A new type of waveguide structures with photonic band structures

Toshio Suzuki and Paul K. L. Yu
Department of Electrical and Computer Engineering

D. R. Smith and S. Schultz
Department of Physics

University of California, San Diego
La Jolla, California 92093-0407

Abstract

We study a new type of waveguide structures -- two-dimensional photonic crystals sandwiched between two metal conductors. In the structures, not only the electromagnetic propagation, but also the radiation spectra can be controlled. Radiation from microwave dipole antennas can be completely suppressed in band gaps and enormously enhanced at specific pass bands frequencies.

Introduction

Recently, attention has been focused on the special properties of wave propagation in two and three-dimensional periodic structures (photonic crystals) which have come to be called photonic band structures[1~3]. Although the term photonic suggests phenomena associated with electromagnetic waves in optical frequencies, it should be appreciated that the concept of photonic band structures, and the novel, indeed unique, properties that they may exhibit, are applicable to any electromagnetic propagation in arbitrary frequencies.

Photonic crystals with specific material and crystallographic configurations can exhibit complete photonic band gaps in the dispersion relations -- finite continuous frequency regions where energy propagation is forbidden for all possible wave directions. Interestingly, it is possible to suppress various types of electromagnetic propagation and radiation completely in such photonic band gaps. In fact, recent studies[1,2] have shown that in properly designed photonic crystals radiation can be controlled from complete inhibition inside photonic band gaps to enormous enhancement at specific pass band frequencies.

Here, we study microwave propagation and radiation in a new type of waveguide structure incorporating two-dimensional photonic crystals, which is expected to have (1) High efficiency, (2) High directivity, and (3) Single mode property.

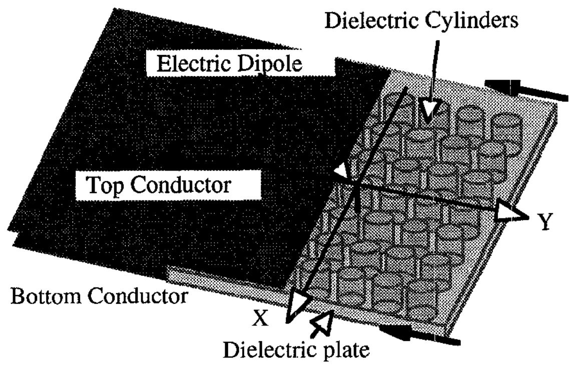

Fig. 1 Waveguide structure with a 2-D photonic crystal

Waveguide Structures

We introduce a new type of waveguide structures -- two-dimensional photonic crystals sandwiched between two conductors.

1996 IEEE MTT-S Digest

Circular holes forming a periodic lattice is drilled vertically on a thin dielectric plate. In the periodic holes, we place scatterers with a different dielectric constant (or air scatterers). The two-dimensional periodic dielectric structure (i.e. a photonic crystal) is inserted between a pair of metal plates as depicted in Fig 1.

Theory

We solved Maxwell's equations (wave equations) by using the plane wave expansion method(1,2,3) for periodic propagating modes under the periodic boundary condition. The computational method for dipole radiation spectra(1,2) is based on (1) the plane wave expansion method for eigenfunctions of the homogeneous wave equation, (2) the dyadic Green's function and Poynting theorem to obtain an analytic expression of radiated power from a dipole in two-dimensional systems, and (3) triangle integration method to approximate the k-space integral.

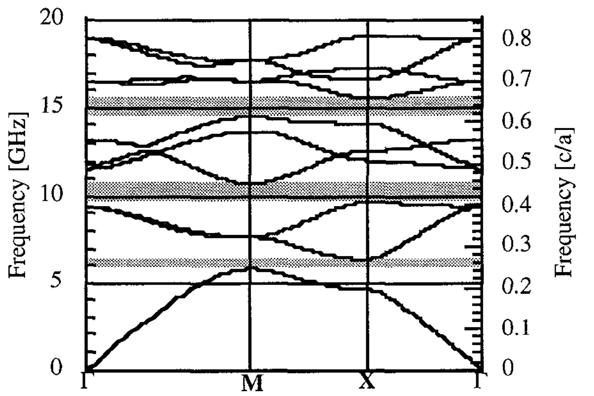

Fig.2 Dispersion relation for fundamental E-polarized modes

A dispersion relation for the E-polarized fundamental modes (the E-field is uniform and only in the z-direction) in the infinite periodic structure is computed in Fig. 2. The two-dimensional square lattice (lattice constant=a) with dielectric cylinders (ε=9, radii=0.378a) is chosen as an example(1,2,3). The shade areas indicate the photonic band gaps -- frequency stop bands in which propagating electromagnetic waves are forbidden in every direction. Electromagnetic waves inside the photonic band gaps have no propagating modes which are analogous to electron waves inside the conventional electronic bands. If the thickness of the two metal plates is sufficiently small, we can exclude the higher order propagation outside the frequency range of interest(3).

