New design rules for planar photonic crystal devices obtained using automatic optimisation, leading to record efficiencies

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Abstract *We present new designs of waveguide components in photonic crystal structures exhibiting high transmission, elaborated with novel optimisation technique. 3D FDTD simulations confirm their unprecedented efficiency and robustness with respect to wavelength and structural perturbations.*

Introduction

The development of integrated optics components based on planar photonic crystals is a very active and rapidly developing field. Following the numerical proposals for efficient waveguiding, sharp bends and junctions in photonic lattices [1], the race is now on to demonstrate these concepts in real optical systems. Straight waveguides with respectable losses [2-5], S-bends [6] and first “systems” consisting of guides connected to cavities [7] have now been demonstrated by a number of groups. Attempts have also been made at designing optimised structures using heuristic approaches [8]. In contrast, we show here how appropriate global optimisation techniques can be successfully used to design novel highly efficient structures and confirm the low loss of our designs using 3D FDTD simulations.

The system to be optimised

We aim to optimise the transmission through a splitter system in a photonic crystal device. The photonic crystal has a triangular lattice of air holes with the ratio between the diameter and the pitch $D/a = 0.70$ etched in a dielectric substrate with (effective) refractive index $n=2.5$. Light is injected into the splitter system via an *injector* with input width of 5μm. The injector is etched in the same material and therefore has the same refractive index. The aim is to optimise the injector, Y-junction and bend geometries in order to maximise power transmission for the given excitation of the fundamental mode of the input waveguide (fig. 1).

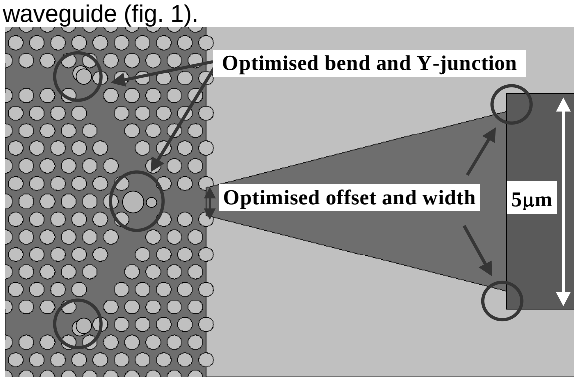

Fig.1 Layout of components with optimised elements of the structure

Choice of working wavelength

For the 2D calculations we use an EME (eigenmode expansion) algorithm [9] to calculate the fields. Losses in the studied system include a) in-plane losses while guiding modes along a line defect and b) out-of-plane scattering. We initially investigate only the bidimensional system where out of plane losses are ignored. The lattice has a band gap in the range $0.31 \leq a/\lambda \leq 0.38$. We further restrict ourselves to the sub range $0.36 \leq a/\lambda \leq 0.38$ of this bandgap where only one mode (of even symmetry) can propagate in the line defect. This way we avoid the problem of modal cross coupling and simplify the design process.

Optimising the injector

We aim to find a taper with the shortest possible length giving efficient transmission into a lattice line defect. For a given length, a *local optimisation* algorithm is used to find the offset at the beginning, and the aperture at the end of the taper giving optimal transmission from the fundamental mode of the input waveguide (fig. 1). We repeated this optimisation for a range of taper lengths and picked the shortest possible length (9μm) giving over 97% transmission.

Optimising the Y-junction

Next we attempt to increase the transmission through the Y-junction by varying the size of the two holes (D1,D2), as well as the horizontal position (L) of one hole, the other been fixed at a lattice point (Fig. 2, left). The ranges for varying of parameters are: $0 \leq D1,D2 < 0.5\mu m$, $-0.5\mu m \leq L < 0.5\mu m$. This means that the two holes are allowed to overlap, or even disappear, thus admitting different shape topologies. This invariably leads to a non-trivial optimisation problem likely to contain several sub-optimal configurations. Clearly local optimisation techniques are inappropriate here, and we are therefore obliged to use some form of *global optimisation*.

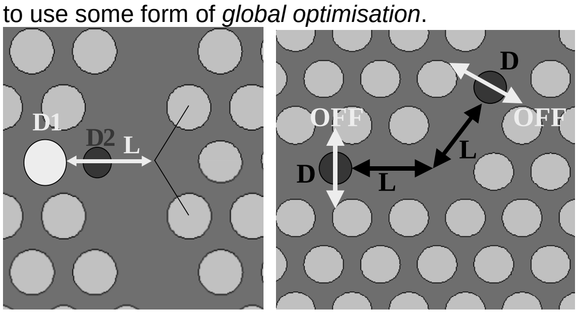

Fig.2 optimisation parameters for Y-junction (left) and bend (right)

The global optimisation algorithm

We chose to use the the global optimisation routine contained in [10]. This technique systematically subdivides the parameter space, using an internal algorithm to split more quickly in regions most likely to contain an optimum. Since the entire parameter space is eventually explored, this optimisation technique is not only guaranteed to (eventually) find the globally optimal solution, but can also show other interesting local optima. This latter characteristic turns out to be essential in the analysis that follows.

