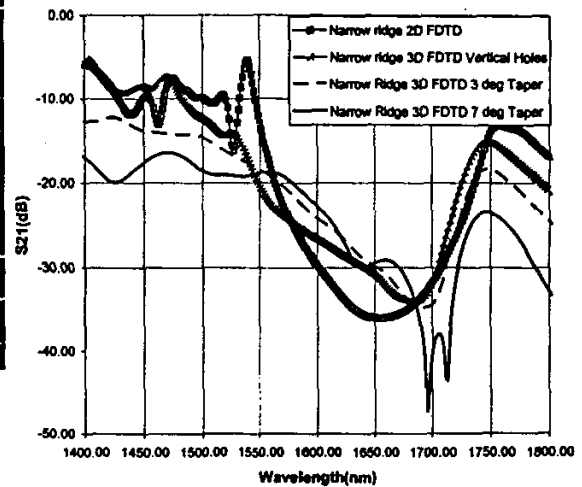


Figure 6. Comparison of transmission coefficient for 2D FDTD and 3D FDTD with vertical and tapered holes.

Figure 6 shows the simulated results for the 3D structure, with the 2D results added for comparison. The 3D vertical holes results have an r/a value of 0.22 in order to compare with the 2D results. The results show that in going to finite depth, vertical holes, losses are increased as might be expected. When tapered holes are introduced a very smooth band edge around 1550nm results with again higher losses.

3. MEASUREMENTS

Figure 7 shows the structure that has been fabricated using FIBE [2]. The PC structure has been etched into a InP slab waveguide with dimensions estimated to be equal to those given in the modelling section above.

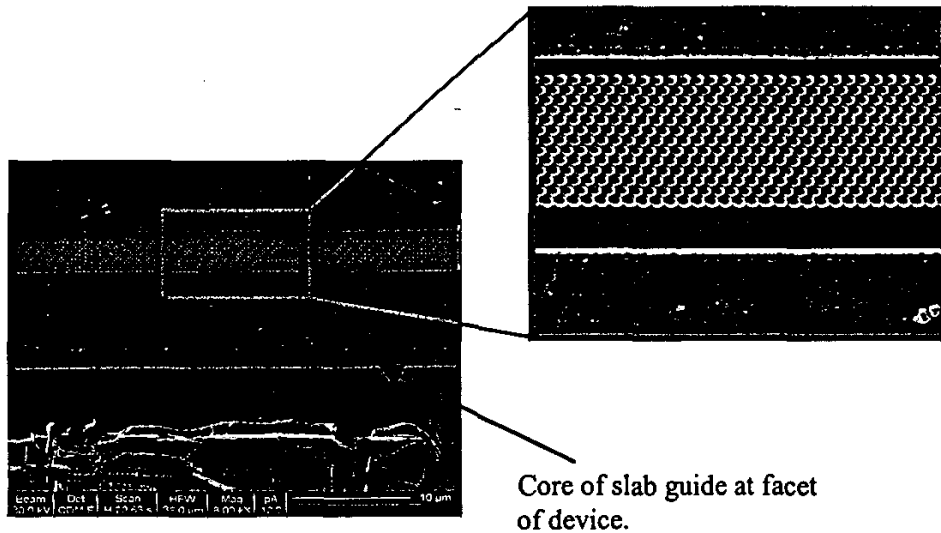


Figure 7. Fabricated 2D Photonic Crystal structure.

The inset in figure 7 shows how the bulk material has been etched away such that the holes are not required to be as deep. The transmission response of the structure has been measured using the set up shown in figure 8. Power is coupled into the structure from a fibre lens.

