# Record transmissions achieved in photonic crystal waveguide components through novel automatic optimisation techniques.

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**Abstract**: We present new designs of waveguide components in photonic crystal structures exhibiting virtually total transmission, and are remarkably stable with respect to wavelength and structural perturbations. 3D FDTD simulations show that these 2D designs provide the basis for real world 3D photonic crystal structures with unprecedented efficiency.

## 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 have now been demonstrated by a number of groups [2-5]. S-bends [6] and first "systems" consisting of guides connected to cavities [7] are also beginning to appear. 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.

The optimiser and field solver are now integrated into FIMMWAVE/KALLISTOS, a software package commercially available from Photon Design [9-10], which was used to produce the results that follow.

## The 2D crystal structure – choice of working wavelength.

We choose as our example as the photonic crystal with a triangular lattice of air holes etched in a dielectric substrate with (effective) refractive index n=2.5. The structure is for now assumed to be bidimensional, i.e. the air holes are infinitely long, and the ratio between the radius and the pitch is $D/2a = 0.35$. The lattice has a band gap in the range $0.31 \leq a/\lambda \leq 0.38$. When a channel defect is introduced along the ΓK direction, two localised modes are allowed to propagate with horizontal electric polarisation. The first has an even symmetry with respect to the waveguide axis and it propagates in the entire band gap region. The second mode has odd symmetry, and it propagates in the smaller range $0.34 \leq a/\lambda \leq 0.36$. So choosing a working wavelength in the middle of the bandgap, we would end up exciting both of these modes as the light propagates (fig. 1, left).

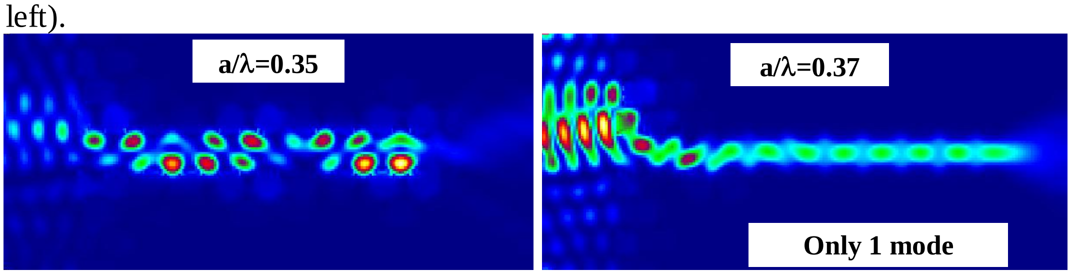


Fig. 1. Multimoded guidance in middle of band gap, and single moded guidance at edge of band gap.

Excitation of multiple modes helps to achieve overall higher transmissions through splitters and bends [8], but with the drawback that the signal at the output remains divided between these two modes with different modal dispersion. We therefore choose a working wavelength in the higher frequency range $a/\lambda = 0.37$, where only the symmetric fundamental mode exists (fig. 1, right). This way we avoid altogether the problem of modal cross coupling as the entire system remains single mode.

## Optimising the crystal guides

*Optimising the Y-junction.*

We attempt to improve 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, see Fig. 2). As the field calculations are done via the scattering matrix approach, the optimisation problem is formulated so as to maximise the total power transmitted out of the crystal exit for a given fixed input field. The input field has been chosen so as to couple completely into the crystal guided mode, so as to obtain 100% power transmission into the crystal.

*The Global optimisation algorithm*

Taking the pitch $a = 0.5\mu m$, we allow the optimisation parameter to vary in the ranges: $0 \leq D1,D2 < 0.5\mu m$, $-0.5\mu m \leq L < 0.5\mu m$. This means that the two holes are allowed to overlap, or even disappear, thus admitting different shape topologies. This invariably leads to an non-trivial optimisation problem likely to contain several sub-optimal configurations. Clearly local optimisation techniques are inappropriate here. Instead we resorted to using the global optimisation routine contained in KALLISTOS [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. However the increased robustness of global optimisation techniques comes at a price: they do require many more calculations than a local descent algorithm to achieve comparable accuracy.

*Results: steering vs. resonant transmission*

The global optimiser was halted after having evaluated 700 points in the parameter space, each one involving one complete field calculation taking approximately 40 seconds on a 2 GHz P4. The optimisation showed up two different optimal configurations (fig. 3, left) , both giving extremely good transmissions. The better one (99.8% transmission) corresponds to a *resonant* transmission (fig. 2, centre)– 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 other optimum is almost as good (99.5% transmission) but the transmission mechanism is radically different, as it exploits a steering effect as opposed to a resonant effect – 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 to only by 2% over the same wavelength shift! This is a clear illustration of the advantage of using this deterministic global optimisation technique: genetic algorithms would not have given the same kind of information.

