Two compact structures for perpendicular coupling of optical signals between dielectric and photonic crystal waveguides

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Abstract: Two structures are analyzed with numerical modeling as candidates for perpendicular coupling of optical signals from a dielectric waveguide to a photonic bandgap (PBG) waveguide. The first consists of a perfectly electric conducting (PEC) grating and PBG mirror to couple power out of the dielectric waveguide, along with a circular-like lens to couple that power into the PBG waveguide. The second consists of a slanted inline fiber Bragg grating to couple power out of the dielectric waveguide, and a graded-index (GRIN) lens to couple that power into the PBG waveguide. Power transfer efficiencies of 50% and 71%, respectively, are reported. Such structures would be useful in WDM applications, and/or where circuit real estate restrictions demand coupling perpendicular to the dielectric guide over small distances.

OCIS codes: (050.0050) Diffraction and gratings; (060.1810) Couplers, switches, and multiplexers; (230.3120) Integrated optics devices.

References and links

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1. Introduction

In the not-so-distant future, engineered photonic bandgap (PBG) structures promise to redefine the backbone of the telecommunications infrastructure. For the interim, it is interesting to investigate methods of bridging the gap between existing technology and possible PBG structures. Mekis and Joannopoulos [1] have demonstrated via numerical simulations that light can be successfully coupled directly from dielectric to PBG waveguides

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and vice versa. Transmission efficiencies on the order of 95% are reached by butt-coupling the waveguides directly. Such excellent coupling is achieved by tapering the dielectric waveguide into the PBG waveguide adiabatically to provide a better matching condition. To achieve such efficiencies, the taper is on the order of 4-10 lattice constants of the PBG material. Others have demonstrated similar coupling schemes [2, 3].

It is also useful to consider components that will help bridge the gap between the existing telecommunications infrastructure (e.g. fiber) and future generations of equipment relying on PBG components. One such component of interest would be an add-drop filter for wavelength-division multiplex (WDM) applications where the signal at a particular wavelength drops from the existing waveguide into the new PBG component. Thus one would like to side-couple one signal wavelength from the existing waveguide into a PBG waveguide, while allowing signals at other wavelengths to continue unperturbed. To capitalize on the compactness that PBG structures promise, it is useful to focus on equally compact coupling structures, e.g., on the order of a few wavelengths.

In this two-dimensional modeling study, we propose two candidate structures capable of side-coupling power from a dielectric waveguide into a PBG waveguide. The first structure consists of a grating-assisted coupler described by Ziolkowski and Liang [4], coupled to the PBG material with a circular lens. The second structure consists of a slanted inline fiber Bragg grating coupler, which couples power to the PBG material with a GRIN lens. Modeling is performed with the finite-difference time-domain (FDTD) method, which is detailed elsewhere in, e.g, [5].

In the following section, we describe briefly the modeling approach. Sections 3 and 4 provide the details of the candidate structures, the parameters used in the modeling, and the results for the efficacy of each structure. Section 5 provides some general discussion, and conclusions are given in Section 6.

2. Modeling

To assess the performance of such couplers, structures are modeled with a two-dimensional finite-difference time-domain (FDTD) method. This simulation approach is very versatile and has the ability to model very complex geometries. In all the FDTD simulations, the spatial discretization was $\lambda_0/50$, where λ_0 is the free-space wavelength of the signal. The computational domain is terminated with the L2TDLM absorbing boundary conditions [6]. For the first structure – the circular lens and coupler – the total problem size is 822x722 discretization cells. For the second structure – the GRIN lens and coupler – the total problem size is 722x522 discretization cells.

The signal launched in the dielectric guide is the fundamental mode at a frequency of 200*THz* (free space wavelength $\lambda_0 = 1.5\mu m$). Simulations are allowed to proceed for 5000 time steps, which was enough to allow for the structure to complete several cycles at steady state. The time step was chosen to satisfy the two-dimensional Courant condition. Approximately 3.5 hours was required for a single simulation on a 500MHz DEC Alpha Workstation.

