IEEE PHOTONICS TECHNOLOGY LETTERS, VOL. 10, NO. 5, MAY 1998

Grating Assisted Waveguide-to-Waveguide Couplers

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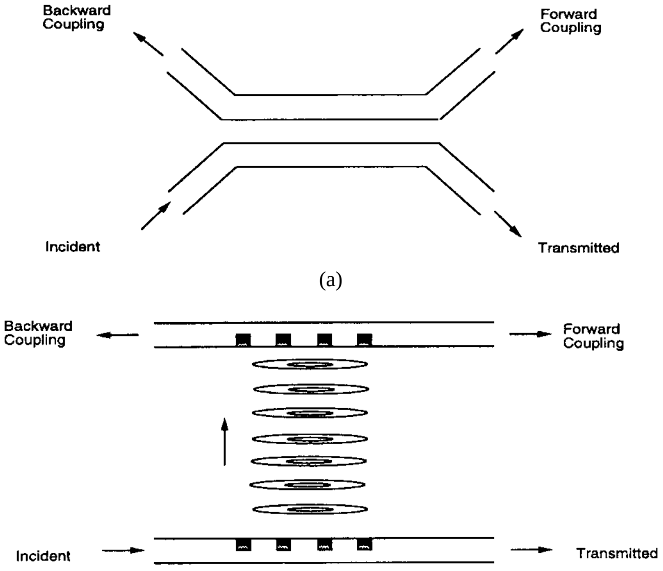
***Abstract*—A new radiation-type waveguide-to-waveguide coupler is proposed. The coupling is realized through gratings embedded on the dielectric waveguides involved. Compared to the conventional hybrid-mode coupler, this type of coupler has advantages in that the two waveguides can be quite dissimilar as well as being separated by large distances. It is demonstrated that the coupling performance of this radiation-type coupler can be enhanced significantly by using photonic bandgap (PBG) structures.**

***Index Terms*—Computational electromagnetics, FDTD, grating assisted couplet, integrated optics, photonic bandgap structure.**

WAVEGUIDE-TO-WAVEGUIDE couplers are important for many microwave, millimeter, and optical applications. A conventional waveguide-to-waveguide coupler consists of two dielectric waveguides in close proximity to each other, as shown in Fig. 1(a). When there is a phase synchronism, i.e., equality of the propagation constants, the energy launched into one waveguide can couple into the other waveguide. The operation of this type of waveguide-to-waveguide coupler can be described accurately by the coupled mode theory [1]. In this letter, we propose a new radiation-type waveguide-to-waveguide coupler as shown in Fig. 1(b). In this configuration, gratings are used to couple energy between different waveguides. In this process, the guided mode in the lower waveguide is converted into a radiation field by its grating, which is in turn converted back into a guided mode in the upper waveguide by its own grating. Since the energy is coupled via a radiation field, the distance between the waveguides can be large. Another advantage is that the two waveguides can also be quite dissimilar.

To design such radiation-type grating assisted waveguide-to-waveguide couplers, we will take a numerical modeling approach by using the finite-difference time-domain (FDTD) method [2]. This discrete numerical method directly solves the full-wave vector Maxwell's equations in differential form. Recently, FDTD simulations have been shown to be very effective in modeling complicated grating structures [3], [4]. It provides an extremely flexible simulation environment that can model arbitrary geometries and material distributions. In the following sections, we will first examine the simple realization of this type coupler. We will then propose a new configuration which is a composite structure consisting of finite length gratings integrated with linear multilayer photonic bandgap mirrors. It will be shown that coupling is greatly enhanced. We will point out possible applications of these new devices.



(a)

(b)

Fig. 1. Two kinds of waveguide-to-waveguide couplers. (a) Hybrid mode coupler. (b) Radiation mode coupler.

I. GRATING ASSISTED WAVEGUIDE-TO-WAVEGUIDE COUPLER

We first look at a simple form of the radiation-type grating assisted waveguide-to-waveguide coupler. Two waveguides are placed 5.0 μm apart, corresponding to 3.33 λ_0 at a frequency of 2.0 × 10^{14} Hz. Each dielectric slab waveguide has a dielectric constant of 2.0 and a thickness of 1.2 μm. The lower guide is excited at its fundamental TE mode. The grating is constructed with perfect electric conducting (PEC) teeth; it has a duty factor of 0.5 and a depth of 0.2 μm. The grating period is determined by the phase matching condition [5] to be 1.12 μm to radiate energy into the normal direction. The two gratings mirror each other, i.e., the system exhibits a mirror symmetry with respect to the plane located through the midpoints between the two waveguides.

