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FDTD analysis of PBG waveguides, power splitters and switches

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Abstract. Finite two-dimensional photonic bandgap (PBG) structures were analyzed with a finite-difference time-domain (FDTD) full wave, vector Maxwell equation simulator. Removal of particular portions of these PBG structures lead to interesting sub-micron-sized waveguiding environments. Several waveguides and power dividers were designed and evaluated. By introducing further defects into the PBG waveguiding structures, control of the flow of electromagnetic energy in these nanometer-sized waveguides can be affected. This effect is demonstrated, and its use to achieve a micron-sized waveguide switch is shown.

Key words: computational optics, microstructure devices, numerical approximation and analysis, photonic band-gap structures, waveguides

1. Introduction

Nanometer and micron-sized optical devices are currently being explored for their applications in a variety of systems associated with communications, data storage, optical computing, etc. However, as the size of optical devices is pushed to the size of an optical wavelength and less, the need for more exact materials and response models is tantamount to the successful design and fabrication of those devices. Moreover, the time scales for many of these devices is rapidly approaching the femtosecond regime. For this reason, the finite-difference time-domain (FDTD) method is receiving intensive study (see, for example, (Taflove 1995, 1998) for an extensive bibliography, and (Ziolkowski and Judkins 1994, 1995; Ziolkowski *et al.* 1995; Liang and Ziolkowski 1997a, b; Ziolkowski 1997; Liang and Ziolkowski 1998a, b, c) for work associated with one of the authors (RWZ)).

The photonic band gap (PBG) structure has become a very important subject in the optics regime for microcavity laser mirrors and filters (Yablonovitch 1987; Maystre 1994; Joannopoulos *et al.* 1995; Villeneuve *et al.* 1996; Mekis *et al.* 1996; Foresi *et al.* 1997; Krauss *et al.* 1997; D'urso *et al.* 1998; Kawakami 1998; Mekis *et al.* 1998; Painter *et al.* 1998; Shawn-

Yu Lin 1998; Shanhui Fan *et al.* 1998). In particular, it has been demonstrated computationally and experimentally that photonic bandgap (PBG) structures can be used to form nanometer-sized waveguiding structures (Joannopoulos *et al.* 1995), (Mekis *et al.* 1996, 1998; Ziolkowski and Franson 1996, 1997; Foresi *et al.* 1997; Shawn-Yu Lin *et al.* 1998; Ziolkowski 1998a, b), for a variety of optical applications. The ability of the FDTD approach to model finite-sized PBG structures and to recover known behaviors has been demonstrated in those works. The simulator used in the present PBG waveguide analysis has been validated previously (Ziolkowski and Franson 1996, 1997; Ziolkowski 1998a, b), and has been extended recently to study dispersive effects in PBG structures (Ziolkowski and Tanaka 1999). The FDTD approach has been used extensively in the microwave regime (see, for example, (Taflove 1995, 1998; Kunz and Luebbers 1993) for numerous references) and even for studying PBG structures at microwave frequencies (see, for example, (Maloney *et al.* 1997; Reineix and Jecko 1996; Thevenot *et al.* 1998)).

This paper further illustrates the ability of the FDTD approach to model finite-sized PBG waveguiding structures. Channels formed by removal of columns and rows in a PBG structure constitute waveguiding environments for the flow of electromagnetic power. Results for basic sub-wavelength waveguiding structures that include right-angle corners have been produced that show that complete power flow through these right-angle corners is possible. Power splitters are then produced from this basic building block. It is then shown that by introducing further defects into the PBG structure, control of the electromagnetic power flow in the waveguides can be achieved. The power splitter with additional defects leads to a switch configuration. The properties of this defect-based switch have been obtained with the FDTD approach and will be shown below.

2. FDTD simulator

To model the interaction of electromagnetic fields with two-dimensional PBG structures, a FDTD simulator has been developed (Ziolkowski and Franson 1996, 1997; Ziolkowski 1998a, b). The FDTD simulator is a full-wave solution to the vector Maxwell equations (see, for instance, (Taflove 1995, 1998; Kunz and Luebbers 1993)). The FDTD approach can handle ultrafast single-cycle pulse cases as readily as multiple-cycle cases having an intrinsic carrier wave. It can incorporate complicated scatterers and materials such as the PBG structures with great flexibility. In this manner, the basic electromagnetic properties of the PBG structures can be determined over a broad bandwidth of frequencies in a single run. This allows a determination of the pass and stop bands of the PBG from an essentially impulse excitation of the PBG structure. The response of the same structure at selected frequencies, such as the resulting electric field patterns, can then be evaluated in detail.