To assess performance, the power passing through various cross-sections of the structures was calculated. Transmitted power was measured in the dielectric guide at a plane past the coupler, in the direction of propagation. Reflected power was measured at a plane before the input plane, opposite to the direction of incident wave propagation. Coupled power was measured at a plane in the PBG waveguide, two lattice cells from the terminating boundary condition. In all cases, the power was measured by calculating the time-dependent Poynting vector at the appropriate perpendicular plane defined above, to the lateral extent of the waveguide that the plane cuts. Values of power quoted below are normalized to the input power, and represent the steady state value achieved.

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3. Side-Mounted PEC Grating with Circular Lens

3.1 Physical Description

Ziolkowski and Liang [4] demonstrated the feasibility of a grating-assisted output coupler defined by a perfect electric conductor (PEC) grating imposed on one side of a dielectric slab waveguide. The grating period Λ is determined from the phase-matching condition:

$$K_0 \sin\theta = K_z + (2\pi/\Lambda)n \qquad (1)$$

where θ defines the scattering direction from the normal to the grating, n is the diffraction order, and K_0 and K_z are the wave numbers in the region outside and inside the waveguide (in the propagation direction), respectively. In this instance, we are interested in normal scattering ($\theta = 0$).

This type of grating couples waves into regions on both sides of the grating. To enhance the coupling in one direction only, and to provide wavelength selectivity, a multi-layer PBG mirror was placed on one side of the grating. This effectively enhances the radiating mode to one side of the grating. Because the grating also presents a reflectance to the reflected wave from the mirror, a resonant effect is established. By controlling the distance between the grating and the mirror, and hence the resonator characteristics, the structure can be tuned for a particular wavelength.

Having reviewed the possibility of selectively coupling power out of an existing waveguide over the distance of a few wavelengths with a PBG-based output coupler, we wish to focus now on a method to concentrate that radiated power into a PBG waveguide. Ideally we would like the coupled wave from the grating to have planar phase fronts, and to have a symmetric amplitude distribution. In actuality, one of the problems with this type of coupler is that the coupling is effectively accomplished via a leaky wave phenomenon. The resultant radiated wave is close to planar, but the amplitude pattern across a plane is highly asymmetric.

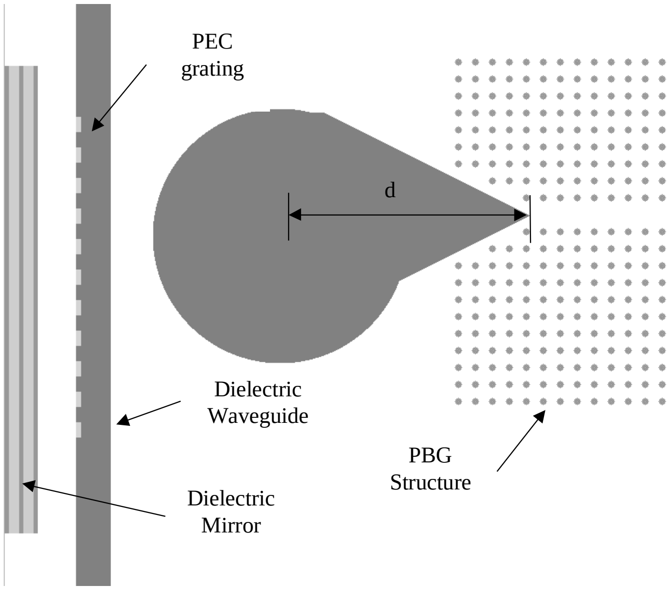

Fig. 1. First configuration: circular lens and wedge with side-mounted PEC coupler.

