Efficient Couplers for Photonic Crystal Waveguides

Ross C McPhedran[1], Kokou Dossou[2], Lindsay C. Botten [2], Ara Asatryan[2],
C. Martijn de Sterke[1], Shigang Chen[1], Jovana Brnovic[1].
[1] *University of Sydney, Sydney, NSW, Australia,*
Phone: (61 2) 9351 3872, Fax: (61 2) 9351 7726, ross@physics.usyd.edu.au
[2] *University of Technology Sydney, Sydney, NSW, Australia,*
Phone: (61 2) 9514 2145, Fax: (61 2) 9514 2260, Kokou.Dossou@uts.edu.au

Abstract

We consider the design of efficient couplers between a photonic crystal waveguide and a uniform background material. We show that horn-shaped tapers can provide efficient bi-directional coupling between the waveguide and the background material.

Introduction. There is much current research centred on the development of devices in two-dimensional photonic crystals (PCs). These may consist of high index cylinders in a low index background material (rod-type PCs), or low index cylinders in a high index background material (hole-type PCs). In either case, an important issue is the achievement of low-reflection coupling between a waveguide in the PC and a uniform material. If reflection losses are significant at such interfaces, then inefficiency results, but, more importantly, fringe visibility is lowered in interferometric devices, and undesirable ripple is introduced into the output of others.

In this paper, we discuss the design of tapers which may be placed between a PC waveguide and a uniform material, and which deliver highly efficient coupling between them. We consider both the coupling from the waveguide into the uniform material, and the coupling of a Gaussian beam in the uniform material into the waveguide. We show that for both rod-type and hole-type PC's, and for both directions of propagation, the same type of horn-shaped taper can achieve very low reflection coupling. Furthermore, we show that optimal tapers can have the very desirable property of converting a waveguide mode into a beam which is very close to Gaussian. Our results also indicate that in the design of waveguide PC devices, it is not necessary to preserve the regular arrangement of cylinders in the PC, provided that during changes the walls of the waveguide are kept smooth.

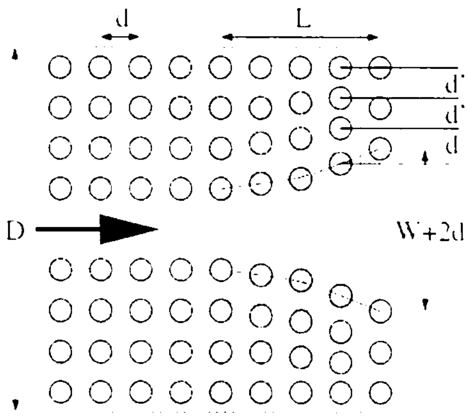

Fig. 1 A coupler of the type we consider from a waveguide in a square lattice into a uniform material, showing the geometric parameters D, W and L. The width $w(y)$ of the taper is $w(y)=2d+2d(W-1)\left(\frac{y}{L}\right)^{\xi}$

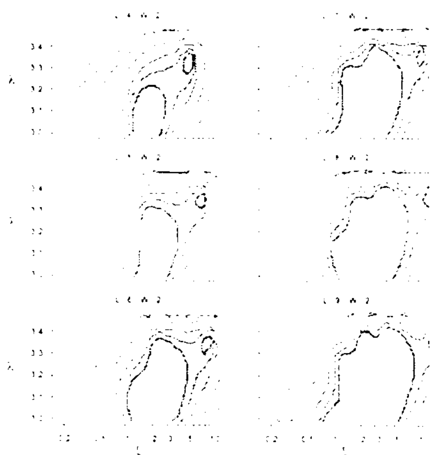

Fig. 2 Transmittance contours as a function of wavelength and taper shape, for tapers with W=2d and various lengths. The contour levels are: 99.5%, 99%, 98%, 95%, 90%, 85%, 80% and 70%, reading outwards from the darkest region.