The discussion in this paper is restricted to the TE_z polarization which requires the E_y, H_x, and H_z field components. The associated FDTD update equations are obtained with the standard staggerred grid, leap-frog time integration scheme (Taflove 1995) and are given by the expressions

$$H_x^{n+1/2}\left(i,k+\frac{1}{2}\right) = \frac{2\mu - \sigma_M \Delta t}{2\mu + \sigma_M \Delta t} H_x^{n-1/2}\left(i,k+\frac{1}{2}\right) + \frac{2\Delta t}{2\mu + \sigma_M \Delta t}\frac{1}{\Delta z}[E_y^n(i,k+1) - E_y^n(i,k)] \tag{1}$$

$$H_z^{n+1/2}\left(i+\frac{1}{2},k\right) = \frac{2\mu - \sigma_M \Delta t}{2\mu + \sigma_M \Delta t} H_x^{n-1/2}\left(i+\frac{1}{2},k\right) - \frac{2\Delta t}{2\mu + \sigma_M \Delta t}\frac{1}{\Delta x}[E_y^n(i+1,k) - E_y^n(i,k)] \tag{2}$$

$$\begin{aligned} E_y^{n+1}(i,k) = &\frac{2\epsilon - \sigma_E \Delta t}{2\epsilon + \sigma_E \Delta t} E_y^n(i,k) - \frac{2\Delta t}{2\epsilon + \sigma_E \Delta t} J_y^{n+1/2}(i,k) \\ &+ \frac{2\Delta t}{2\epsilon + \sigma_E \Delta t}\frac{1}{\Delta z}[H_x^{n+1/2}(i,k+1/2) - H_x^{n+1/2}(i,k-1/2)] \\ &- \frac{2\Delta t}{2\epsilon + \sigma_E \Delta t}\frac{1}{\Delta x}[H_z^{n+1/2}(i+1/2,k) - H_x^{n+1/2}(i-1/2,k)] \end{aligned} \tag{3}$$

The PBG structure used in our investigation is a 15×13 square lattice of dielectric rods each of which has an infinite length along the y-axis. These rods, unless indicated otherwise, are assumed to be GaAs with a relative permittivity of $\epsilon_r = 11.4$ and relative permeability $\mu_r = 1.0$ surrounded by air. The radius of the rods is taken to be $r = 0.2a$, where $a = 0.5\lambda$ is the distance between the centers of the rods. With the choice of $\lambda = 1.5$ μm, one has $a = 0.75$ μm and $r = 0.15$ μm. This PBG structure is two dimensional by design.

The waveguide structure is formed by removing one column of rods as shown in Fig. 1. The waveguide width is $2a - 2r = 0.8\lambda = 1.2$ μm. The z-direction is taken along the waveguide; the y-direction is taken along the dielectric rods. The TE_z polarization thus has the electric field component along the dielectric corresponding to the PBG structure. An electromagnetic field is injected into the simulation space as a gaussian beam focused into the PBG waveguide from a total field/scattered field boundary (Taflove 1995) which is located 1.0λ away from the center of the first row. A Berenger PML (Perfect Matched Layer) absorbing boundary condition (Berenger 1994), (Taflove 1995) is used to truncate the FDTD mesh essentially without numerical reflection.

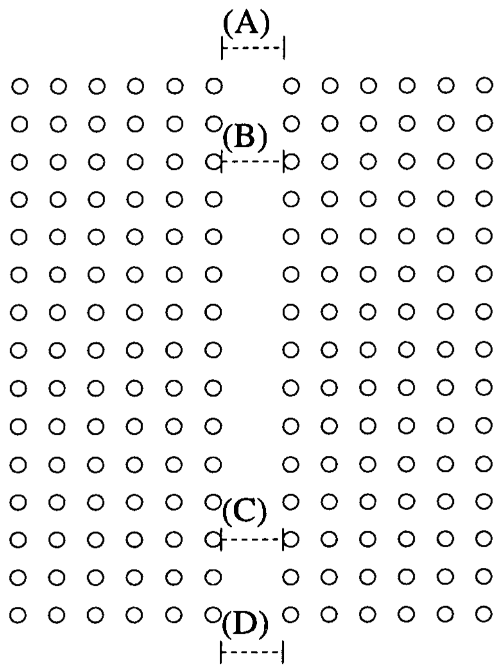

Fig. 1. Model of a straight waveguide.