To capture as much of the radiated (coupled) power as possible, we propose a structure that combines the features of a circular lens, to focus the wave, and a wedge, to adiabatically couple the focused wave to the PBG structure. The two elements are effectively combined to

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create the non-intuitive structure indicated in Fig. 1. This combination of elements attempts to compensate for the asymmetric field amplitude pattern of the radiated wave. The structure is composed of material with refractive index 1.4, and the circle has a radius of 4.5 microns. The wedge has a flare angle of 53° degrees (a two-to-one length to height ratio) and a length d of 7.2 microns as indicated in Fig.1. The PBG structure into which the radiated wave is coupled consists of a square array of dielectric rods of lattice constant $a = 0.4\lambda_0$, where λ_0 is the free-space wavelength of the signal. The rods have a circular cross-section of radius $0.2a$ and refractive index $n = 3.4$, which results in a bandgap near 1.5 microns. Removing one row of rods creates the PBG waveguide. The center of the sphere is located at (x = 6.0 microns, y = 4.5 microns) with respect to the first tooth of the grating. The planar PBG mirror is as reported in [4].

The PBG and lens structure was combined with the side-mounted PEC grating discussed in [2]. The dielectric waveguide has an index of refraction of $n_g = 1.4$ and a width of 1.2 microns, surrounded by an air cladding. The grating consists of PEC ridges at a height of 0.2 microns with a duty cycle of 50%. The period of the grating is 1.12 microns as determined from Eq. (1), and 11 periods are used for this case.

3.2 Results and Discussion

With judicious placement of the circular lens and wedge, the coupled power can be maximized. Several configurations and placements were attempted, but only the optimum configuration is reported here. In this case, the amount of power coupled into the PBG waveguide is 51%, with 8% being reflected back in the direction of the source in the dielectric guide, and 8% transmitted along the dielectric guide. The remainder is lost as radiated power. Fig. 2 shows the intensity of the fields in the composite structure. Notice that a significant amount of power is lost in radiated fields, or stored in the resonator. After modeling several configurations to discover this optimal configuration, it became evident that the geometry is the largest contributing factor to the efficacy of the coupler. We believe a more rigorous optimization of the structure could be achieved, however the leaky wave modality of the grating makes this a difficult task. The purpose of this study was merely to show that satisfactory coupling could be achieved with the limited size available.

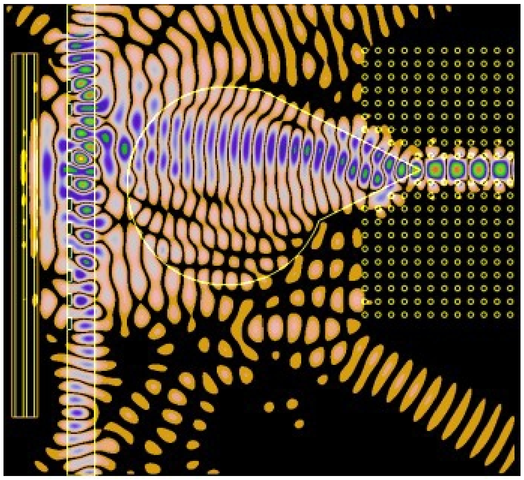

Fig. 2. (2.23 MB) Movie of the electric field intensity coupling from the dielectric guide into the circular lens and wedge structure discussed in section 3.1.

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4. Slanted Inline Fiber Bragg Grating with GRIN Lens

4.1 Physical Description

The structure detailed above is non-intuitive, and is not particularly compact. Moreover, it would be preferable to have something other than a circular lens. For this reason a GRIN lens was also investigated. GRIN lenses are described by a waveguide of a particular length, for which the refractive index profile can be described by $n^2(y) = n_0^2[1-(\alpha y)^2]$, where y is the transverse distance from the center of the waveguide, n_0 is a nominal index of refraction, and α describes the rate of the index change. Optical rays in this waveguide structure always curve towards its center, producing the guiding effect. By cutting the waveguide at a particular length L, the structure acts as a lens. In particular, for rays coming into the structure parallel to the guide axis (i.e. plane waves), the corresponding outgoing rays will reach a focus at a distance $f = \frac{\cot(\alpha L)}{n_0 \alpha}$ from the output face of the lens.

