

**Figure 1** Cross section of coupled interconnection lines on chips

Once the even- and odd-mode propagation constants, voltage, and currents have been obtained by running 2-D FDTD twice for every frequency point, we can obtain the frequency-dependent  $[R(\omega)]$ ,  $[L(\omega)]$ ,  $[C(\omega)]$ , and  $[G(\omega)]$  matrices from (6).

### 3. NUMERICAL RESULTS

In this section, we will follow the above procedure to extract the equivalent distributed circuit parameter matrices of the coupled interconnection lines on chips. Figure 1 shows the cross section of a typical on-chip interconnection line, which is widely used in VLSI chips. The materials are aluminum ( $\sigma = 3.33 \times 10^7$  S/m) for the signal and ground lines, Si ( $\epsilon_r = 11.9$ ,  $\sigma = 1.0$  S/m) for the semiconducting substrate, and  $\text{SiO}_2$  ( $\epsilon_r = 4.0$ ) for the insulator layer. The geometry parameters are  $w = s = 5.0 \mu\text{m}$ ,  $t = 0.75 \mu\text{m}$ ,  $b_1 = 0.5 \mu\text{m}$ , and  $b_2 = 500 \mu\text{m}$ . The parameter matrices extracted by this method as functions of frequency are shown in Figure 2. Due to the existence of a semiconductor, it is shown that these parameters are strongly frequency dependent, which must be considered in the circuit simulation.

### 4. CONCLUSIONS

In this paper, a new method has been presented for the extraction of frequency-dependent equivalent circuit parameters of coupled interconnection lines on chips. The results obtained from this method can reflect the combined performance of the conductor, semiconductor, and dielectric insulator for the on-chip interconnects.

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## WAVEGUIDE BENDS IN THREE-DIMENSIONAL LAYER-BY-LAYER PHOTONIC BANDGAP MATERIALS

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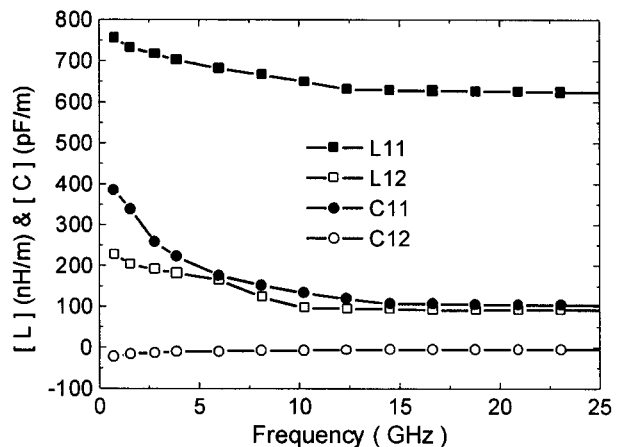
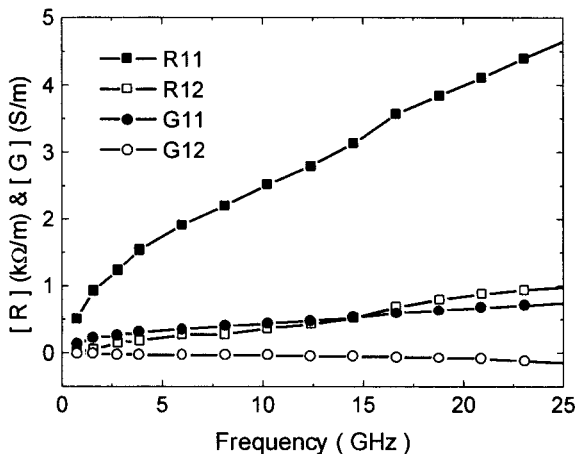
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**ABSTRACT:** We theoretically investigate waveguide bends in three-dimensional dielectric photonic bandgap (PBG) materials. The PBG materials used in this study consist of layers of alumina rods. An L-shaped waveguide is created by removing part of the rod in one layer and part of the rod in the next layer. The removed rods are perpendicular to each other. Using finite-difference time-domain (FDTD) simulations,