We characterize the electromagnetic behavior of the PBG and the resulting waveguide structures by a set of transmission coefficients. Two transmission coefficients T_{AD}, T_{BC} which indicate the energies that propagate from the planes A to D and from B to C, as shown in Fig. 1, are defined in terms of the total time-averaged Poynting's vector through the surfaces A, B, C and D:

$$T_{AD} = \frac{P_D}{P_A} \tag{4}$$

$$T_{BC} = \frac{P_C}{P_B} \tag{5}$$

where the power

$$P_{A,B,C,D} = -\frac{1}{2}\mathrm{Re}\left[\int_{\mathrm{Width}} E_{y,\omega}(x, z = A, B, C, D) H^*_{x,\omega}(x, z = A, B, C, D)\mathrm{d}x\right] \tag{6}$$

where $E_{y,\omega}$ and $H_{x,\omega}$ represent in the frequency domain the incident electric and magnetic fields at the surface A and the total electric and magnetic fields at the surfaces B, C and D; and where $*$ represents the complex conjugate. The surfaces A and D are, respectively, $\lambda/2$ in z away from the front and back of the PBG structure; and the surfaces B and C are, respectively, 1.0λ in z inside the PBG structure from the center of the first and the last row of rods. These frequency domain fields are obtained from the FDTD-generated time domain fields via a Fast Fourier Transform (FFT).

3. Numerical results

Several PBG waveguide structures were considered in our investigation. They included a straight waveguide, a rectangular Y-shaped power splitter and a switch based upon the rectangular Y-shaped power splitter. The performance of each structure was characterized by the transmission coefficients T_{AD} and T_{BC} obtained with the FDTD simulator.

3.1. STRAIGHT WAVEGUIDE

A waveguide as shown in Fig. 1 is formed in a PBG structure because the removal of a column of rods separates the 15×13 structure into a pair of smaller 15×6 PBG structures. If those smaller structures individually have high reflectivity, the resulting composite structure – the PBG waveguide – will allow guiding waves to exist. Figure 2 shows the transmission coefficient T_{BC} through the straight waveguide geometry shown in Figure 1. The effects of the band gaps in these waveguiding environments are readily seen. Only an electromagnetic wave with particular frequency can propagate through the PBG waveguiding structure. For the pass bands, Fig. 2 indicates that efficient

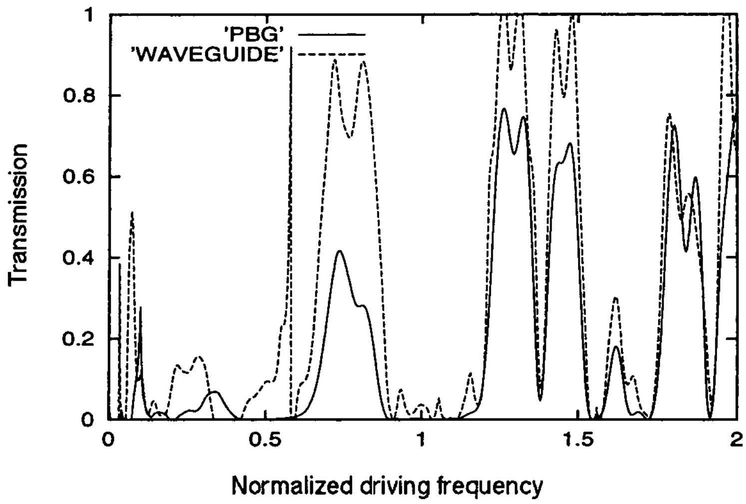

Fig. 2. Transmission coefficients T_{BC} through a portion of a straight wavguide in a square PBG lattice and T_{AD} through the entire PBG waveguide versus the normalized frequency (ω/ω_c).

power transmission, 80% to 100%, through the structure can be obtained once the guided wave is initiated in it. The transmission coefficient T_{AD}, which includes the coupling effects into and out of the PBG waveguide, is also provided in Fig. 2 for comparison purposes. The through power of these waveguides can be from 40% to 80%. The issue is that one may wish to move optical power from one position in space to another with low power loss. Figure 2 demonstrates that this is possible, but also that there is a cost involved with initiating the waveguiding mode and extracting power from it.