Assuming a nominal index profile of $n_0 = 1.4$, this means that for a grating of length ~$10\lambda_0$ we need a lens that is of similar size to the sphere/wedge lens described in the previous section. Also, the pattern of the field radiated from the grating is non-uniform. As a result, there is no particular focal spot. It would be preferable to have the field radiated from the dielectric guide over a more compact length (less than $10\lambda_0$), and in a more uniform manner.

To achieve such a goal, an attempt was made to combine the effects of the PEC grating and PBG mirror. The structure considered was a slanted inline Bragg grating, which essentially converts the wave in the dielectric guide into the radiated mode. For our studies, the inline grating was similar to the PBG mirror described in [2], consisting of five layers of material alternating between high and low refractive index values of 2.5 and 1.4. Maximal radiation in the direction perpendicular to the guide was achieved for the structure slanted at $\theta = 53°$. The depth of each dielectric layer in the grating was determined from the recursive formula given in Wait [7] to maximize reflectivity at the signal frequency of 200*THz* ($\lambda_0 = 1.5\mu m$). Simulations indicate a radiated field that has a diverging circular pattern. This pattern is confined to a sector arc of approximately 150° centered on the perpendicular to the dielectric guide, and originating from an origin at the first layer of the grating.

The next consideration was to couple this symmetric, radiated field into a GRIN lens. This was achieved by considering the fields to be emanating from the effective source point, and placing the lens accordingly. Then by choosing the length of the lens judiciously, the waves coming out of the lens would be planar. Let this distance be $x = L$. The focal distance and the angle of the arc containing the radiated field determine the width of the lens.

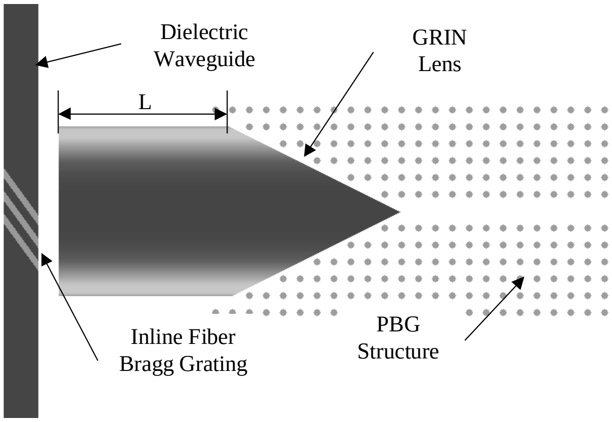

Fig. 3. Second configuration: inline slanted fiber Bragg grating and GRIN lens.

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Finally it must be recalled that we are attempting to couple this field into a PBG structure. Thus, rather than terminating the lens to achieve a plane-wave output, we taper the GRIN lens from $x = L$. In a ray optics sense, one would then expect the rays to bend *towards* the axis from the plane $x = L$, thereby maximizing the field distribution towards the tip of the taper. The expectation would then be better coupling to the PBG waveguide into which the taper would extend. This structure is visualized in Fig. 3.

4.2 Results and Discussion

A more complete study was performed for the structure proposed in Section 4.1. The PBG structure is the same, but parameterization studies to uncover the optimal GRIN lens parameters were conducted. The parameters of the lens that did not change are the width, W = 6.0 microns; the length of the straight section, L = 6.0 microns; and the flare of the tapered section, $\theta = 53°$.

The parameters that were varied were the frequency f (which ranged from 150*THz* to 210*THz*), the distance from the side of the dielectric guide to the GRIN lens d (which ranged from $0.1\lambda_0$ to $0.8\lambda_0$), the nominal refractive index n_0 (which ranged from 1.4 to 2.0), and the graded index profile parameter α (which ranged from 0.0068m^{-1} to 0.004m^{-1}).

