

## Waveguides in three-dimensional metallic photonic band-gap materials

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We theoretically investigate waveguide structures in three-dimensional metallic photonic band-gap (MPBG) materials. The MPBG materials used in this study consist of a three-dimensional mesh of metallic wires embedded in a dielectric. An  $L$ -shaped waveguide is created by removing part of the metallic wires. Using finite difference time domain simulations, we found that an 85% transmission efficiency can be achieved through the  $90^\circ$  bend with just three unit cell thickness MPBG structures. [S0163-1829(99)13831-1]

Photonic band-gap (PBG) crystals are periodic dielectric structures, which can suppress the transmission of electromagnetic (EM) waves within certain frequency ranges.<sup>1</sup> Most of the earlier research work was concentrated on the development of PBG crystals built from frequency-independent dielectrics. At lower microwave and millimeter-wave frequencies, however, metals act like nearly perfect reflectors with no absorption problems, and there are certain advantages of introducing metals to photonic crystals.<sup>2-9</sup> These include reduced size and weight, easier fabrication, and lower costs.

An exciting potential application for PBG materials is for constructing improved high-frequency energy-transmission structures. A microstrip transmission line, which consists of a thin transmission line separated from a ground plane by a dielectric substrate, is a commonly used transmission structure at millimeter-wave frequencies. It is compatible with standard printed circuit-construction techniques, and is nearly ideal for use in constructing millimeter-wave circuits (amplifiers, mixers, etc). However, it suffers large radiative losses if sharp bends are used, which can lead to cross-talk and faulty circuit operation. A waveguide implemented within a PBG material having a band gap at the frequency of interest would suffer little or no radiative losses, even at sharp  $90^\circ$  bends.

Recent theoretical simulations<sup>10,11</sup> and experimental studies<sup>12</sup> have shown that two-dimensional (2D) dielectric PBG structures can be used as efficient waveguides with  $90^\circ$  bends, when frequencies within the in-plane band gap are used. Bending efficiencies as high as 100% have been achieved. However, the waves are not confined in the direction perpendicular to the plane. Imperfections 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. Here we use waveguides in a 3D metallic photonic band-gap (MPBG) crystal, and investigate frequencies below the cutoff. Such systems are easily fabricated using conventionally printed circuit board techniques.<sup>6,9</sup> Such waveguides can be used for communication between different components at microwave, millimeter-wave and even far-infrared wavelengths. As we approach

optical wavelengths, the absorption of the metal will be a significant drawback. Hence we do not expect applications of MPBG's at optical wavelengths, unless superconductors are used.

We study a MPBG crystal with a tetragonal unit cell. The lattice constant along the  $x$  and  $y$  axis is 0.8 mm and along the  $z$  axis is 1.31 mm. It consists of metallic wires with direction along the  $x$ ,  $y$ , and  $z$  axes. The wires along the  $x$  and  $y$  direction are 0.2-mm wide and 0.131-mm thick. The  $z$  direction wires are centered at the intersection of the  $x$  and  $y$  direction wires and they have a square cross section with a size of 0.2 mm. The whole metallic mesh is embedded in duroid with dielectric constant of 2.25. The MPBG crystal consists of  $10 \times 10 \times 3$  unit cells along the  $x$ ,  $y$ , and  $z$  axes. In the middle layer, we create an  $L$ -shaped waveguide by removing part of the metal (see Fig. 1). We use a dipole parallel to the  $z$  axis to excite the waveguide modes. The dipole is located in the entrance of the waveguide (filled circle in Fig. 1).

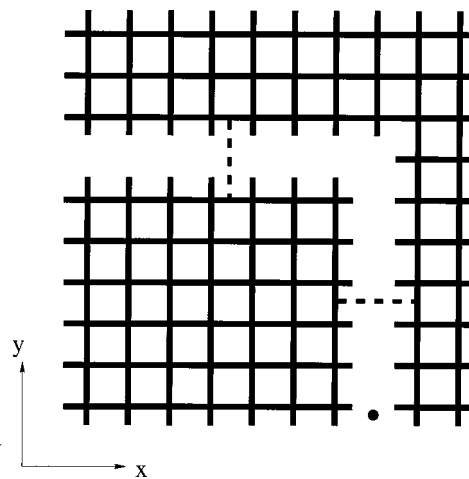


FIG. 1. A diagram of the middle layer of the structure in which the waveguide is created by removing part of the metal. Metal wires are shown by black lines; the filled circle indicates the location of the dipole. Dashed lines show the locations where the Poynting vectors are calculated.

