Design and characterization of a grating-assisted coupler enhanced by a photonic-band-gap structure for effective wavelength-division demultiplexing

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We report a novel grating-assisted coupler that incorporates a photonic-band-gap structure. It is shown that by virtue of the resonant cavity formed by the structure and the grating the relative amounts of the output scattered and the transmitted guided-wave powers can be significantly modified. The potential applications for optical switches and wavelength demultiplexers based on this new configuration are discussed.

Grating structures have been studied extensively[1] for use in microwave, millimeter-wave, and optical devices and systems. Some of the many grating applications include gratings that can be used in waveguide environments as directional couplers to transfer energy into radiating modes that propagate in predefined directions[2] or as mode converters to convert energy among various modes in the same waveguide[3] and that can be used as diffraction components to transfer energy among waves propagating in different directions.[4] Optical switching is also a subject that is drawing increasing attention. A typical configuration incorporates a Bragg reflection grating and nonlinear materials.[5,6] Switching is achieved by modifying the incident intensity of the guided wave to affect the reflection and transmission properties of the grating. We propose a new configuration that exhibits a strong differential switching effect between the guided wave and the scattered radiation wave. This configuration is a composite structure that consists of a finite-length grating-assisted coupler integrated with a linear multilayer photonic-band-gap (PBG) mirror. It is shown that switching can be realized with a compact form of this structure. The configuration may find applications as a switching device or a wavelength demultiplexer in integrated optics or millimeter-wave systems. For the present investigation we first examine the scattering of a guided wave from a finite grating to achieve a directional coupler that transfers energy into a predefined direction. We then investigate the switching effect associated with the proposed composite configuration.

For a grating-assisted output coupler, defined by a perfect electric conductor (PEC) grating imposed upon one side of a dielectric slab waveguide, the grating period Λ is selected to yield a desired scattering direction, based on the phase-matching condition

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

where θ is the direction, n is the order of the scattered output wave, and K_0 and K_z are, respectively, the wave numbers in the region outside and inside the waveguide (in the propagation direction). The phase-matching condition also implies that the grating will couple the incident guided wave into both regions outside the waveguide. For our model problem, the dielectric slab waveguide has a refractive index of 1.4 and a thickness of 1.2 μm. The fundamental TE mode at the frequency 2×10^{14} Hz (wavelength, 1.5 μm) is launched into the waveguide. The PEC grating consists of 11 periods, each with a duty factor of 0.5 and a depth of 0.2 μm. The period is calculated from Eq. (1) to be 1.12 μm for the normal scattering ($\theta = 0$), in which case only the -1 order of the output exists. These parameters can easily be scaled to other frequencies of interest, such as in the millimeter-wave regime.

Although analytical methods can handle infinite, periodic gratings well, numerical methods usually are needed for general finite, aperiodic gratings. We thus carried out a numerical investigation of the proposed finite-length grating-assisted coupler with the finite-difference time-domain (FDTD) approach.[2–4,7] The FDTD approach was selected because of its ability to model complex structures and materials. Recently FDTD simulators were shown to be effective in modeling complicated grating structures.[2–4] In all the following FDTD simulations the spatial discretization was approximately $\lambda_0/30$, where λ_0 is the free-space wavelength of the source and the time step size is the two-dimensional Courant value.[7]

The electric field pattern obtained with the FDTD simulation of the finite-length grating-assisted coupler is shown in Fig. 1. The labels on the x and y axes refer to the FDTD cell indices. Figure 1 illustrates, as expected, that the incident wave is coupled into the designed direction but into both the upper and the lower regions outside the waveguide. We also sampled the energy in the transmitted guided wave and the scattered waves into the upper and lower regions outside the waveguide. The energy in the transmitted, upward-directed, and downward-directed waves is 29%, 25%, and 35% of the incident energy, respectively. The energy in the reflected field (~10%) results mainly from the perturbation to the slab waveguide from the PEC grating.

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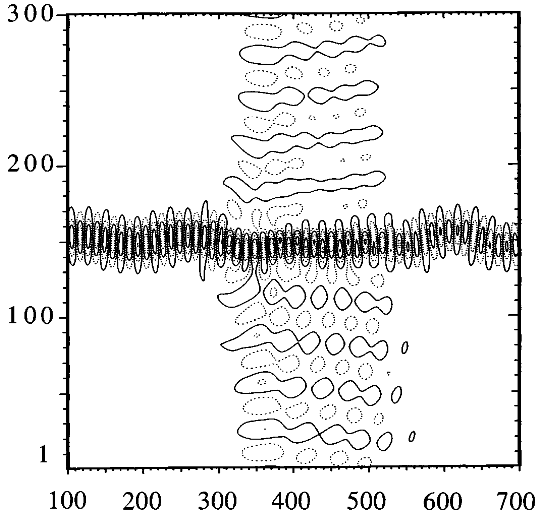

Fig. 1. Grating output without PBG structure.