Fig. 2 shows the near-field pattern of the electric field of the waveguide-to-waveguide coupler which has 11 periods on each waveguide. The labels on the horizontal and vertical axes refer to the FDTD cell indices along the longitudinal and transverse directions with respect to the waveguide. The efficiencies for the forward and backward coupling into the second waveguide are 7.75% and 1.84%, respectively. In Fig. 3, we show the coupling efficiency measured as a function of the number of grating unit cells. As the number of grating

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Manuscript received August 7, 1997; revised January 28, 1998. This work was supported in part by the Office of Naval Research under Grant N0014-95-1-0636 and in part by the Air Force Office of Scientific Research, Air Force Materials Command, USAF, under Grant F49620-96-1-0039.

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Publisher Item Identifier S 1041-1135(98)03015-8.

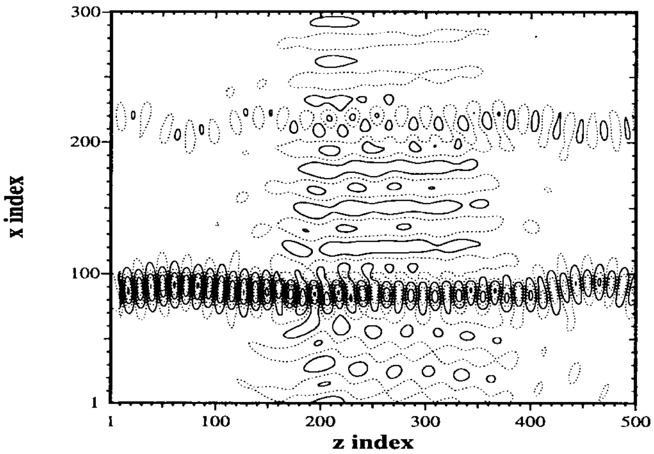

Fig. 2. Field distribution of a simple waveguide-to-waveguide coupler.

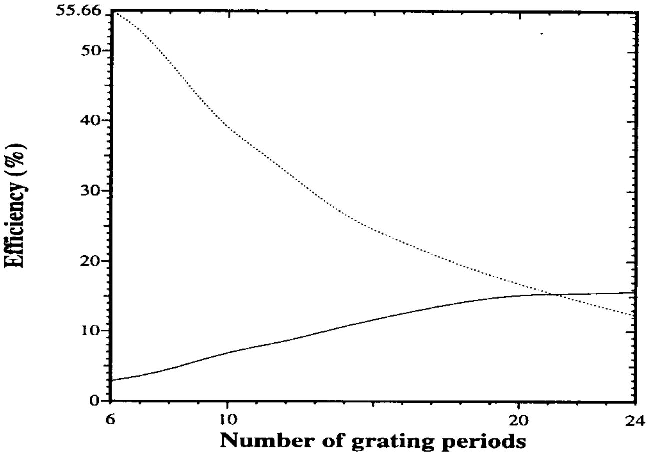

Fig. 3. Coupling efficiencies for forward coupling and transmission (dashed line) as a function of number of grating periods used.

unit cells increases, the forward coupling increases and the transmitted energy in the lower waveguide decreases. These changes saturate as the result of the leaky wave antenna nature of the grating assisted output coupler. We see that the coupling efficiency is relatively low. This is due to the fact that the lower grating radiates energy into both upward and downward directions and some of the upward directed energy is lost as a result of the penetration of the field energy through the upper waveguide. We sampled the energies radiated by the lower grating into the upper and lower regions to be 25% and 35% of the incident energy, respectively.

II. PHOTONIC BAND-GAP STRUCTURE

To improve the coupling, we can place a reflective surface at one side of the grating assisted coupler in order to achieve one-sided radiation into the opposite side of the waveguide. Consider a stratified medium composed of $2N+2$ isotropic dielectric layers with alternating high and low permittivities, ϵ_h and ϵ_l. Regions $1, 3, 5, \cdots, 2N+1$ are high-permittivity layers; and regions $2, 4, 6, \cdots, 2N$ are low-permittivity layers. Region 0 has permittivity ϵ and permeability μ. The thickness of each layer is a quarter-wavelength inside that dielectric. The transmitted region is $2N+2=t$ and has permittivity ϵ_t.