3.2. POWER SPLITTER

The power flow through a right angle waveguide corner was investigated and the results shown in (Joannopoulos *et al.* 1995) were recovered. Complete transmission of the guided wave power through such a corner can be achieved. This basic building block then allows us to consider the rectangular Y-power splitter shown in Fig. 3. Several cases were tested to determine how many rods in the sidewalls were necessary to maintain waveguiding. The number of rods at the exit side of the PBG structure determine these cases; they are 1-5-1, 2-5-2, 3-5-3. The 3-5-3 structure is the one shown in Fig. 3. Note that this Y-power splitter has the whole circuit-sizes in the left and right arms completely the same.

Figure 4 shows the transmission coefficient T_{AD} for these cases; Fig. 5 shows the corresponding transmission coefficients T_{BC}. One finds that only

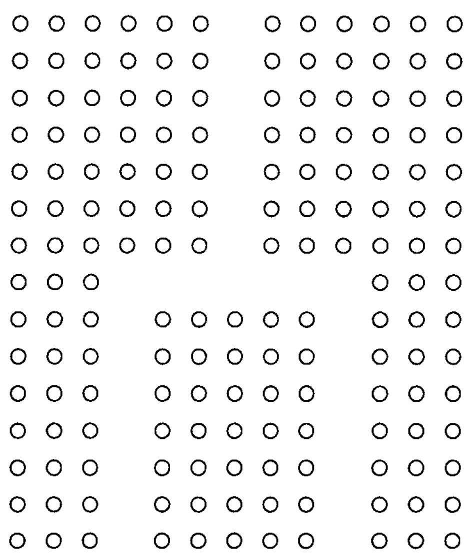

Fig. 3. Model of the 3-5-3 power splitter.

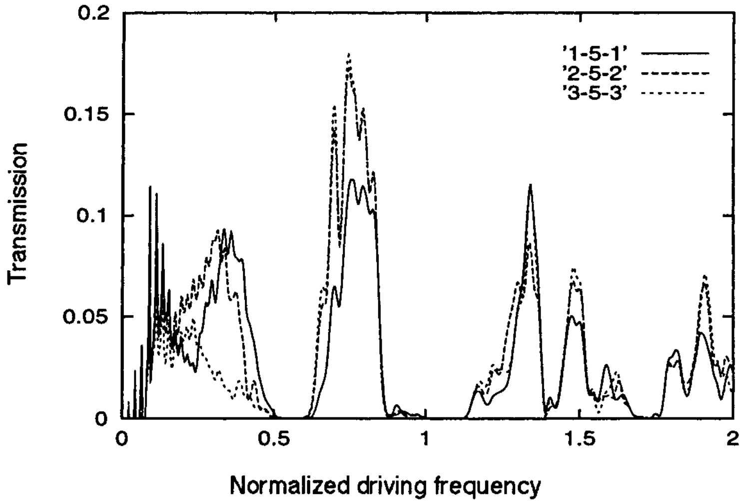

Fig. 4. Transmission coefficient T_{AD} through a portion of a rectangular Y-power splitter versus the normalized frequency (ω/ω_c).