**Figure 2** Frequency-dependent equivalent circuit parameters

**Key words:** photonic bandgap materials; waveguide bends; multiple-layer materials

## I. INTRODUCTION

Photonic bandgap (PBG) crystals are periodic dielectric structures, which can suppress the transmission of electromagnetic (EM) waves within certain frequency ranges [1]. The layer-by-layer structure suggested by the Iowa State group [2] is one of the most widely used bandgap structures in this field. Such structures have been successfully fabricated and demonstrated as three-dimensional (3-D) photonic bandgaps in the microwave and millimeter wavelengths [3–8], and more recently in the near-infrared region [9, 10].

A very promising application of PBG materials is for improving the performance of waveguides. Conventional dielectric or metallic waveguides are efficient for transporting waves in straight lines, but have large radiation losses when sharp bends or small bending radii are introduced. The ability to efficiently bend and guide light on a single chip is very important in optoelectronics. New waveguide designs are needed to bend EM waves around sharp corners.

Recent theoretical simulation [11, 12] and experimental studies [13] have shown that two-dimensional (2-D) dielectric PBG structures can be used as efficient waveguides with 90° bends, when frequencies within the in-plane bandgap are used. Bending efficiencies as high as 100% have been achieved. However, the waves are not confined in the direction perpendicular to the plane. Imperfection or disorder may scatter the wave out of the plane in experimental structures. A way to eliminate the out-of-plane scattering is to instead use a three-dimensional PBG which has also shown very encouraging results [14, 15]. Recent theoretical studies showed that highly efficient waveguide bends can be constructed using 3-D metallic PBG crystals [16]. However, metals become lossy as we approach the optical wavelengths.

Here, we theoretically study waveguide geometries in layer-by-layer photonic crystals consisting of alumina rods (dielectric constant of 9.61). The rectangular cross section of the rods measures  $w = 0.667$  mm by  $c/4 = 0.7$  mm. The separation between the rods in each layer is  $d = 2.5$  mm. The unit cell consists of four layers of rods, with a total thickness of  $c = 2.8$  mm. We study a system consisting of 14 rods within each layer, and having 20 layers. We remove part of one rod in the 10th layer and part of the rod in the 10th layer and part of the rod in the 11th layer. The two rods are perpendicular to each other, and they form an L-shaped waveguide. This is an experimentally feasible design. We use a dipole parallel to the stacking direction to excite the waveguide modes. The dipole is located at the entrance of the waveguide.

## II. MODEL

For all of the following cases, we calculate the integrated Poynting vector over two two areas located two unit cells before and two unit cells after the bend. These areas are centered at the waveguide section. The cross section of these areas is 6.67 mm within the layers and 7 mm along the stacking direction.

We are using the finite-difference time-domain (FDTD) method. The grid points used in our calculation were  $464 \times$

$464 \times 200$  along the  $x$ -,  $y$ -, and  $z$ -directions ( $z$  is the stacking direction). Each grid point is 0.083 mm, and the time step is 0.163 ps. The numerical space is terminated with second-order Liao boundary conditions [17]. Our previous study of dielectric photonic bandgap materials showed very good agreement between FDTD calculations and measurements [18].