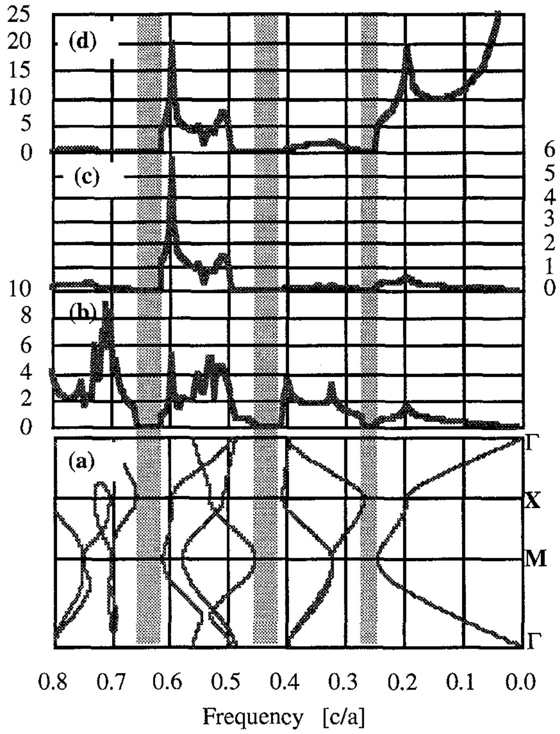

Fig.3 (a) Photonic band structure, (b) Density of states in the units of $[48V/(2\pi)^2]$, (c) Computed Radiation Power in the units of $[I_0^2\eta(d/2a)^2]$, (d) Relative radiation power to that in free space.

Radiation spectra in the waveguide structures can be completely different from those in free-space(1,2). The unusual radiation property in the waveguide structures with two-dimensional photonic crystals originates intrinsically from non-free-space electromagnetic dispersion relations and corresponding spatial field distributions generated in the photonic crystals. For instance, radiation power from an electric dipole at the center of a dielectric scatterers in the waveguide structure (depicted in Fig. 1) is calculated in Fig. 3. Fig. 3 (b) shows the density of photon states. We plot the calculated radiation power and normalized radiation power by the free-space radiation in Fig 3 (c) and (d) respectively. The results indicate that inside photonic band gaps, radiation is completely suppressed, and enormously enhanced at specific pass band frequencies (e.g. around 14 GHz, or 0.6 [c/a] in Fig. 3).

Experiments

The theoretical results are compared with experimental measurements in a microwave frequency region. Lossless antennas transmit exactly the same amount of energy as radiation to the surrounding system. In other words, antennas emitting more energy should generate smaller power reflections for constant input current. Therefore, if the dipole antennas are supplied the leveled off input in the frequency range of measurements, the radiation power spectra of the dipole antennas can be obtained by measuring the reflected power from the antennas.

An electric monopole antenna, namely, a coaxial cable with the top-end stripped off, was inserted in the waveguide structure through vertical holes opened on the top aluminum cover plate as shown in Fig. 4 (a). The thin conducting wire lead by the coaxial cable with the length sufficiently less than the radiating wavelengths on the conducting aluminum plate can be approximately regarded as an electric dipole antenna. The dipole antenna is connected to a sweep oscillator through a directional coupler. The reflected power through the directional coupler was detected by a crystal detector, and measured by a scalar network analyzer. The experimental set up is also summarized in Fig. 4 (b). In order to minimize the effects of the unknown frequency dependent current distributions along the antennas, we calibrated the antenna's frequency characteristics by use of the previously measured radiation spectra in the empty waveguide without the photonic crystal.