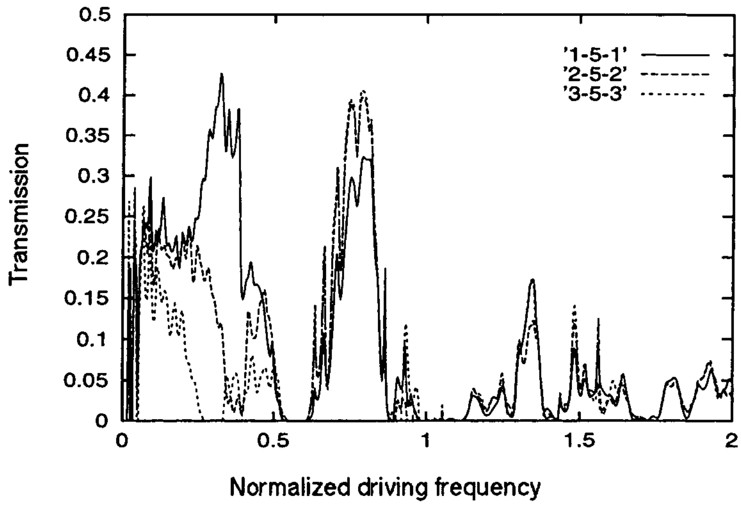

Fig. 5. Transmission coefficient T_{BC} through one side of a rectangular Y-power splitter versus the normalized frequency (ω/ω_c).

two rod layers are needed to achieve excellent guiding performance. One can also see that the optimal operating regime in these cases is centered approximately at $\omega/\omega_c = 0.75$ which is almost the same value as was found in the case of the straight waveguide structure shown in Fig. 2. Figure 5 shows that once the waveguiding modes near this optimal frequency are initiated, there is about 80% of the total energy that flows into the arms of the power splitter. The remaining energy is lost in reflections from the T-junction and the right angle corners. Because the arms are symmetric, equal amounts of power flow in each. As shown in Fig. 4, the total through power is maximum at $\omega/\omega_c = 0.75$ as well and is about 18% for each arm. Thus the total through power is nearly equal to the value associated with the straight waveguide itself, i.e., there is only about a 4% through power loss between the straight waveguide geometry and the more complicated rectangular Y-power splitter.

3.3. SWITCH

The previous results demonstrate that a power splitter can be achieved in a micron-sized environment using PBG waveguiding structures. It has been found that by introducing additional defects into this splitter, a switch can be obtained that regulates the amount of power flow between each of the arms of the splitter. The additional defect(s) control the flow of light in the waveguide system.

One way to introduce additional defects to affect control over the electromagnetic power flow is to change the permittivity and/or permeability on both sides of one arm as shown in Fig. 6. The introduction of the additional

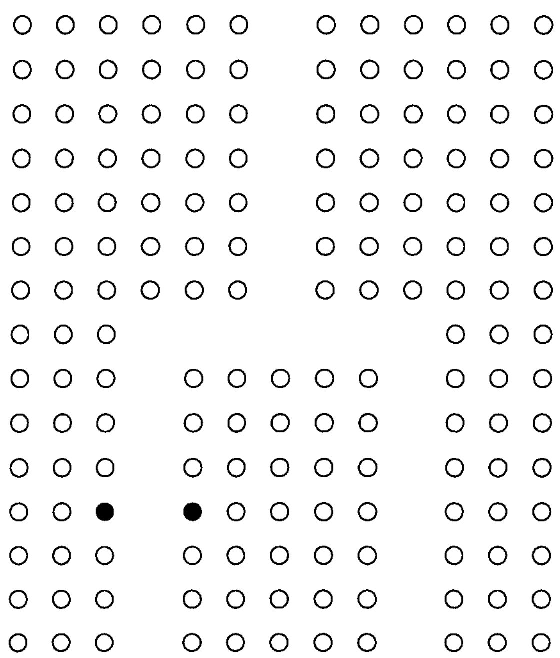

Fig. 6. Model of an optical switch.

defects breaks the symmetry of the original structure. The power of each arm will no longer be equal to that of the other.

Since these structures have applications to both microwave and optical frequencies, we decided to investigate the switching effects of defects introduced through large variations in both the electric permittivity and magnetic permeability. While it is recognized that such large variations in permeability are not directly available at optical frequencies, this investigation provides insights into and bounds on what types of defects would contribute most to the light control. Moreover, if there is a noticeable magnetic defect effect, it would be relatively easy to affect such a change in the relative permeability at microwave frequencies with an additional background magnetic field and the appropriate magnetic materials.