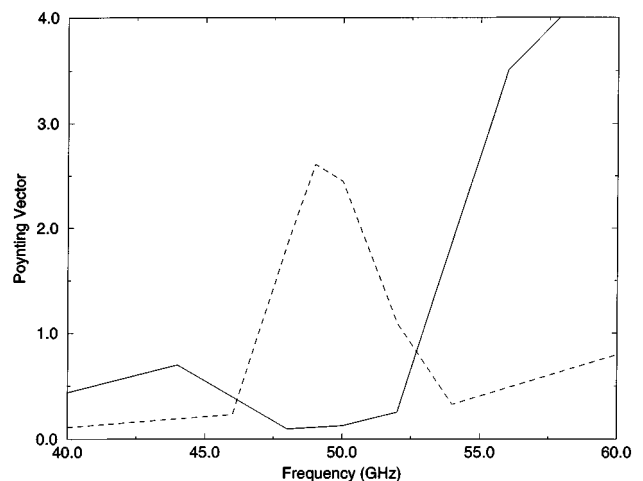
## III. RESULTS

Figure 1 shows the maximum value of the Poynting vector as a function of frequency. The Poynting vector is calculated in an area located four unit cells away from the dipole. For the periodic case (solid line in Fig. 1), there is a drop of the Poynting vector between 45 and 54 GHz due to the photonic bandgap. By removing one full rod (dashed line in Fig. 1), a sharp maximum of the Poynting vector appears at 49 GHz, which is due to the waveguide mode.

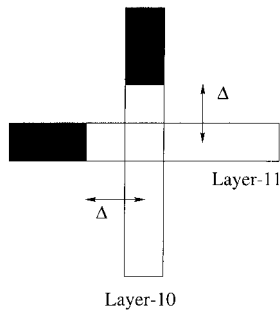
For the waveguide bend, we remove part of one rod at the 10th layer and part of one rod at the 11th layer (the rods are perpendicular to each other; see diagram in Fig. 2). In particular, we remove the rods up to the intersection of their axes plus an additional length  $\Delta$  (Fig. 2).  $\Delta$  is the distance between the edge of the rod and the axis of the perpendicular rod. Both rods are handled in a symmetric way.

Figure 3 shows the transmission ( $T$ ) along the bend as a function of the parameter  $\Delta$ . The transmission is calculated by dividing the integrated Poynting vector before and after the bend. There are two maxima of the transmission at  $\Delta/w = 0.125$  with  $T = 0.75$  and at  $\Delta/w = 1$  with 100% transmission. For  $\Delta/w < -0.25$ , there is very low transmission since the overlap between the defect rods reduces. There is also a minimum of the transmission at  $\Delta/w = 0.5$ , while for  $\Delta/w > 1$ , the transmission is always greater than 95%. So, removing an extra segment  $\Delta$  creates a microcavity that helps in reflecting the wave from one layer to the next.

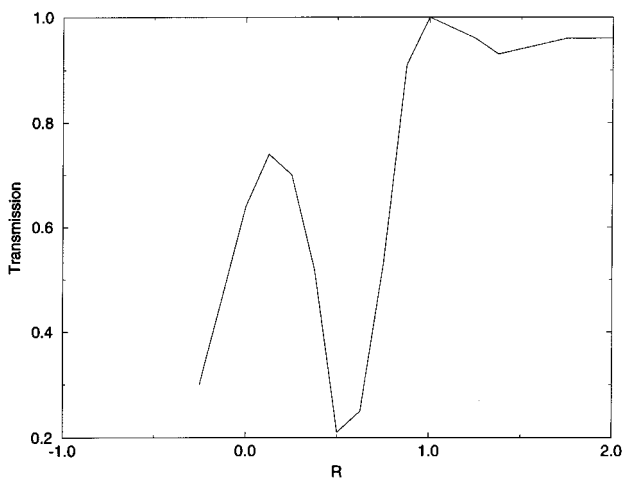
The Poynting vector along the waveguide bend is shown in Figure 4 for the optimal transmitted case ( $\Delta/w = 1$ ). The Poynting vector oscillates over time with the frequency of the excitation. We use a ramp sinusoidal excitation; for that reason, the envelope of the Poynting vector increases until it reaches a maximum value. After that maximum value, the envelope of the Poynting vector decreases slightly due to the interference of the incoming wave with the reflected wave



