Properties of directional couplers using photonic crystal waveguides

Thorhauge, Morten; Borel, Peter Ingo; Frandsen, Lars Hagedorn; Kristensen, Martin; Lavrinenko, Andrei; Chong, H.

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first describe the properties of the high index inclusions (layers or cylinders). Each high index layer is considered as a step index waveguide that supports bound normal modes and associated cutoff conditions for those modes. In what follows it is shown that the spectral minima for the light propagating in the core are in fact determined by the modal cutoff condition for the modes of these high index layers in the cladding of the waveguide. In the case of step-index planar and cylindrical waveguides, the cutoff condition for these modes can be found analytically. At the cutoff (resonant) wavelength for a particular mode, the high-index layer becomes "transparent" and light escapes from the core resulting in minima in the transmission spectrum.

For twisted ring structures, the location of the transmission minima using this method are the same as those derived in Ref. [5] for the ARROW waveguide using a Fabry-Perot approach. This should be expected as the resonance condition for the cascaded Fabry-Perot sections matches the mode cutoff condition in the slab waveguide. The present approach, however, has an advantage over the Fabry-Perot analogy when considering complex MOF structures, where the Fabry-Perot resonances are no longer obvious, while the mode cutoffs are still obtainable. Because of their similarities, the planar and ring structures will be considered together.

I. Planar and ring structures (Fig. 1(a,b))

For these geometries the cutoff conditions (and the spectral minima) for the one-dimensional structure can be found from the following equation:

$$\tan\left(\frac{\pi d}{\lambda} \sqrt{\frac{2}{\gamma} - \frac{2}{\gamma_0} - \frac{m^2}{\gamma_n^2}}\right) = 0,$$

and are given by

$$\lambda_m = \frac{2d}{\gamma_n^2 - \gamma_0^2} \left(\frac{m^2}{\gamma_n^2} - 1\right).$$

A comparison of the predictions obtained from Eq. (2) with numerical simulations using beam propagation method, are shown in figure 2 along with a schematic of modal cutoff.

Along with verifying the accuracy of our predictions for the spectral minima, figure 2(c) indicates that it is generally higher order modes that are excited in the high index inclusions. Although any mode is allowed by equation 2, the light is launched into the low index region, thus Snell’s law determines the angles of the light in the high index areas. Because the index difference between these regions is large, the low angles necessary to excite the lowest modes cannot be reached. Thus the primary mode excited will be the lowest one possible. Higher modes can exist, but in typical layout conditions, these modes will have little energy.

I. Two-dimensional structure - cylinders

Again we look for the location of the transmission dips in the MOF to be at the mode cutoff locations. The natural modes of the most general circular cylinder with arbitrary isotropic internal and external media are given by Stratton [6]. The structure shown in Fig. 1(c) supports three mode types: TE, TM, and hybrid EH modes.

Similar to section I, we find the resonant condition as follows

$$\lambda_m = \frac{2d}{\gamma_n^2 - \gamma_0^2} \left(\frac{m^2}{\gamma_n^2} - 1\right).$$

Figure 3 (a) shows real and imaginary parts of the effective index as a function of wavelength for the structure shown in figure 3(b). The imaginary part corresponds to loss in the structure, which means large $\Im(\gamma_n)$ corresponds to high loss or transmission spectrum minima. The locations predicted by Eq. (3) are compared to those obtained using the multipole method and are shown by straight lines in figure 3(a). Also described in the figure is the resulting modal structure (longitudinal part of the Poynting vector $S_x$ and cross section of $S_y$ along $x$ axis) in the inclusions.

3. Conclusion

In summary, we proposed a simple analytical model to describe the spectral properties of photonic crystal waveguides and fibers with low-index core and high-index inclusions. This model suggests that the positions of spectral minima can be found by calculating the cutoff wavelength for the modes of high-index regions and therefore depend only on the mode structure of those inclusions. These predictions were compared with numerical simulations.

4. References


Introduction

Photonic Band Gap (PBG) materials are important building blocks for future optoelectronic devices. In principle they can be used instead of usual index-guiding components, utilising the original properties of PBG effects in Photonic Crystals (PCs). The more confined guidance provided in PCs may be beneficial to linear and non-linear components, and the PC structure may allow novel types of components. One of the interesting components, which can be made in PC, is the wavelength selective waveguide coupler. Such a coupler may show new features not realisable in traditional index-guided ridge waveguide couplers due to the much higher confinement of light and the fundamentally different guiding properties.

We have done extensive modelling of such coupled waveguide structures in a 3D Finite Difference Time Domain (FDTD) scheme, and fabricated the designed components in Silicon-on-Insulator (SOI). The modelled and experimental results are in good agreement.