First, we introduce a magnetic permeability of 11.4 into the rods at $(12, 3)$ and $(12, 5)$, i.e. the relative permittivity and permeability of those rods are now 11.4 and 11.4. This geometry is depicted in Fig. 6 where the solid circles represent the newly introduced defects. Figure 7 shows the transmission coefficient T_{AD} of the left and right arms, and the reference case, i.e., that of the 3-5-3 splitter. We can see that the coefficient of the left arm decreases and that of the right arm increases between $\omega/\omega_c = 0.6 \sim 0.9$. There is now a 1:19.12 contrast at $\omega/\omega_c = 0.760$ between the left and right arms. This would lead to an interesting switch if the magnetic properties of these rods could indeed be affected by a background magnetic field.

Next, we left the rods at $(12, 3)$ and $(12, 5)$ with this higher relative permeability and changed their relative permittivity to 1.0, i.e. the relative permittivity and permeability of those rods are now 1.0 and 11.4. Figure 8 shows

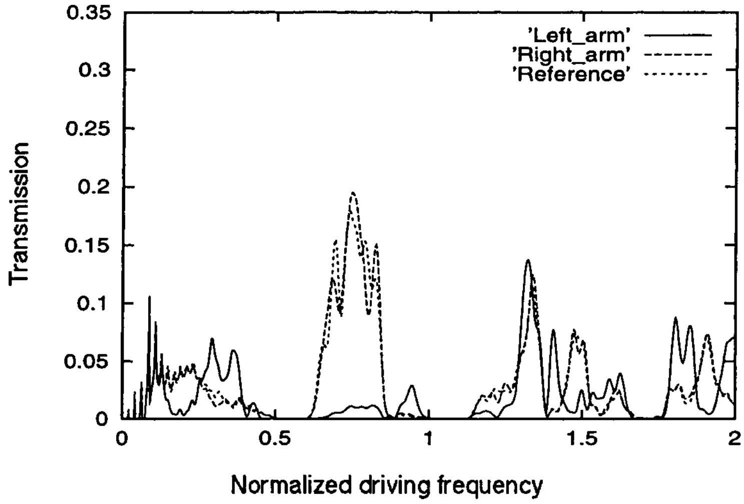

Fig. 7. Transmission coefficient T_{AD} through a rectangular Y-power splitter with defects ($\epsilon_{\mathrm{def}} = 11.4$ and $\mu_{\mathrm{def}} = 11.4$) in its left arm versus the normalized frequency (ω/ω_c).

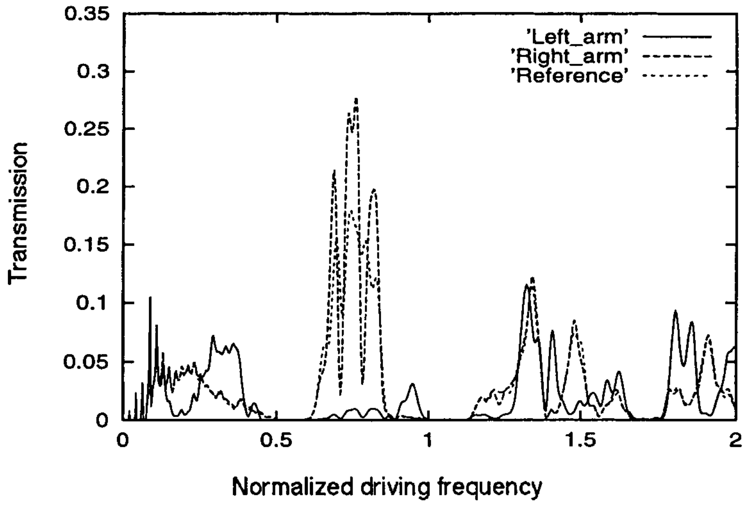

Fig. 8. Transmission coefficient T_{AD} through a rectangular Y-power splitter with defects ($\epsilon_{\text{def}} = 1.0$ and $\mu_{\text{def}} = 11.4$) in its left arm versus the normalized frequency (ω/ω_c).

the transmission coefficient T_{AD} of the left and right arms, and the reference case, i.e., that of the 3-5-3 splitter. In the same frequency regime we find that the contrast has risen to almost 1:29.15 at $\omega/\omega_c = 0.760$.