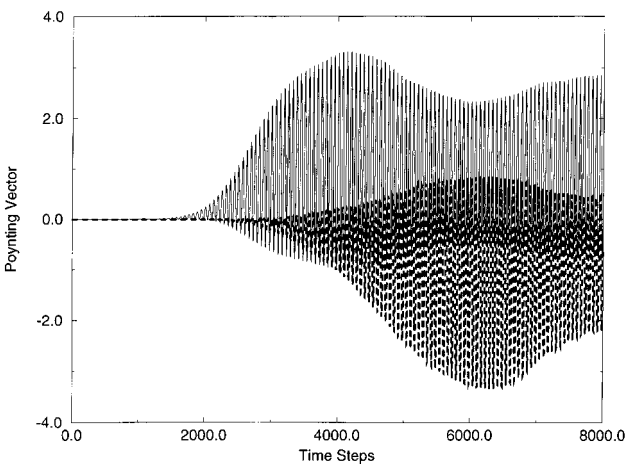
**Figure 1** Maximum value of the integrated Poynting vector for the periodic and straight waveguide cases (solid and dashed lines, respectively)



**Figure 2** Diagram of the waveguide bend showing the remaining part of the rods (black area) and the part of the rods which has been removed (white area). Rods are in two different layers of the crystal



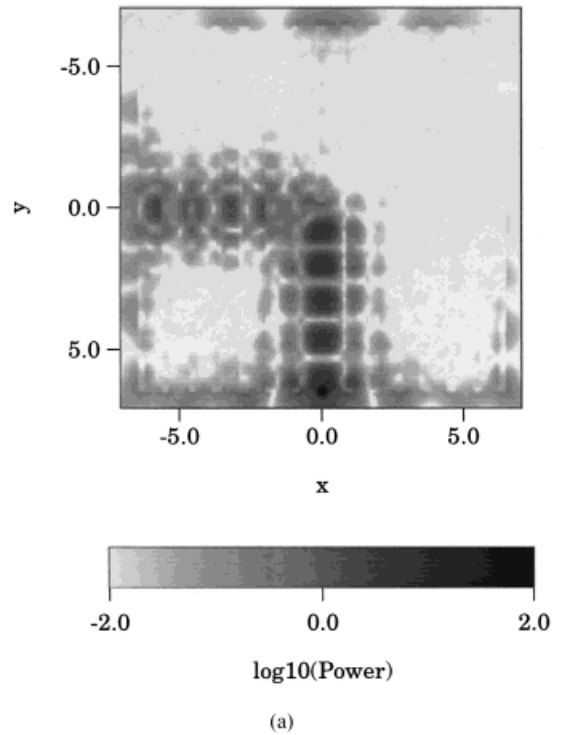
**Figure 3** Transmission along the bend as a function of the ratio  $R = \Delta/w$



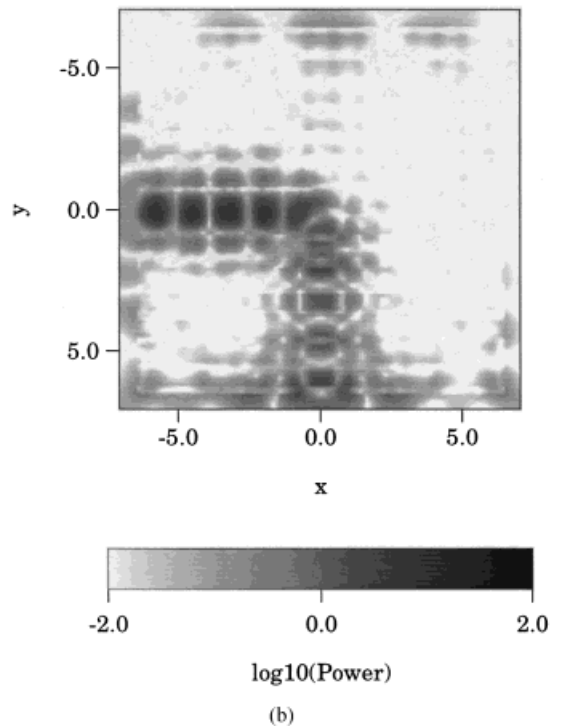
**Figure 4** Poynting vector before and after the bend (solid and dashed lines, respectively) as a function of the time step

from the end of the structure. The maximum of the Poynting vector before the bend (see solid line in Fig. 4) is the same as the maximum of the Poynting vector after the bend (see dashed line in Fig. 4), indicating that a 100% transmission has been achieved in that case.