Modeling

The software used for modelling is the Oxyx-x FDTD code [2] modified for 3D computation. As pointed out recently by several authors [3-7] the transmission spectrum in the PBG zone is rather broad, indicating leaky mode contributions to the transmission. Propagation losses are determined by the coupling of leaky modes lying above the light cone with and substrate radiative modes, and can therefore only be described correctly in 3D calculations.

The PC structures modelled consist of a triangular pattern of air holes made in SOI. The holes were chosen to have a normalised radius of 0.375 (radius/lattice pitch), as this gives the largest band-gap [8]. The holes in the calculations were given a dielectric constant $\varepsilon = 4.411$, in order to mimic the fabricated samples, which have a layer of silica on the hole wall.

The waveguides were defined by removing one row of nearest-neighbour holes, thereby making a line defect. The layer structure for the 3D calculations consisted of 1 A silica base cladding, 5/8 A silica core, 1/4 A silica top cladding, and 3/4 A air, A being the lattice pitch, the centre-to-centre distance between nearest-neighbour holes.

Figure 1

Port 1a
Port 1b
Port 2
Port 3
The modelling structure had a coupling region consisting of two waveguides next to each other separated by a single row of holes. The coupling length was 27 A. After the coupling region one waveguide was continued for an additional 7 A, while the other channel was left away from a row of holes next to the first two 60-degree bends and a short intermediate waveguide section, creating an output port separating the two components.

The IOWs were optimised in order to increase transmission (one hole moved) [9]. The component has four ports, two input ports 1a and 1b, respectively, and two output ports 2 and 3. Only one input port was excited at a time, the input port not in use being blocked by three holes following the triangular pattern.

Experiment

For the experimental part two samples were fabricated with structures resembling the ones modelled (figure 1), one with port 1a blocked, and the other with port 1b blocked (figure 2). To be able to define in- and out-coupling ridge waveguides it was necessary to separate the output ports further with a longer intermediate section in the waveguide with two sixty degree bends, so the output ports were spaced by 28 rows. E-beam lithography was used to define the hole pattern in resist on silicon wafers. The e-beam resist acted as a mask in the subsequent transfer of the pattern to the Silicon layer by Reactive Ion Etching (RIE). After removal of the resist, the pattern was further transferred to the Silicon base layer by RIE, using the Silicon core layer as a mask. Finally, a Silicon top cladding was grown on the surface of the Silicon layer by thermal oxidation. The Silicon top cladding serves to make the structure vertically symmetric and more robust. The lattice pitch \( A \) was chosen 420 nm.

Ridge waveguides gradually tapered down from 4 \( \mu \text{m} \) to 1 \( \mu \text{m} \) at the PC structure were used to route the light without reflection. We performed transmission measurements using tapered fused fibers to couple light into and out of the sample. The light sources consisted of unpolarized light emitting diodes with centre wavelengths at 1310 nm and 1550 nm. The spectra were recorded using an ANDO AQ6317 optical spectrum analyzer. Before each measurement the coupling to the sample was optimised for maximum transmission. All measurements were normalised to a fibre-to-fibre-to-fibre measurement.

Results and comparison

For the coupling with port in 1a, (see figure 1), we get the results plotted in figure 3. This fits the straight-through result with transmission measured at port 2. As the 3D FDTD model uses a TE polarisation, and the sources in the experiment were unpolarised, the measured results have been added to account for this. The TM modes are expected to have a highly lossy due to the lack of band gap at the examined wavelength band [1,8].

In figure 4 modelled and measured results for a flux with input into port 1a and transmission measured at port 2 is shown. This is the coupled result. Again a good resemblance is seen, though the measured results at 1315 nm is completely missing in the experimental data. The reason for this is currently not fully understood. Between 1400 nm and 1480 nm the measured data are quite noisy, which is due to the weakness of the source in this region together with the low level of coupling. The data have been added to the measured data here, too. Looking at figures 3 and 4 a strong dependence of coupling on frequency can be seen. Around 1560 nm the uncoupled transmission drops rapidly more than 20 dB, and the structure acts as a low-pass filter. For the coupled transmission in figure 4, the spectrum peaks around 1545 nm with a peak level around 10 dB higher than the dip at 1500 nm.

Conclusions

We have investigated coupled waveguides in photonic crystals with triangular geometry by 3D FDTD modelling and in real life samples. We have shown that we can fabricate samples showing qualitatively correct transmission spectra when compared to 3D FDTD modelling results. We have also shown, we can design and fabricate structures exhibiting highly wavelength selective transmission spectrum behaviour. These promising results have provided us with valuable insights into the behavior of coupled PBG waveguides, which can be used in the design and modelling of new, efficient components utilising such structures.

References