Surface-Wave Guiding Using Periodic Structures

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Abstract

In this paper, we present finite-difference time-domain (FDTD) simulations of two periodic frequency-selective waveguides: (1) a periodic lattice of dielectric rods where the waveguide is formed by removing some of the rods; and (2) a periodic lattice of metallic plates above a ground connected to the ground by metallic posts. The first photonic bandgap (PBG) waveguide is designed to operate in the optical region from 1.5 to 2μm wavelength, and it exhibits over 30dB rejection in unwanted directions. The second PBG structure is designed to exhibit a bandgap in the microwave range from 10 to 12GHz, and also shows over 30dB attenuation of guided field in the unwanted directions.

I. INTRODUCTION

Groundbreaking work on photonic bandgap structures done by Eli Yablonovich [1] suggested that a photonic crystal could create a bandgap by utilizing the different refractive indices of the periodically placed materials. Joannopoulos has written a comprehensive text on the subject [2], and analytic expressions, along with measurements, were reported for defects in photonic bands structures [3]. A photonic bandgap structure prohibits propagation over a frequency band. Defects in the PBG lattice, however, will give rise to field localizations within the structure. Creating a line of defects in the lattice provides a waveguide where propagation is allowed, and energy will be contained in the line defect because it cannot propagate in the surrounding structure. This principle was applied in [4] to show that photonic bandgap structures can be used to guide waves through bends with very low radius of curvature at millimeter wave frequencies. The experimental results at 100GHz presented in [4] showed that high bending efficiencies, or transmission comparisons to straight waveguides, of greater than 80% were possible.

In this paper, we present two- and three-dimensional FDTD results for PBG waveguides in the optical and microwave regions. The two structures we present could have several applications. For example, a 90-degree, low-loss bending of an optical signal by using a defect in a periodic structure would be very useful for optical ICs, as this would ease the design layout rules. A similar use of periodic metallic shapes on an antenna ground plane might be used to direct unwanted surface currents away from radiating antenna edges, thus diminishing side lobes in the radiation pattern.

II. PERIODIC GUIDING STRUCTURE AT OPTICAL WAVELENGTHS

The structure analyzed here, based on [4], is a square lattice of dielectric rods ($\varepsilon_r = 8.9$, $n = 2.98$) in an air background. This material is similar to GaAs, which has an index n between 3.3 and 3.6. By using air as the background material filling the waveguide, material losses suffered by dielectric waveguides are not present. The structure used in [4] was composed of 0.254mm

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diameter cylindrical rods spaced 1.27mm apart in a square lattice. This structure had a bandgap from 80 to 100 GHz. One motivation for this work was linear scaling into the optical region. We studied this possibility using a 2-dimensional FDTD [6] model. To reduce the complexity of the model, square rods of equal volume fraction were used instead of cylindrical rods, since the volume fraction of the dielectric rods is the critical design variable. As in [4], the FDTD model consists of a 13 by 14 grid of dielectric rods ($\varepsilon_r = 8.9$, $n = 2.98$) with straight and bent waveguides formed by removing rods. The spacing of the square lattice is 6.4μm, and the rods are 2.3μm square, designed for a bandgap in the infrared region. A line source located at the edge of the grid is used to excite a cylindrical wave into the structure.

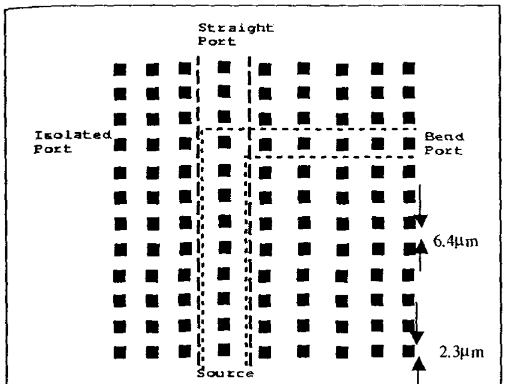

Figure 1: Optical frequency PBG grid of dielectric posts with waveguides formed by removing a line of posts.

Figure 1 shows the lattice and the two defect waveguides: the straight port and the bent port. The isolated port is included for comparison. Two separate simulations were run, one with the straight waveguide elements removed and one with the bent waveguide elements removed. For the straight port simulation (Figure 2a), over 30dB more electric intensity is received at the end of the waveguide in the range of wavelengths between 1.6um and 2um than elsewhere in the structure. Over this range the field magnitude is greater than the $(r)^{-1/2}$ fall-off associated with a cylindrical wave, showing that energy is indeed being guided within the waveguide. The signal received at the bent port is further attenuated than the isolated port because waves must travel through more of the

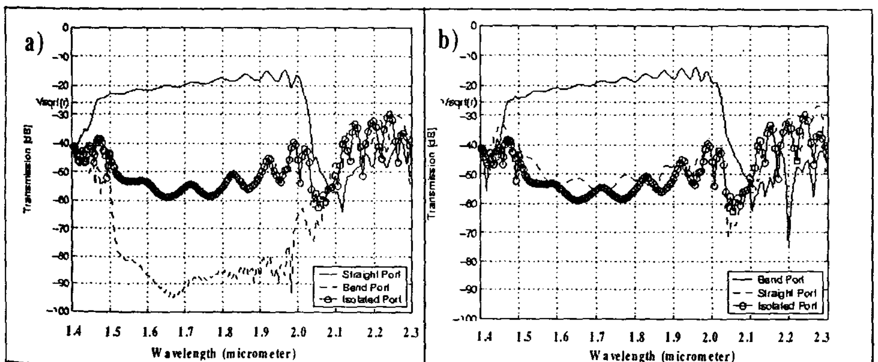

Figure 2: a) optical straight waveguide transmission. b) optical bent waveguide transmission
In both graphs, the solid line indicates waveguide transmission, while the dashed and circle lines represent unwanted directions.