The amount of coupling into the various output channels is determined by the material and the depth of the grating as well as by the polarization. We propose a new configuration to control the output energy distribution. This configuration incorporates a PBG structure as shown in Fig. 2. Such a structure, when properly designed, will exhibit a high reflectance to a normally incident plane wave. In principle, it can be thought of as a Bragg grating reflector. We use five dielectric layers in the PBG structure; each layer is a quarter-wavelength thick. The refractive indices alternate between the adjacent layers with a high value of 2.5 and a low value of 1.02. The theoretical reflectance of this PBG structure is calculated to be 0.98. Thus the PBG structure acts effectively as a lossy mirror to any energy normally incident upon it. Because the incident guided wave is restricted mainly to the slab, it is only weakly perturbed by the PBG mirror.

Inasmuch as the PEC grating also presents a reflectance to a wave incident upon it, a resonant cavity is formed for the upward-directed output wave by the PBG structure and the grating. Thus the upward-directed output energy is partially trapped in this cavity region. The energy leaving this cavity back through the waveguide grating will have one portion transferred into the downward-directed wave and another portion converted into a guided wave by the grating. Whether there will be a constructive or a destructive interaction between these fields and those generated by the original interaction of the guided wave with the grating determines the resulting increase or decrease of the energy coupled into these output channels.

This phase matching explains the rapid variation in the amount of energy that is coupled into the downward-directed and into the waveguide transmitted waves, shown in Fig. 3, as the spacing between the PBG structure and the waveguide edge (PEC grating) changes. The normalized energy stored within the cavity region is included in Fig. 3. Figure 3 clearly illustrates the resonant switching behavior that is established with the composite structure. A rapid diversion between the output channels is seen to occur near the cavity resonance, repeating itself for every half-wavelength. Notice that when the energy in one path reaches its maximum, the energy in the other is at its minimum. Figures 4 and 5 show the electric field patterns when the energies in the two paths reach their respective maxima.

The switching behavior exhibited by this composite structure has a variety of potential applications. One could use it as a switch that allows the incident guided-

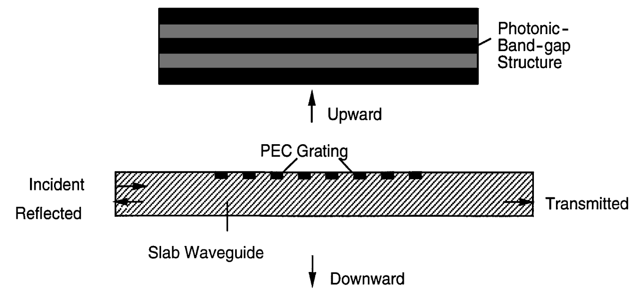

Fig. 2. Geometry of the problem.

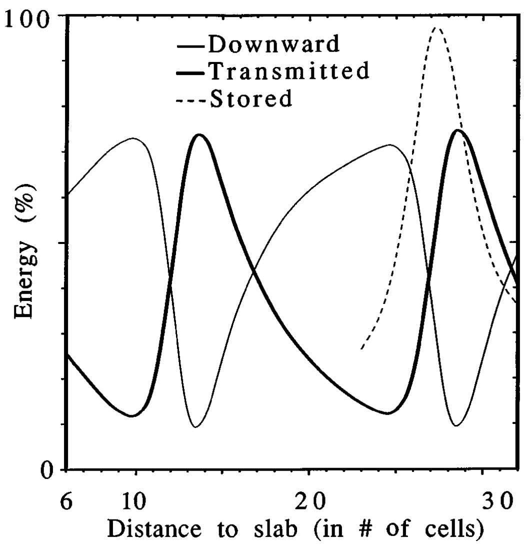

Fig. 3. Percentage of the incident energy coupled into downward-directed and transmitted waves.

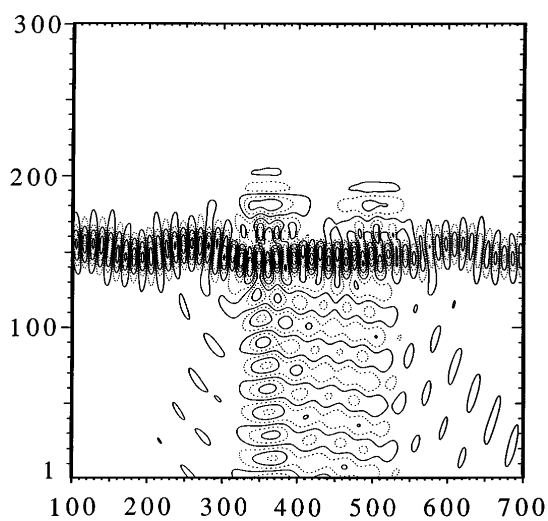

Fig. 4. Enhanced output with PBG structure.