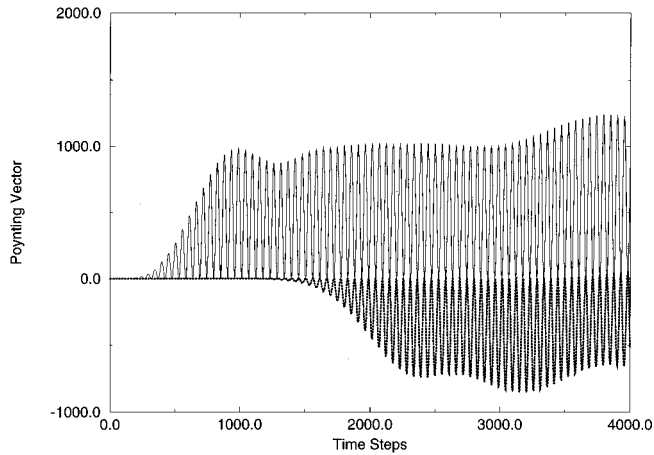


FIG. 2. Poynting vectors before and after the bend (solid and dotted lines) as a function of time.

For all the following cases, we calculate the integrated Poynting vector over two areas before and after the bend (see dashed lines in Fig. 1). The  $z$  side of these areas is 0.655 mm and the side along the  $x$  or  $y$  axis is 1.6 mm.

We are using the finite-difference time-domain (FDTD) method.<sup>13</sup> The grid points used in our calculation were  $120 \times 120 \times 50$  along the  $x$ ,  $y$ , and  $z$  directions. The numerical space is terminated with second-order Liao boundary conditions.<sup>14</sup> Our previous study of dielectric photonic band-gap materials showed very good agreement between FDTD calculations and measurements.<sup>15</sup>

Figure 2 shows the integrated Poynting vector before and after the bend for 81.5 GHz and for waveguide widths of  $0.2 \times 0.26$  mm. Both curves oscillate with a frequency of 81.5 GHz. We are using a ramped sinusoidal excitation in order to eliminate high-frequency components in our fields. For that reason the envelope of the Poynting vector grows at the beginning until it reaches a maximum value. For the Poynting vector before the bend, this value is reached at around 1000 time steps (each time step is  $\Delta t = 0.114$  ps) while after the bend the Poynting vector reaches the maximum value at around  $2400\Delta t$ . After reaching the maximum, the envelope of the Poynting vector has small fluctuations due to the reflections from the end of the waveguide as well as from the bend itself.

Figure 3 shows the first maximum of the envelope of the Poynting vector before the bend as a function of frequency obtained by calculations of sources at different frequencies. This curve has two maxima at 81.5 and 89 GHz, which are due to the waveguide mode. The cutoff frequency for the present MPBG crystal is 120 GHz. For that reason, we observe an increase of the Poynting vector for frequencies higher than 120 GHz. Comparing the results for three waveguides of different cross sections, we found that the power increases as the width of the waveguide decreases (compare the three different lines in Fig. 3). As we mentioned earlier, we are calculating the integrated Poynting vector over the same area for all the cases. Since the fields in the narrower cross section waveguides are more well localized around the waveguide, we expect most of the power will be concentrated around the calculated area. The double peak appearing in Fig. 3 is most probably coming from the anisotropy