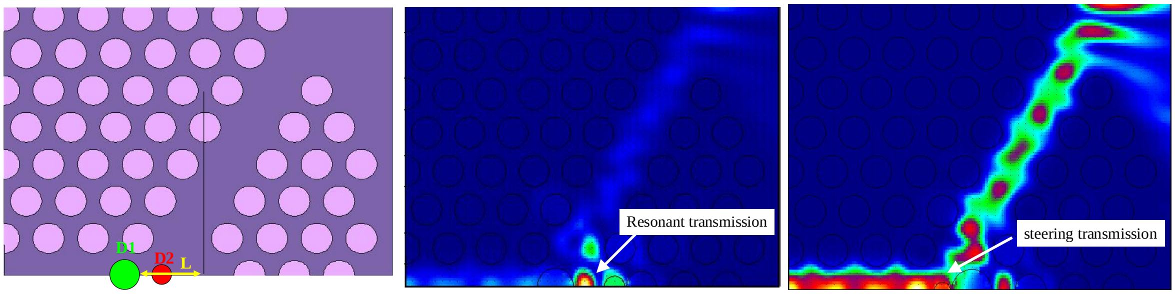


Fig. 2. Optimisatiomn of Y-juncion showing optimisation parameters and the two types of solutions found by the global optimiser

*Optimising the bend.*

We attempt to improve the transmission through the bend by varying the size (D) of two holes placed in the line defect symmetrically on either side of the bend (fig. 3, left). We also vary distance (L) from the bend origin and the offset (OFF) from the axis of the line defect. We allow the optimisation parameters to vary in the ranges: $0 \leq D < 0.5\mu m$, $0 \leq L < 0.5\mu m$, $0 \leq OFF < 0.5\mu m$. The global optimiser shows the appearance of one optimal solution (fig. 3, right). Again, this is clearly a steering type transmission with extremely good frequency response. The global optimiser also gives a good indication of the structural sensitivity of the optimal design –indicating this optimal solution to be very insensitive to structural perturbations.

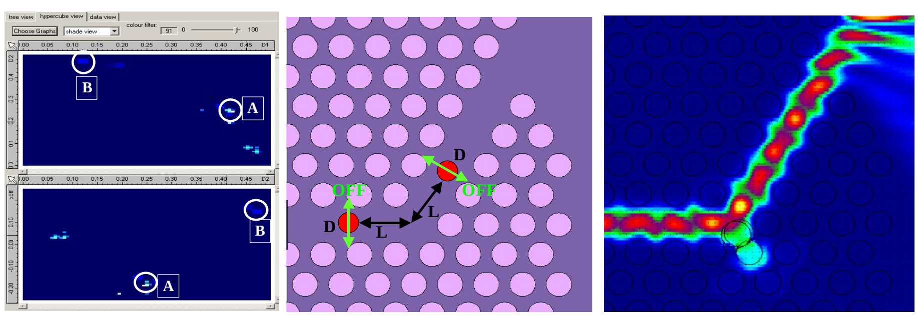


Fig. 3. Left: global optimiser showing two different optimal points for Y-junction problem, A,B. Right: Optimisation of bend

## The complete structure and 3D FDTD analysis (verification)

Automatic optimisation can also be used to design the optimal injector maximising the transmission into the crystal from the fundamental mode of a given waveguide. In this example we choose an input waveguide of 5µm and the same refractive index as the crystal material (2.5). We aim to find a taper with the shortest possible length giving virtually complete transmission in to a straight line defect in the crystal. For a given fixed length, we 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 4). Again, this was done using KALLISTOS. We repeated this calculation for a range of taper lengths, and we picked the shortest possible length (9µm) giving over 97% transmission. As expected, when the individually optimised bits are reassembled, an excellent transmission of almost unity is seen (fig. 4). The frequency response of the whole system is also very good.

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 the air. The line defect is still a single mode waveguide for this thickness, the membrane still being too thin to carry any vertical modes. 3D FDTD was used, but injecting a pulse into the line defect and measuring the power exiting at both branches. The results clearly show that around the wavelength of interest ($\lambda$ = 1.34µm) the optimised structure still exhibits very high transmissions (more than 76% in both channels) over a 40nm spectral diapason. In comparison 3D FDTD shows that transmission of the Y-splitter in the same membrane before any optimisation is 22% only and abruptly falls down more than in two times in 20nm spectral range.

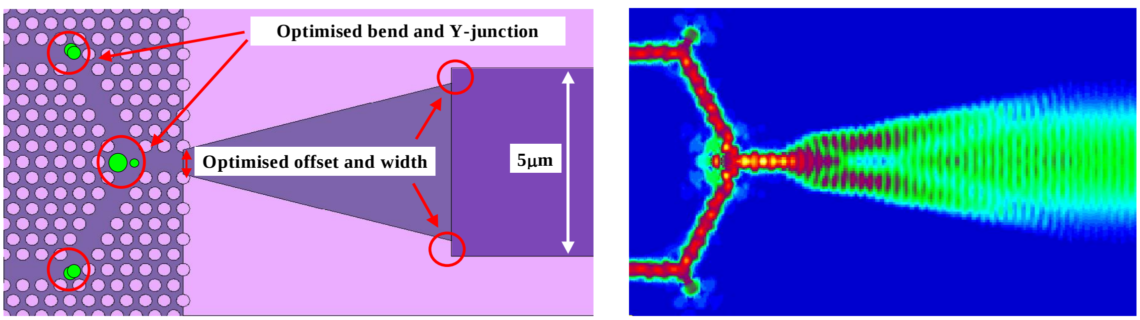


Fig. 4. The complete optimised structure in 2D and field plot,. Excitation is the fundamental mode of the RHS waveguide.

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