The power distribution at the middle of the defect layers is shown in Figure 5. Close to the dipole, the power has a maximum [see Fig. 5(a)]. The wave propagates first in the



(a)



(b)

**Figure 5** Power distribution for the case where the transmission along the bend is 100%

layer where the dipole is located [Fig. 5(a)], then turns around the bend and moves to the next layer [Fig. 5(b)]. Comparing the maximum of the power inside the guide, we can see that the maximum of the power just before the bend is equal to the maximum of the power just after the bend.

#### IV. CONCLUSIONS

In conclusion, we have studied waveguides in three-dimensional layer-by-layer photonic bandgap (PBG) materials. A complete rod or part of two rods in neighboring layers have been removed for the creation of a straight waveguide or a waveguide bend. There is one particular frequency where a maximum transmission through a straight waveguide occurs. In that particular frequency and for certain configurations, a 100% transmission can be achieved along the waveguide bend.

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## ON THE CONCEPT OF THE TRANSPARENT ABSORBING BOUNDARY

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**ABSTRACT:** *The transparent absorbing boundary (TAB) was recently suggested for grid termination in finite methods. Previously, it was shown that this boundary is matched with free space if the TAB region extends to infinity. In this paper, reflection from a TAB layer backed by a boundary (electric or magnetic wall) is analyzed both analytically and numerically. It is shown that, although the auxiliary fields can be attenuated in the TAB region to as low a level as desired, the reflected wave from the backing boundary is then amplified back to the original level of the incident wave. A modification of the Yee algorithm as suggested by the TAB authors is shown to be equivalent to a usual absorbing boundary condition at the truncation interface. © 1999 John Wiley & Sons, Inc. *Microwave Opt Technol Lett* 23: 59–62, 1999.*

**Key words:** *absorbing boundary; truncation method; wave impedance; reflection*

#### 1. INTRODUCTION

The transparent absorbing boundary (TAB) is a technique for the truncation of the computational domains in finite methods which was recently introduced in [1] (a more detailed presentation is given in [2]). In that method, a numerical solution is first found for auxiliary fields  $\mathbf{E}$  and  $\mathbf{H}$ , which are connected to the physical fields  $\mathbf{E}_0$  and  $\mathbf{H}_0$  by the relations

$$\mathbf{E}(t, \mathbf{r}) = F(\mathbf{r})\mathbf{E}_0(t, \mathbf{r}), \quad \mathbf{H}(t, \mathbf{r}) = F(\mathbf{r})\mathbf{H}_0(t, \mathbf{r}). \quad (1)$$

Here, the real function  $F$  is chosen so that the fields  $\mathbf{E}$  and  $\mathbf{H}$  vanish at the boundary of the computational domain ( $F = 0$  there). The physical fields can be further found from (1).

As is established in [1], the interface between free space and such an “absorbing” TAB region is nonreflecting for arbitrary frequencies and arbitrary incidence angles, provided that the permittivity and permeability (as well as conductivities) do not change across the interface (see also [3]). In the numerical calculations, the auxiliary field becomes very small at the truncation boundary due to the modulation by function  $F$ . It appears from first sight that a TAB layer allows us to obtain zero reflection from the grid boundary. However, the analysis presented here shows that it is not quite so. Actually, if the dumping function  $F$  is not exactly zero at the truncation boundary, the reflection coefficient from the backed TAB layer is exactly the same as that from a backed dielectric slab with the same  $\epsilon$  and  $\mu$ . Thus, waves are reflected from boundaries which back TAB layers, although the interface between free space and a TAB half space is matched for arbitrary incidence angles and frequencies. According to the authors of [2], this problem can be eliminated by the use of the Lax–Wendroff scheme. Here, we will also show that this would be equivalent to introducing a usual absorbing boundary condition at the truncation interface, so there is little advantage in using the TAB.