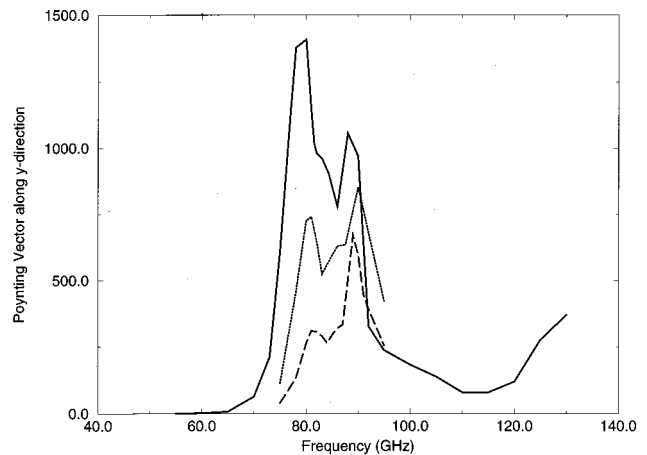


FIG. 3. Poynting vector before the bend as a function of frequency. Solid, dotted, and dashed lines correspond to waveguide cross sections of  $0.2 \times 0.26$  mm,  $0.4 \times 0.39$  mm, and  $0.6 \times 0.525$  mm, respectively.

of our lattice. We are currently investigating this point. Interestingly, the relative intensity of the two peaks change as the cross section of the waveguide increases.

In Fig. 4, we show the efficiency of the waveguides as a function of frequency. We define efficiency as the ratio of the integrated Poynting vector after the bend to the one before the bend. As we mentioned in the discussion of Fig. 2, the envelope of the integrated Poynting vector fluctuates over time. For that reason, in the calculation of the efficiency, we use the first maximum value reached by the envelope of the integrated Poynting vector, so, we most probably eliminate any interference due to back reflections from the edges of the waveguide. In all the cases, the maximum efficiency is achieved at around 81.5 GHz, which coincides with the first peak shown in Fig. 3. The maximum efficiency is 0.85 and it has been achieved for the narrower waveguide. It is surprising that such high efficiency has been achieved with only three unit-cell structures. This is an encouraging result and lead us to believe that an efficiency of 1 can be

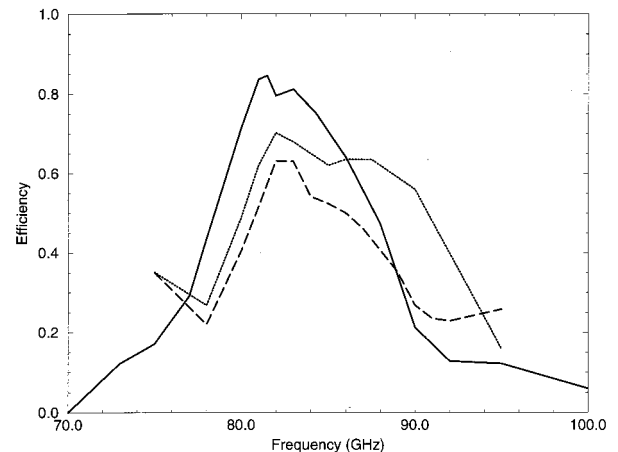


FIG. 4. The efficiency (ratio of the Poynting vectors before and after the bend) versus frequency. Solid, dotted, and dashed lines correspond to waveguide cross sections of  $0.2 \times 0.26$  mm,  $0.4 \times 0.39$  mm, and  $0.6 \times 0.525$  mm, respectively.