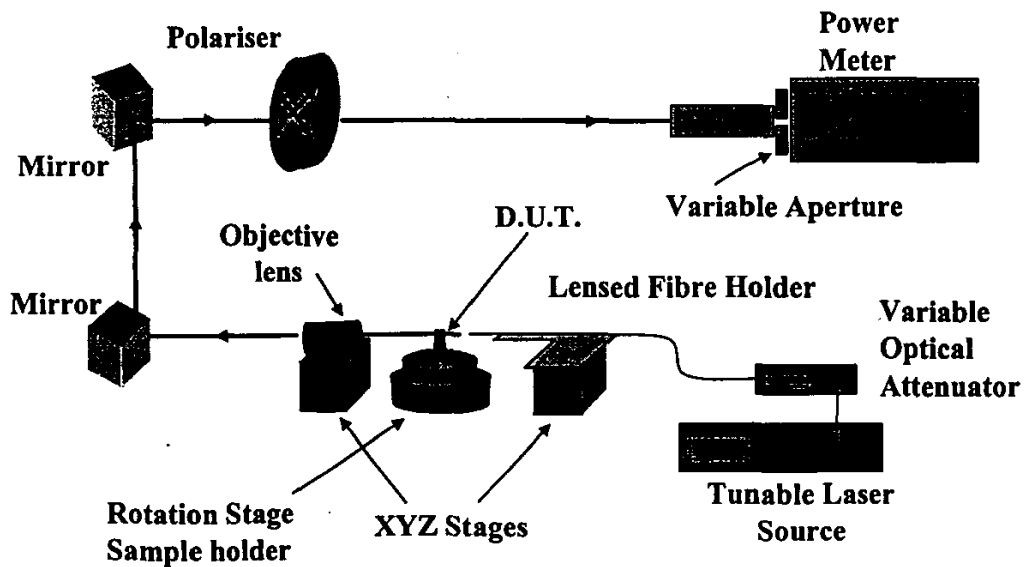


Figure 8. Transmission measurement set-up.

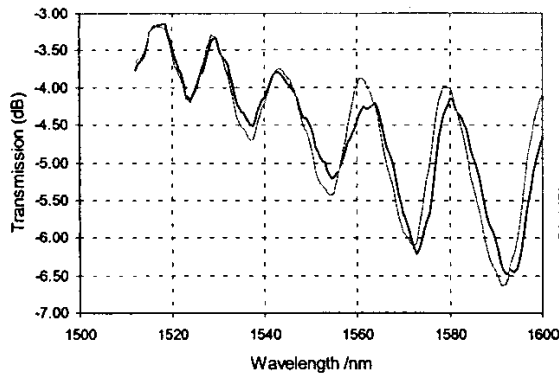


Figure 9. Measured transmission data for structure shown in figure 7. Two separate measurements of the same device are shown.

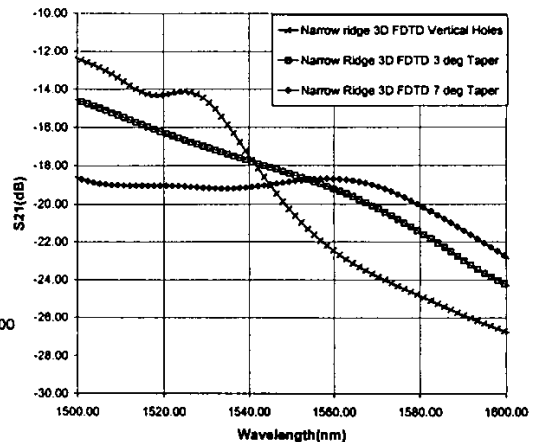


Figure 10. Zoom of figure 6 for comparison with measured data.

Figure 9 shows the measured transmission data, a slope in the order of 3dB is observed. The compares reasonably well with a simulated slope for the 7 degree angled hole of 4dB. The ripples occurring in the measured data appear to be due to a Fabry-Perot effect and it is interesting to note that the ripple period is changing substantially across the band, this could be due to the highly dispersive nature of the PC section. 3D simulations will be carried out coupling power from air into the structure to further study these Fabry-Perot effects. The relative levels of the signals are somewhat different this is due to the fact that the 3D simulation are excited from a narrow ridge guide, whereas the measurements use a slabguide. Work is now under way to use FIB etching to define input and output waveguides enabling improved comparison, also 3D simulation with wide ridge guides are being carried out.

4. CONCLUSIONS

This paper has used both 2D and 3D FDTD and measurements to study the effects of hole tapering in Photonic Crystal structures. It has been shown that the tapering has the effect of smoothing out the band edges and increasing the losses outside the band gap, also evidence for strong dispersive behaviour has been observed. A number of further developments are being carried out including the use of deep etched ridge guides for coupling and advanced FIB based processing for decreasing hole tapering. Also a study of the TE/TM mode conversion properties of the tapered hole PCs is being carried out.

ACKNOWLEDGEMENTS

The authors would like to acknowledge the PHOTON consortium funded by UK EPSRC for partial support of the work.

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