Finally, we completely removed the rods at $(12, 3)$ and $(12, 5)$, i.e. the relative permittivity and permeability of those rods are now 1.0 and 1.0. Figure 9 shows the transmission coefficient T_{AD} of the left and right arms, and the reference case, i.e., that of the 3-5-3 splitter. In the same frequency regime

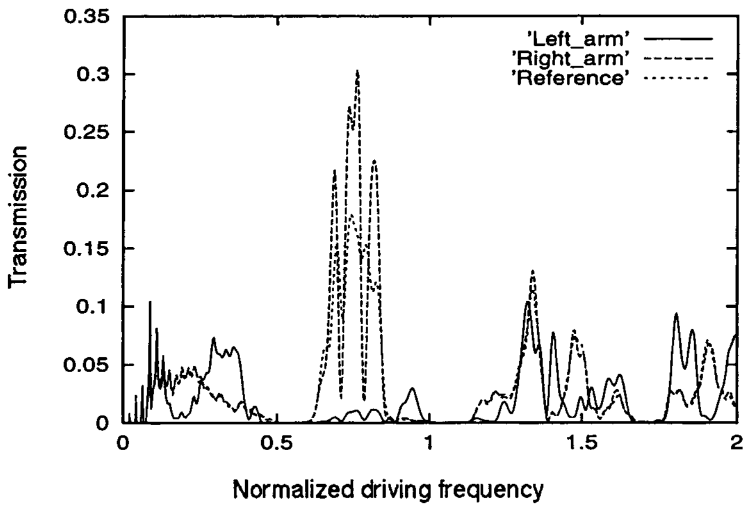

Fig. 9. Transmission coefficient T_{AD} through a rectangular Y-power splitter with defects ($\epsilon_{\text{def}} = 1.0$ and $\mu_{\text{def}} = 1.0$) in its left arm versus the normalized frequency (ω/ω_c).

we find that the contrast is about the same as the previous case and has the value 1:28.33 at $\omega/\omega_c = 0.760$.

From these results, one observes that a very large switching effect can be realized by changing either the permittivity or permeability. While the magnetic permeability defect alone does produce a large switching effect, it is not as large an effect as one could achieve with variations in the electric permittivity. Variations in the permittivity of the defects significantly impact the flow of light in the PBG structure.

One possibility to introduce a large permittivity change in the defect rods associated with Fig. 9 would be to introduce a pair of highly resonant dielectric rods whose relative permittivities near their resonance frequency and away from it have the correct values. These permittivity values could then be controlled by introducing an additional electric field to excite (or de-excite) the resonant materials. If the resonance frequency were selected in a passband of the PBG waveguide walls, the permittivities of the defect rods could be excited (de-excited) to the desired values without affecting the properties of the PBG structure that provide the confinement of the electromagnetic energy to its waveguiding portions. Another possibility would be to integrate an MEMS device with the PBG structure that could selectively insert or remove the defect rods much like the control rods in a nuclear pile. Although this would most probably result in a slow switch, the resulting device would have interesting isolation capabilities between the two arms of the splitter. All of these possibilities and related issues are currently being investigated.

4. Conclusions

We have shown the ability of an FDTD simulator to model PBG waveguiding environments. It was shown that by removing particular portions of a PBG structure, one can obtain interesting sub-micron-sized waveguiding environments. The performance of a straight waveguide in a square lattice of dielectric rods was characterized with the FDTD simulator by measuring the power coupled into and out of the waveguide in addition to the power flow in it. Next a power splitter was introduced which was based upon combinations of this simple straight waveguiding geometry. The power flow characteristics of the power splitter were also obtained with the FDTD simulations. It was found that the composite structure had frequency responses different from the straight waveguide alone. Moreover, it was demonstrated that walls which are only two dielectric rods thick are sufficient to provide very good waveguiding properties. Further defects were introduced around one arm of the power splitter to control the flow of electromagnetic energy in the arms of this PBG waveguide structure. These defects led to a switching effect where the presence of the defects caused the power flow to become asymmetric in the two arms. Contrasts as large as 1:28.33 were obtained with dielectric defects. Suggestions as to how one might realize the requisite variations in the dielectric permittivity were made. More complex defect structures are currently being investigated to determine how much isolation between the arms of the power splitter can be achieved for given variations in the permittivity values of the defects.

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