PBG structure to reach the bent port. Figure 2b shows the results of the bent waveguide simulation. The electric field magnitude received at the opening of the bent waveguide is much greater than that at the other two ports, and is also above the level expected for a cylindrical wave. These results verify that an electromagnetic wave at optical frequencies can be guided around a 90-degree bend with zero radius of curvature.

III. Periodic Guiding Structure At Microwave Frequencies

Extending the idea of periodic structures used to direct and filter certain frequencies in the optical range, we now present an analog of this situation in the microwave range. Instead of using the dielectric rods, metallic elements in mushroom-type shapes are used to prohibit surface waves, shown in Figure 3 [5]. This particular shape creates distributed inductive and capacitive elements, which can be calculated with the following formulas, using the dimensional notations shown in figure 3:

$$C = \left(\frac{1}{\pi}\right) w(\varepsilon_0 + \varepsilon_d) cosh^{-1}\left(\frac{a}{g}\right) \quad (1)$$

$$L = \mu t\left(\frac{l}{w}\right) \quad (2)$$

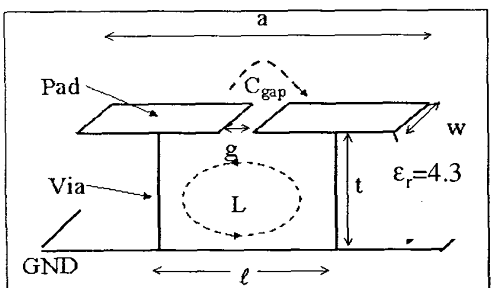

Figure 3: Metallic mushroom structures used for microwave periodic surface.

The following dimensions were used in our model: a = 6.35mm, t = 2.286mm, w = 3.048mm, g = 0.254, l = 3.302, ε_d = 4.3 (Polyimide). These dimensions yielded an equivalent L of 4.82nH, an equivalent C of 0.583pF, and a resulting resonant frequency of 4.97GHz.

The one-dimensional mushroom structure can be extended to an array of structures in two dimensions. The 2D array is then used for the same purpose as the optical PBG rods: to guide energy along waveguides cut through an array of periodic structures that inhibit transmission in a certain range of frequencies. Figure 4 shows the arrays of mushroom structures with both the straight and bent defect waveguides. A 3D FDTD code was used to simulate the models, and electric field values were recorded at the same relative locations used for the optical simulations. Figure 4 also shows the results of these simulations. The bandgap frequency is double that of the simple LC circuit, as the two-dimensional nature of the surface effectively halves the L and C. In a frequency band between about 10 and 12 GHz, both the straight and bent models show that the energy traveling in the dielectric is contained almost exclusively in the waveguide, with as much as a 40dB reduction at the other ports. This result demonstrates the filtering and waveguide capabilities of the design.

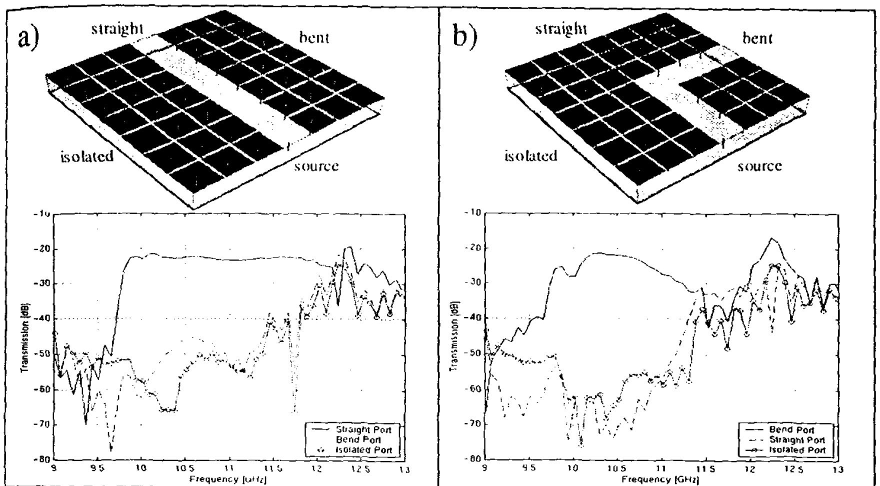

Figure 4:a) Straight mushroom waveguide model and results. b) Bent mushroom waveguide model and results. In both graphs, the solid line indicates waveguide transmission, while the dashed and circle lines represent unwanted directions.

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