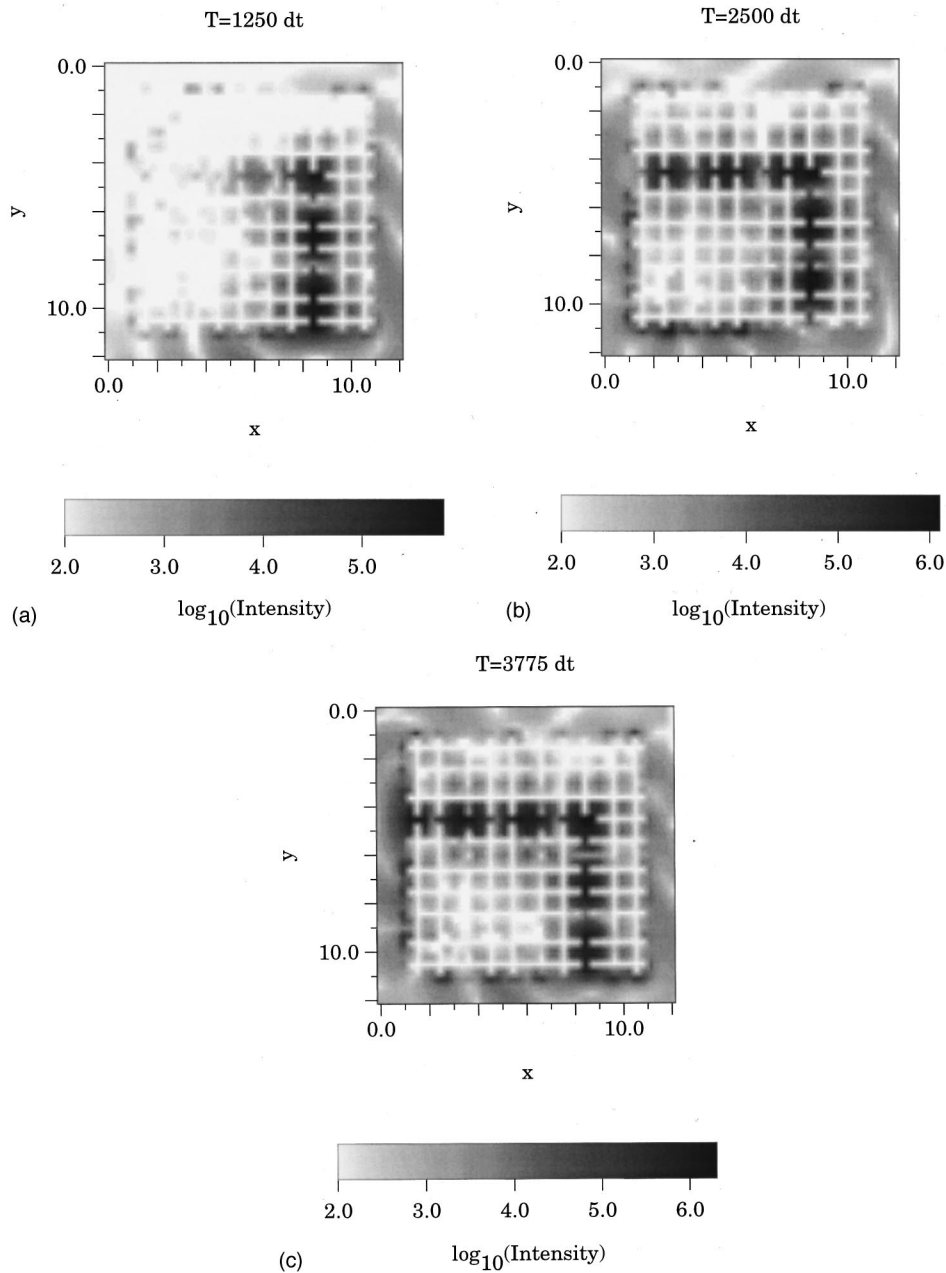


FIG. 5. The logarithm of the intensity along the middle layer of the structure after time steps 1250, 2500, and  $3775\Delta t$  [panels (a), (b), and (c), respectively].

achieved for thicker MPBG crystals and probably slightly different structures (more symmetric structures).

We also studied the power distribution along the waveguide for the  $0.2 \times 0.26$ -mm cross section waveguide and 81.5 GHz. Figure 5 shows the power distribution at the middle layer. The metallic mesh can clearly be seen [especially in Figs. 5(b) and 5(c)] since the power is zero inside the metal. We can clearly see how the wave is propagating through the waveguide as the time increases. In all the cases the field is very well localized around the waveguide (notice the logarithmic scale in the power distribution). Interestingly, some amount of power radiated from the dipole does not enter the waveguide and it is propagating around the surface of the structure.

In conclusion, we studied waveguides in three-dimensional MPBG materials. Using just three unit-cell thickness structures, we were able to achieve transmission of energy as high as 85% through  $90^\circ$  bends. This encouraging result lead us to believe that higher transmission efficiencies can be achieved using thicker structures. Another possible way to increase the transmission efficiency is to introduce a mitre as in conventional metallic waveguide bends. Such waveguides can be used for the communication of different circuits in printed circuit boards.

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- <sup>1</sup>For a recent review, see the articles in *Photonic Band-Gap Materials*, edited by C. M. Soukoulis (Kluwer, Dordrecht, 1996).
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