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Design and Simulation of a Photonic Crystal Waveguide Filter Using the FDTD Method

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Abstract. *The FDTD method is used to design a InP photonic crystal (PC) waveguide filter operating at 1534nm. The filter uses strong mode coupling effects which result in a small device area of 8μm x 10μm.*

Introduction

Photonic crystal (PC) based technology is seen as a potential route to the next generation of photonic integrated circuits (PICs) which can be implemented in mm^2 instead of cm^2 [1]. A key component in this technology is the PC waveguide, figure 1 shows a typical configuration for an InP based waveguide system. The guide is formed by removing 3 rows of holes from a 2D PC etched into a slab waveguide structure. These 2D based PC waveguide structures have been the subject of much study as they are seen as ideal candidates to integrate both passive and active functions onto one PC based PIC [1,2,3].

It has been observed recently that the periodic nature of the boundary of a PC waveguide can give rise to coupling between the fundamental and higher order modes [4]. This leads to the formation of sharp dips in transmission, termed mini-stopbands (MSBs). The possibility of using MSBs to create filters has been suggested [2] and work has been done on predicting the spectral location of the MSBs. However, for filtering applications the amplitude of the MSB dip is also critical and this paper aims to show how the spectral location and amplitude of the MSB dips can be tuned in order to obtain good filter action.

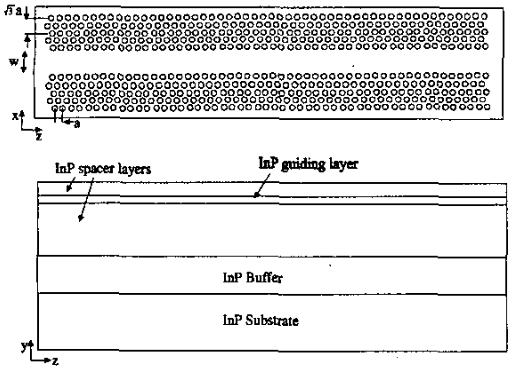

Figure 1 : InP photonic crystal waveguide, a=lattice constant, L=30a.

Modelling

The finite difference time domain (FDTD) method has been used to design the filter[5,6]. This is a full-wave vector 3D electromagnetic method which directly solves Maxwell's curl equations in the time domain. It is ideally suited to the study of PC structures since it can readily analyse arbitrary combinations of lossy dielectrics and metals. An in-house code has been used to simulate the structures. The code is fully 3D but is being used in a 2D configuration for this initial investigation. The 3D aspect of the code will be important for assessing the role of hole depth on the performance of the structure [7]. The 2D configuration is achieved by using only 4 FDTD cells in the height of the structure and terminating the top and bottom boundaries with perfect magnetic conductors, thus restricting the simulation to TE modes only.

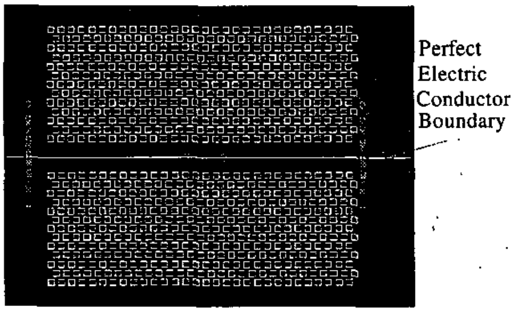

Figure 2 : FDTD model for structure of figure 1

Figure 2 shows the structure simulated using the Bristol FDTD user interface. Since the strcuture is symmetrical about the centre of the guide and is being excited symmetrically, a perfect electric conductor boundary can be introduced and only one half of the structure need be simulated. The simulation proceeds by first calculating the effective refractive index for the structure in figure 1. This then is used as the background refractive index for the 2D structure into which square air holes are placed. Square holes are used since they more readily match the Cartesian grid used in the FDTD method. Equivalent areas can be used to calculate the radius for round hole based structures. The waveguide is excited with a Gaussian modulated sine wave centred at 1.55μm and Mur first order boundaries are used to terminate the structure [6]. The transmission response of the structure is caculated by first performing a simulation with no holes present and monitoring 10 field points across the input of the waveguide (circles in figure 2). From this the frequency domain Poynting vector at each of the probes is calculated and summing across all probes

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gives the total input power. This procedure is repeated at the output of the guide with the PC waveguide present. The ratio of these two powers gives the transmission coefficient.