Results of the parameterization study indicated that the nominal refractive index, and the index profile, had little effect on the coupling efficiency. For the values of the parameters $f = 200THz$ ($\lambda_0 = 1.5\mu\text{m}$), $d = 0.5\lambda_0$, $n_0 = 1.4$, and $\alpha = 0.0068m^{-1}$, coupling of 71% to the PBG waveguide was achieved, with 7.6% of the signal power transmitted along the dielectric waveguide, and 3% of the signal power reflected back along the dielectric guide. The remainder of the signal power is lost to power stored in the PBG structure itself and to radiation fields not captured by the lens. This is considered the baseline configuration. Fig. 4 demonstrates the intensity of the fields transmitted and coupled to the PBG structure. Observe that there is much less radiative loss for this structure than with the circular lens case.

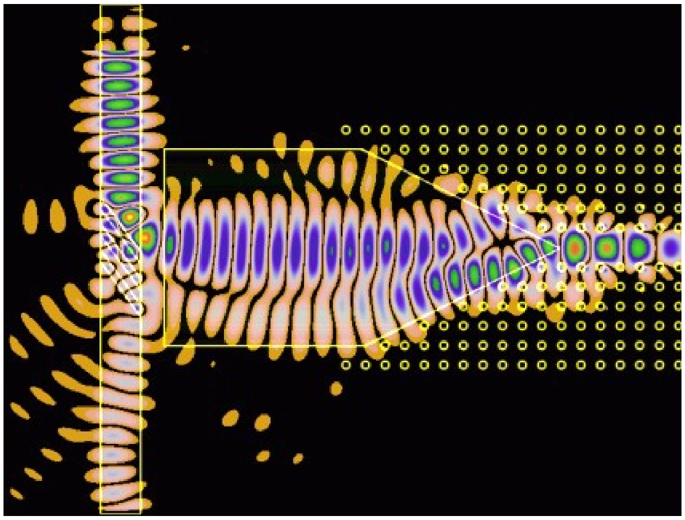

Fig. 4. (1.98 MB) Movie of the electric field intensity coupling from the dielectric guide into the GRIN lens structure discussed in section 4.1.

Next we consider the parametric study. It was found that the parameter d, the distance from the guide to the lens, had the most dramatic impact on the coupling to the PBG guide. Fig. 5 shows how the coupled power changes (for unity input), as a function of the distance to the GRIN lens. For instance, with a shift from this optimal distance of only $d = 0.05\lambda_0$, the transmission to the PBG waveguide drops to only 40%.

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Similarly, Fig. 6 demonstrates how the coupled power changes as a function of the frequency, with all other parameters remaining at their baseline configuration values. Note that although the transmission is optimal at the design frequency of 200*THz* (λ_0 = 1.5μm), there is still significant coupling in a large frequency range around the design frequency. The large bandwidth of the coupler configuration is a result of the extremely short length of the inline fiber Bragg coupler. The large bandwidth may be a disadvantage for WDM applications, but the increased coupling efficiency and lower radiated power makes this structure attractive for coupling power from a dielectric waveguide to a PBG structure at right angles to it.