Coupling from a Waveguide into a Uniform Medium. Fig. 1 shows some of the parameters for a coupler which connects the PC waveguide at left with free space at right. The PC consists of cylinders of index 3.0 and radius 0.3 d in an air background, the waveguide is formed by leaving out a single row of cylinders, and light is polarized with its electric field along the cylinders (E_z polarization). The shape of the coupler is governed by a parameter ξ, with bell-shaped tapers having this less than unity, linear tapers having it equal to unity, and horn-shaped tapers having ξ greater than one. Note the principle of construction of the taper: the cylinders defining the taper wall and their nearest neighbours are placed with the separation they would have in the perfect crystal; other cylinders are placed so as to revert gradually to the square lattice occurring without the taper. We have followed the results of Kwan *et al* [1], in choosing to keep the first two layers of cylinders along the waveguide wall aligned as in a perfect crystal, and regarding layers further than two periods from the waveguide as having little influence on optical properties. Other studies of high transmission couplers for PC waveguides [2, 3] have chosen to use linear taper walls, and slant the photonic crystal structure to follow the taper walls. We calculate the optical properties of layered systems such as those of Fig. 1 by regarding them as stacked diffraction gratings, having a supercell of D periods (where here typically D=21). The scattering matrices for each layer are calculated using highly accurate multipole techniques, and then recurrence methods are used to go from the layer properties to those of the system. Bloch mode methods [4] are used to characterize the properties of the waveguide. Typically, transmittances are calculated to 0.1% accuracy or better.

In Fig. 2 we display a typical contour map which shows coupler performance as a function of wavelength and shape, for various lengths. Note that the wavelength range shown covers the single-moded region of the photonic band gap. The central dark region shows designs with transmission above 99.5%; the size of this region tends to increase with taper length, but L=6d offers very good performance. The high transmission region is centred on $\xi \in [2,3]$, and we have found this horn-type profile is generally optimal, both for rod-type PC's in E_z polarization and hole-type PC's in H_z polarization. These high transmission values and the bandwidth over which they occur are above those reported for the best linear tapers [1, 2], in which both the waveguide walls are kept smooth and the photonic crystal structure is preserved. The very high transmission values we show here indicate that it is sufficient to keep smooth waveguide walls in transitions, while preservation of crystal structure is not necessary. Note that in designs where the waveguide walls have not been kept smooth in the taper, we have found the transmission values to be lowered. Note also that for hexagonal lattices, the alternating nature of successive lattice planes renders it more difficult to achieve smooth waveguide walls in tapers of general shape. Nevertheless, by placing the wall cylinders in odd layers at the centroid of the parallelogram formed by the cylinders in neighbouring layers, we have been able to achieve comparable performance for hexagonal lattice tapers to those shown in Fig.2.

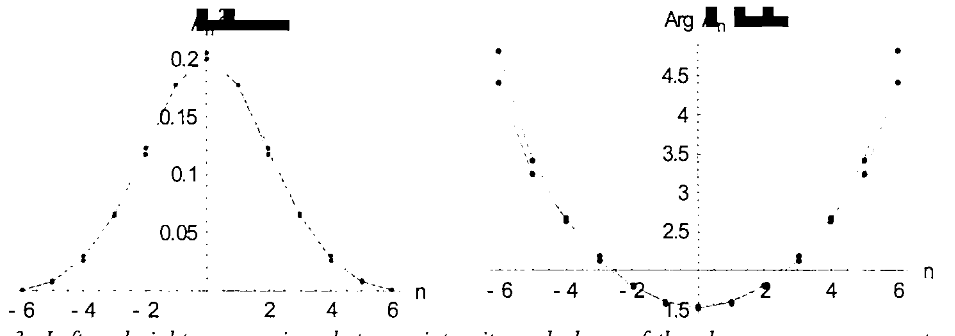

Fig.3 Left and right: comparison between intensity and phase of the plane wave components of the beam emerging from a high-transmittance taper into free space, together with an optimized Gaussian fit. The abscissa is the diffraction grating order n, and is constrained to integer values. Points are connected by lines for visual clarity, with the solid line the radiated field, and the dashed line the Gaussian fit.