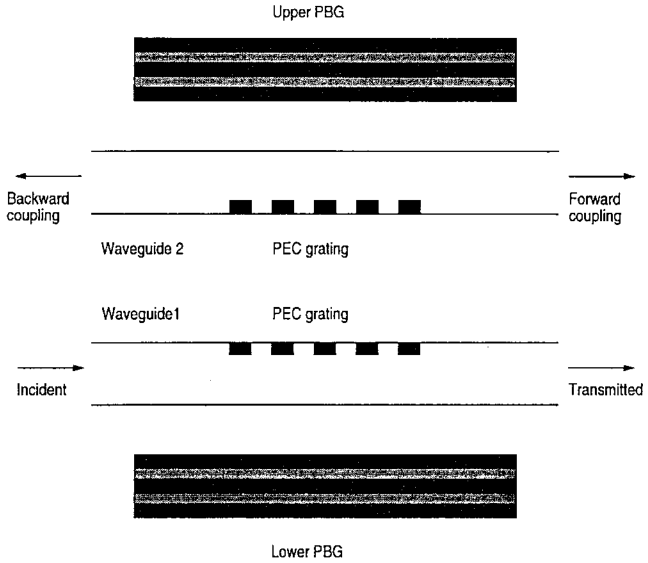

Fig. 4. Geometry for a grating assisted waveguide-to-waveguide coupler integrated with PBG structures.

Permeabilities for all layers are equal to μ_0. The structure can be analyzed following [6]. For a wave normally incident on the structure, the reflection coefficient R_0 at $z=0$ is found to be

$$R_0 = \frac{\left(\frac{\epsilon_t}{\epsilon_h}\right)^{1/2}\left(\frac{\epsilon_l}{\epsilon_h}\right)^{N}\left(\frac{\epsilon}{\epsilon_h}\right)^{1/2}-1}{\left(\frac{\epsilon_t}{\epsilon_h}\right)^{1/2}\left(\frac{\epsilon_l}{\epsilon_h}\right)^{N}\left(\frac{\epsilon}{\epsilon_h}\right)^{1/2}+1.} \tag{1}$$

If we choose a high ϵ_h/ϵ_l ratio and a large number of layers, the reflection coefficient R_0 approaches the value of -1, and the structure is highly reflective. Such a structure exhibits a high reflectance to a normally incident plane wave at a specific frequency, i.e., it exhibits a stop band and is thus called a photonic bandgap (PBG) structure. For a five-layer structure having $\epsilon_h = 6.25$ and $\epsilon_l = 1.035$ and the thickness for each layer being a quarter wavelength in that layer (0.015 μm for high dielectric layer and 0.035 μm for low dielectric layer) and starting with a high dielectric layer, the theoretical reflectance $|R_0|^2$ for a normally incident plane wave at a frequency of 2 $\times$ 10^{14} Hz is 0.9815. This five layer PBG structure will be used as a lossy mirror in the simulations below.

III. ENHANCED WAVEGUIDE-TO-WAVEGUIDE COUPLER WITH PBG STRUCTURES

We propose the new configuration shown in Fig. 4 to improve the coupling efficiency for a grating assisted waveguide-to-waveguide coupler. We place two identical five-layer dielectric-layer PBG structures, one below the lower waveguide and one above the upper waveguide, to enhance the radiation-to-guided-mode conversion. The PBG mirrors are placed at the same distance relative to the waveguides to which they are associated since the conversion by the two gratings in the coupled waveguides are reciprocal to each other.

Resonant behavior, as shown in Fig. 5, is observed among the wave energies in the transmitted guided mode in the lower waveguide and the modes coupled into the upper waveguide.

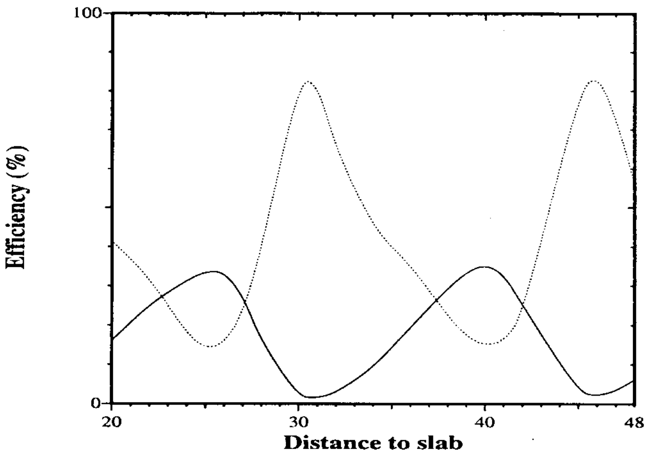

Fig. 5. Coupling efficiencies for forward coupling and transmission (dashed line) as a function of the distance from the PBG structure to the waveguide it is enhancing.