Genetic algorithms could also have been used, however they do not have these useful properties, as they use stochastic search criteria to converge only on one single optimum, which is likely, but not guaranteed, to be the global one.

Steering vs. resonant transmission

The optimisation results showed up two different optimal configurations, both giving extremely good transmissions - nearly 100%. The first one corresponds to a *resonant* transmission (fig. 3, left) where the cavity mode formed by the two "variable" holes plays a decisive role in this optimal transmission. However it has a very bad response with respect to wavelength variations: the transmission drops to below 40% with 20nm variations (at frequency $a/\lambda=0.378$). The second optimum has radically different transmission mechanism, as it exploits a *steering* effect (fig. 3, right) - the incoming signal is "smoothly" split into the two branches. As expected the frequency response of this optimal configuration is much better: the transmission drops by only 2% over the same wavelength shift! Perturbation information from the optimiser also shows the steering type bo be more structurally stable: for example 30nm perturbations of the variable holes reduce the transmission by 10% for the resonant type and only by 2% for the steering type.

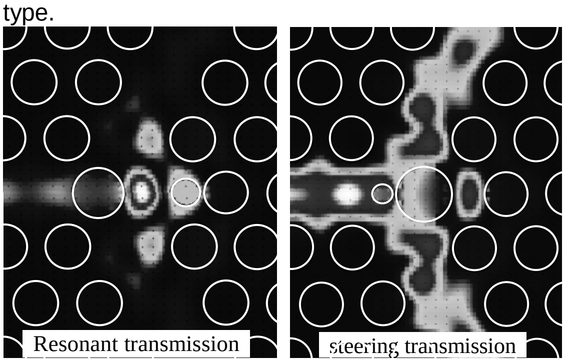

Fig. 3. Two optimal Y-junctions, both giving virtually 100% transmission. However the steering type is more stable WRT wavelength and structure perturbations.

Optimising the bend

Finally we attempt to improve the transmission through the 60^{o} sharp bend by varying the size (D) of two holes placed in the line defect symmetrically on either side of the bend, the distance (L) from the bend origin and the offset (OFF) from the axis of the line defect (fig 2, right). Taking the pitch $a = 0.5\mu m$ we allow the optimisation parameters vary in the ranges: $0 \le D < 0.5\mu m$, $0 \le L < 0.5\mu m$, $0 \le OFF < 0.5\mu m$. The global optimiser shows the appearance of several optimal solutions. Again, there is an optimum with steering type transmission with extremely good frequency response. The global optimiser also indicates that this optimal solution is more insensitive to structural perturbations.

3D FDTD analysis

To understand how these results carry to 3D, we applied this optimal configuration to an equivalent three dimensional photonic crystal membrane with thickness 1.5D suspended in air. The line defect is still a single mode waveguide for this thickness as the membrane is too thin to carry any vertical modes. 3D FDTD was used, and the power exiting at both branches was measured. The results (Fig. 3) clearly show that around the wavelength of interest ($\lambda = 1.34\mu m$) the steering optimum (more than 76% in both channels) gives a much better improvement than the resonant optimum over a 40nm spectral range. Both of these are a marked improvement over the original structure which exhibited only 10% transmission, and over a much smaller spectral range. The marked improvement of steering vs. resonant optima may be explained by resonant structures having generally higher out of plane losses, as photons have more time to escape up or down.

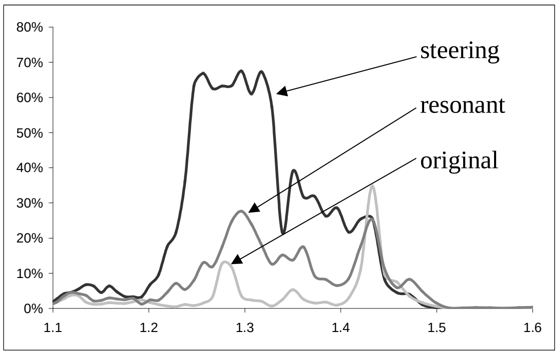

Fig. 3. Transmission vs. wavelength for 3D structures.

Conclusions

Automatic optimisation using 2D EME and 3D FDTD studies have suggested highly efficient designs for photonic cystal circuit elements including Y-junctions, bends and injectors. These studies suggest a simple rule:

Photonic crystal circuit elements ***must*** *avoid resonant features.* The reasons for this rule are:

- non-resonant structures generally have much wider bandwidth
- non-resonant structures generally are more tolerant to manufacturing errors
- non-resonant structures generally have much lower out-of-plane losses.

Applying this design rule with the aid of automatic optimisation, we have obtained record theoretical transmission efficiencies of over 76% for a 3D Y-splitter.

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