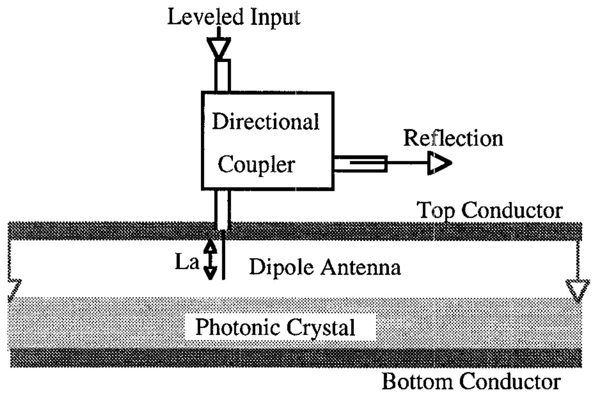

Fig. 4 (a) Reflection Measurement

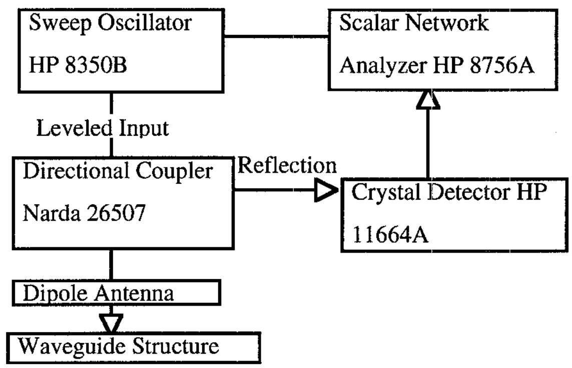

Fig. 4 (b) Experimental Set-up

In Fig. 5 (b) and (c), the experimentally measured emission power $P^{exp2D}_{lattice}=P^{exp}_{lattice}/P^{exp}_{Plates}$ and frequency weighted emission power $\frac{c}{\omega}P^{exp2D}_{lattice}$ are plotted respectively, to be compared with the computed emission power $P^{2D}_{lattice}$ (shown in Fig. 5 (a)). The dipole antenna (La=3 mm) is positioned in the center of the dielectric cylinder (0,0), of a 22 by 18 photonic crystal. Clearly, both of the two experimental spectra, for $P^{exp2D}_{lattice}$ and $\frac{c}{\omega}P^{exp2D}_{lattice}$ show good agreements to the computed spectrum $P^{2D}_{lattice}$, particularly, around 12~14 GHz where the fundamental modes couple strongly to the dipole antenna. The signature of the emission spectra under this setting was stable, particularly, the position of the sharp peak at 14 GHz; hence, we do not believe the results were coincidental.

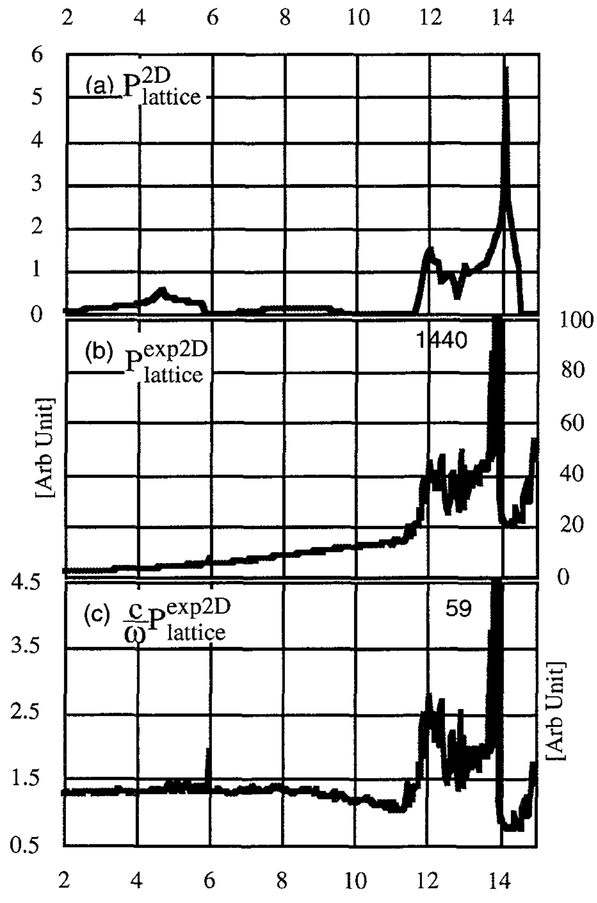

Fig. 5 (a) Computed emission power in the units of $[I_0^2\eta(d/2a)^2]$, (b) Experimentally measured emitted power normalized to experimentally measured emission in the empty chamber, (to be compared with (a)), (c) Quantity measured in (b) multiplied c/ω.

Conclusion

The novel waveguide structures can have the following properties:

(1). High efficiency

In the waveguide structures with a two-dimensional photonic crystal, the coupling efficiency between the dipole antenna and the fields are enormously enhanced at the specific pass band frequency and completely prohibited inside the photonic crystal as shown in Fig. 3. The enhanced radiation is mainly caused by 1) the higher local intensity of the electric field generated in dielectric cylinders and 2) the singularities at the symmetric points of k-vectors which are caused by zero group velocity. If the oscillation frequency and location of the dipole are chosen intentionally at the proper photonic band edges, the radiation power can be 10~20 times as high as that in free space as computed in Fig. 3.

(2). High directivity

If proper photonic band edges are selected, the directions of energy propagation can be limited in only one crystallographic direction. For the conventional two-dimensional structures without photonic crystals, dipole radiation spreads out cylindrically in the two-dimensional space. However, our new structure can force the dominant radiation in very limited directions.

(3). Single mode

Since only one propagation mode is available in the photonic crystal at the selected frequency, electromagnetic propagation in the waveguide structures can be single mode at the frequencies.

References

(1). T. Suzuki and P. K. L. Yu, J. Opt. Soc. Am. B.**12**, 570 (1995).

(2). Toshio Suzuki, Ph.D. Dissertation (1995).

(3). David Smith, Ph.D. Dissertation (1994).