Results

Figure 3 shows the transmission coefficient results for three guides of different widths. Initially a guide with 3 missing rows was simulated and marker "A" shows the position of a mini-stop band. It can be seen that the filter characteristic here is not good, also the wavelength is far removed from the important region around 1550nm. In [2] it has been shown how the MSB wavelength can be estimated by treating the waveguide walls as the mirrors of a Fabry-Perot cavity, thus by reducing the waveguide width it is anticipated that the MSB wavelength will also reduce. This is observed in figure 3 with the 140nm narrower waveguide results. The point B corresponds to the same mode coupled MSB and now good filter performance is observed. The transmission coefficient is –16dB with a 3dB bandwidth of approximately 1.6nm, centred at 1534nm (see inset in figure 3). As the waveguide is narrowed further, the MSB wavelength reduces to point C and the filter characteristic worsens.

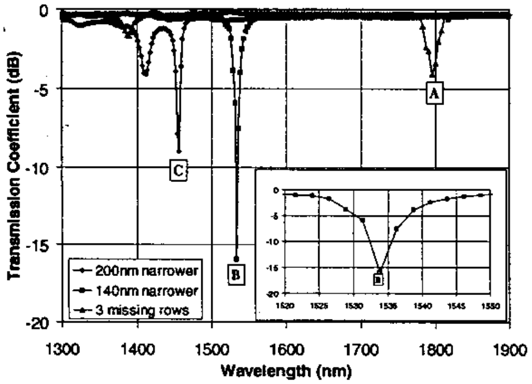
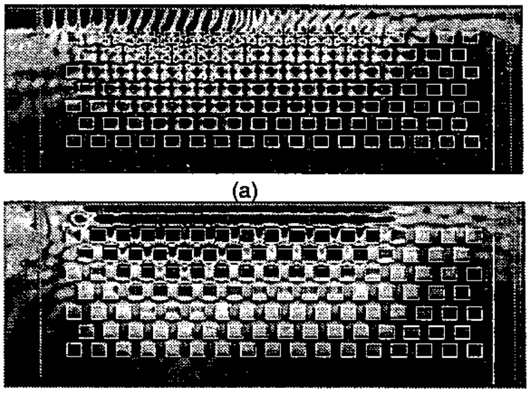


Figure 3 : Transmission response for structure of figure 1 with 3 different waveguide widths

One of the key features of the FDTD method is that the fields within the device can be observed both in the time domain and using Fourier transforms, in the frequency domain. This can greatly increase the understanding of devices such as the PC waveguide filter. Figure 4 shows frequency domain Electric field plots calculated at the MSB wavelength, point "B". From figure 4a the E_x component can be seen to decrease in amplitude from the input to the output of the guide corresponding to the large dip in transmission at point "B". The mode coupling behaviour can be observed by looking at the E_z component in figure 4b, where the presence of a higher order mode is clearly observed.


(a)

(b)

Figure 4 : Frequency domain electric field plots at 1534nm, (a) E_x, (b) E_z (Darker=higher intensity within waveguide region, plot has a dark background)

Conclusions

It has been shown how the FDTD method can be used to design PC waveguide filters. Good filter performance, with potential application in coarse WDM, has been shown around 1534nm. The filter is extremely small, measuring 8μm x 10μm. The use of FDTD will allow more advanced structures, including defects, to be investigated enabling the optimisation of the filter response to that required in real applications. The InP waveguide structure and processing facilities are available in-house and mask design is under way.

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