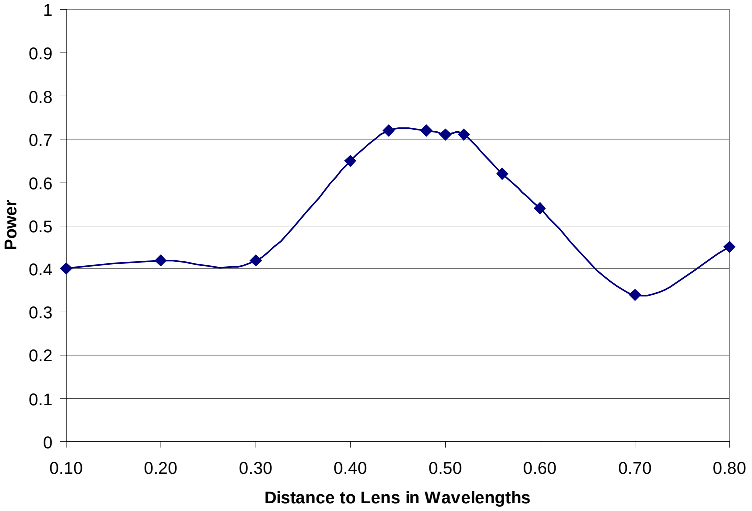

Fig. 5. Coupled power vs. distance to GRIN lens.

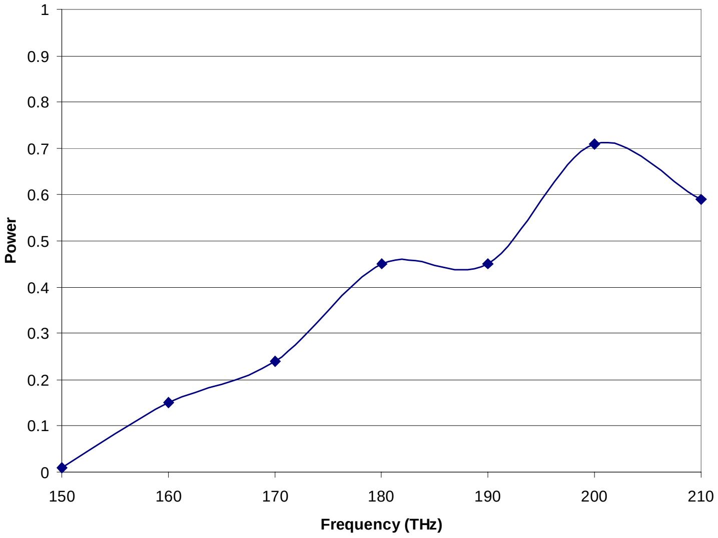

Fig. 6. Coupled power vs. frequency of signal.

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5. General Discussion

The coupling efficiencies of both of the configurations introduced here are less than the >90% efficiencies discussed by Mekis and Joannopoulos for their adiabatic couplers [1]. However, it must be remembered that in [1] the photonic crystal and dielectric waveguides were coupled as butt-couplers, i.e. inline. Both of our configurations are meant for coupling to the side of the dielectric waveguide.

Futhermore, the first configuration lends itself to WDM applications, since the resonant structure can be tuned to channel drop the signal of interest. The second configuration, though more wideband, is more applicable for configurations where physical constraints do not allow inline coupling. In this case, a coupling efficiency of 71% is deemed very satisfactory.

6. Conclusions

In this paper we have modeled two configurations for coupling power from existing dielectric waveguides into PBG waveguide structures. The first configuration captures the radiated power from the output coupling structure proposed by Ziolkowski and Liang with the combination of a circular lens and wedge. Modeling indicates that even with judicious placement and optimization of the overall structure, only 50% of the power can be effectively coupled to the PBG structure. The advantage of this structure is that it can be used in narrowband applications by tuning the side-mounted grating and the dielectric mirror.

The second configuration attempts to create a more uniform radiated field by way of a slanted inline fiber Bragg grating that can be effectively coupled to a GRIN lens which then adiabatically couples the light power to the PBG structure. Detailed parametric studies were conducted to optimize the configuration, and an overall power coupling efficiency of 71% was achieved. Although this is a much more broadband structure than the first, better coupling was achieved through detailed parameterization and optimization studies.

Both of these structures demonstrate that significant side coupling of power into a PBG waveguide can be achieved with compact structures. Future studies will look at other possible mechanisms for achieving the coupling, such as using other resonant structures for the narrowband, channel drop feature, while maintaining compactness.

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