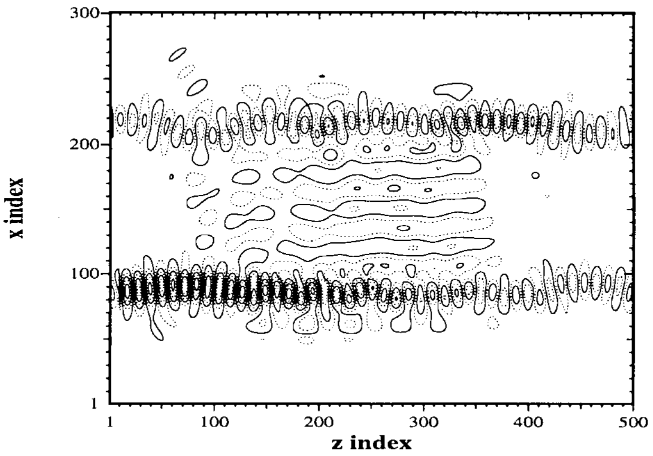

Fig. 6. Near-field pattern of PBG enhanced waveguide-to-waveguide coupler.

This resonance results from the resonant cavity formed by the PBG mirror and the grating-assisted waveguide output coupler. For example, for the lower waveguide, the downward-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 upward-directed wave and another portion converted into a guided wave by the grating. Whether there will be a constructive or 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 upper waveguide and that is maintained in the transmitted waves in the lower waveguide, as shown in Fig. 5, when the spacing between the PBG structure and its associated waveguide varies. Such a rapid change in the energy in the various output channels is seen to occur around the cavity resonance, repeating itself for every half a wavelength. Notice that when the energy in one channel reaches its maximum, the energy in the other is at its minimum. Fig. 6 shows the near-field pattern of the electric field of a waveguide-to-waveguide coupler having eleven grating periods on each waveguide. The maximum waveguide-to-waveguide coupling occurs with forward and backward coupling efficiencies of 33.60% and 17.59%, respectively.

Notice that the energy is coupled into both the forward and backward propagating guided modes in the upper waveguide. The ratio of the forward and backward coupling is close to 2:1 with the PBG structures present. To enhance the coupling into the forward direction, we can terminate one end of the upper waveguide. To have the reflected energy from the termination constructively interfere with the original coupled guided mode in the opposite direction, we had to tune the position of the termination. We obtained an increase of 10.64% in the forward coupling by terminating properly the left (source) end of the upper waveguide. We could also terminate the lower waveguide to further increase the coupling efficiency. By terminating the right (opposite-to-the-source) end of the lower waveguide and the left (source) end of the upper waveguide, we realized a forward coupling efficiency of 63.76%. This is a significant increase over the value obtainable with the simple grating-assisted waveguide-to-waveguide coupler.

The configuration we proposed has a variety of potential applications. It can be used to couple energy between dissimilar waveguides which may be separated by many wavelengths. In optical integrated circuits, the configuration may provide another form of interconnect when, for example, simple connection is not possible due to routing restrictions. We considered the various waveguide terminations to further enhance the waveguide-to-waveguide coupling. These terminations, in practice, may take the form of a PEC coating or a PBG structure having a high reflectance. While the first form is easy to realize, the second form is more flexible. For example, if the PBG layers consist of electrooptic materials whose dielectric constants can be modified by externally applied means, we may put PBG reflecting layers at each end of the coupling waveguide and choose which end of the PBG structure is to be reflecting. This could make it possible to realize a switch between the forward coupling and backward coupling directions. Other potential applications include using this configuration as a transmitter/receiver pair. The proposed radiation-type coupler may have applications other than in integrated optical circuits. Extensions of our results to three-dimensional waveguides in the presence of lossy materials would be necessary to determine its effectiveness for those applications and deserves future investigation.

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