Radiation from Waveguides. We have also analysed the beams emanating from the couplers into the uniform medium. We have used a least-squares fitting procedure to determine the parameters of the Gaussian beam most closely approximating the radiated beam. Both the Gaussian beam and the radiated beam are treated as superpositions of plane waves (grating orders) of a grating with period D=21d. The orders have propagation directions given by $\sin\theta_n = n\lambda/\mathrm{D}$.

In Fig. 3 we show a comparison between the beam emerging from a high transmission (99.5%) taper linking a waveguide in a rod-type PC with free space, and an optimised Gaussian fit. We can see that the taper radiates a beam which is very close to Gaussian. Note that for the case shown in Fig 3 and Fig. 4 (left), the waist of the Gaussian is located well inside the taper. In contrast, we have studied the nature of the field radiated in the absence of a taper: the transmission is lower (77%), and the beam is far from Gaussian, with, in fact, the best fit corresponding to a cylindrical wave emanating from a point situated in the centre of the mouth of the waveguide (Fig. 4, right).

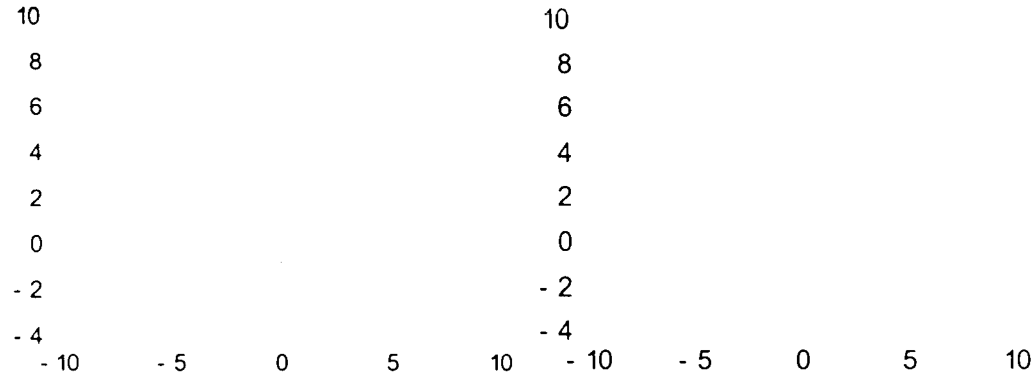

Fig. 4 At left we show the spatial dependence of the real part of the field emerging from the taper of Fig.3; the taper ends at y=0, where y is the vertical coordinate. At right, we show the same case, without a taper.

Coupling a Gaussian Beam into a Waveguide. Given that an optimal taper can couple with very high transmittance into a beam which, to a high degree of accuracy, is Gaussian, it follows by the Reciprocity Theorem that the same taper couples very efficiently a Gaussian beam from free space into the waveguide. Also, note that the above fitting procedure tells us the parameters to choose for the input beam (beam waist, position of beam waist).

We have confirmed numerically that this deduction actually works in practice, and that good taper designs for coupling from the waveguide into free space work equally well when coupling Gaussian beams into the waveguide. This has two advantages: first, the same design can be used on the input and output ends of the waveguide, and second, it is a much simpler design problem to optimize the radiation from the waveguide into free space than in the other direction (there being two fewer parameters to choose—the beam waist and its position). In circumstances where the waveguide radiates a near-Gaussian beam whose parameters do not vary sensitively with wavelength, waveguide-free space designs will provide the fastest route to couplers for Gaussian beams into a PC waveguide.

Conclusion. We have shown that horn-shaped tapers can provide very good coupling between waveguides in free space and uniform media. The designs do not depend very sensitively on PC parameters, type of lattice, polarization or whether the PC is rod-type or hole-type. Very advantageously, tapers which provide good coupling also radiate beams which are essentially Gaussian. Perhaps the most important conclusion from our work is that in designing PC waveguide circuits, the guiding principle is to ensure a smooth waveguide wall throughout transitions. The waveguide fields are moulded by the first two rows of cylinders in the waveguide walls, and cylinders further into the PC can be moved around without significantly detracting from coupling efficiencies.

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