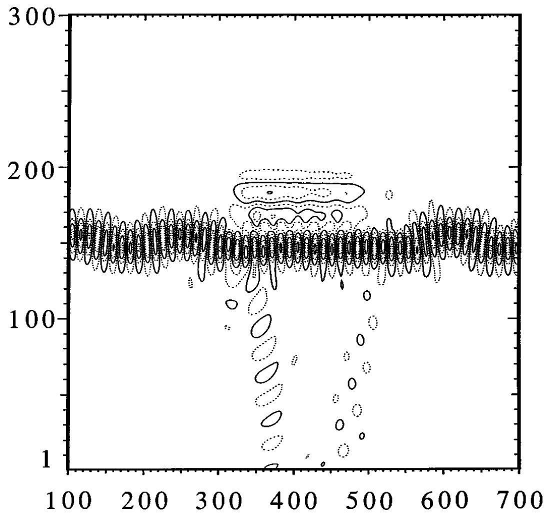

Fig. 5. Enhanced transmission with PBG structure.

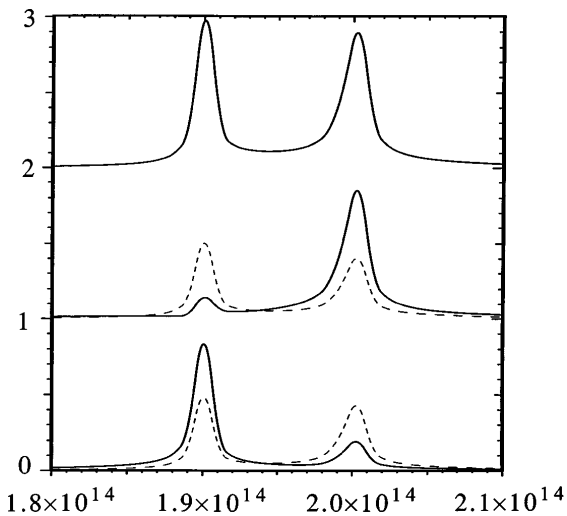

Fig. 6. WDM demultiplexer frequency spectra: (top) incident wave, (middle) transmitted wave and (bottom) radiated wave with (solid curve) and without (dashed curve) the PBG structure.

wave energy to be either transmitted by or coupled out of the waveguide by simply modifying the reflective properties of the PBG structure, i.e., by affecting the resonance, with some external means. This composite structure could also be used as a wavelength-division multiplexing (WDM) demultiplexer. In particular, consider two signals with slightly different frequencies that are propagating simultaneously in the slab waveguide. If these two signals interact with the grating and have frequencies that are close to its phase-matching condition, some of their energy will be converted selectively into radiated fields while the remaining energy continues to propagate as guided waves. If we then introduce a PBG structure designed such that these two frequency components fall onto different sides of the cavity resonance, the resonance can be used to redistribute the energy of two signals in a distinctive manner. One of the guided waves can be strongly converted into a radiated field while the other remains strongly guided.

We tested this WDM demultiplexer application, and the results are shown in Fig. 6. Two cw guided modes with frequencies that correspond to the wavelengths, 1.5 and 1.58 μm, are launched into the waveguide. The waveguide parameters are the same as those described above, except that now the number of grating periods used is 20. The PBG structure is located 28 FDTD cells, i.e., 1.4 μm, from the waveguide edge. We see from Fig. 6 that the energy associated with the two input signals is selectively separated into two different paths when the PBG structure is present. Clearly this composite grating-assisted coupler and PBG mirror could be used as a demultiplexer component in many WDM systems.

A similar structure can be designed for TM polarization. However, certain polarization dependencies exist. For example, for TE polarization the electric field is forced to be zero along the grating teeth, thus deflecting energy away into the direction opposite the grating. This effect is illustrated in Fig. 1, where more energy is scattered into the downward-propagating waves. For TM polarization this does not occur, and the field energy penetrates into the grating region, thereby reducing its reflectivity for normally incident waves. Therefore the resonant cavity will have a lower Q, and the switching effect should be less pronounced. These polarization effects, along with the potential use of nonlinear materials in the grating region, in the PBG structure, or in both, are issues for a follow-up investigation.

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