ELIMINATING SURFACE CURRENTS WITH METALLODIELECTRIC PHOTONIC CRYSTALS

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ABSTRACT

We report results on a new type of metallodielectric photonic crystal, which can act as an engineerable, artificial metal. These structures completely expel electromagnetic wave just as metals do. Like metals, they also support surface currents. By engineering the geometry of the surface, we have produced a structure that also has a band gap for the surface currents which overlaps the bulk band gap. This new material should be useful as a ground plane in low profile antenna applications.

INTRODUCTION

Photonic crystals are three-dimensional periodic structures that expel electromagnetic waves over a certain frequency range, called the band gap. [1,2] Conventional photonic crystals are made of two different dielectric materials, arranged in a periodic lattice. A new type of photonic crystal has recently emerged, in which metallic islands are incorporated into the dielectric lattice. [3-9] These structures can be regarded as a three-dimensional version of frequency selective surfaces.

If the metallic elements are brought very close together, capacitive interaction can lead to extremely wide band gaps, spanning more than an octave. [3] The frequency of the upper band edge is determined mainly by lattice constant of the crystal, and is given by $\omega_c \approx \pi c / na$, where c/n is the phase velocity of light in the background dielectric, and a is the lattice constant of the crystal. The frequency of the lower band edge is is given by $\omega_v \approx 1/\sqrt{LC}$, where C and L are the capacitance and inductance, respectively, of the metal elements. Thus, both band edges can be tuned independently by varying two different parameters, the capacitance and the lattice constant. This is illustrated in figure 1, which shows frequency versus wave vector for a metallodielectric photonic crystal with large capacitive coupling between the metallic

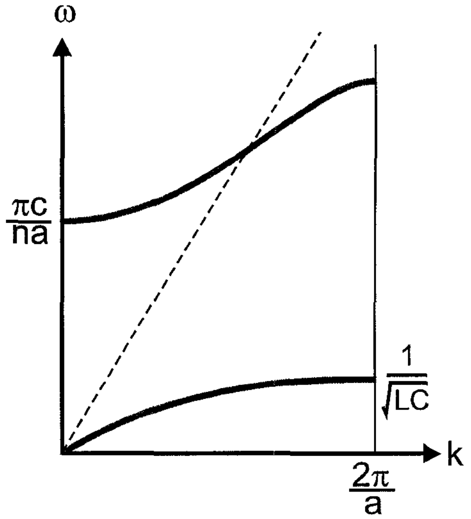

Figure 1: Dispersion diagram for a metallodielectric photonic crystal. c/n is the phase velocity of light in the background medium, a is the lattice constant, and C and L are the capacitance and inductance, respectively, of the metallic elements. The dotted line has a slope of c/n

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islands. At frequencies within the band gap, the photonic crystal completely expels electromagnetic radiation, for any direction of propagation.

CONSTRUCTION

We fabricated our capacitively coupled PBG structures using printed circuit board technology. The circuit boards are stacked and bonded together to form 3-D, periodic structures, and the combination of vertical metal vias and horizontal wiring allows many different topologies to be implemented. High capacitance is achieved by stacking the boards very close together, with facing metallic elements separated by thin dielectric layers.

The substrate is Rogers Duroid 5880, a commercial microwave circuit board material with a dielectric constant of $n^2=\varepsilon=2.2$. The capacitive interconnections are made using 25 μm thick layers of polyimide ($\varepsilon=4$) to separate each circuit board. Metal patches on each adjacent board are aligned to form a metal/polyimide/metal capacitor. The full stack is then bonded under pressure with phenolic butyral adhesive. A cross section of the structure is shown in figure 2.

Our photonic crystals are based on the diamond crystal structure, since that geometry tends to produce large band gaps. [10] The versatility of the printed circuit board fabrication method allowed several possible orientations for our diamond lattice. In the two structures we studied, the layers of circuit boards formed either the <001>, or the <111> planes of the crystal. [11] A perspective view of our first structure, with <001> orientation is shown in figure 3.

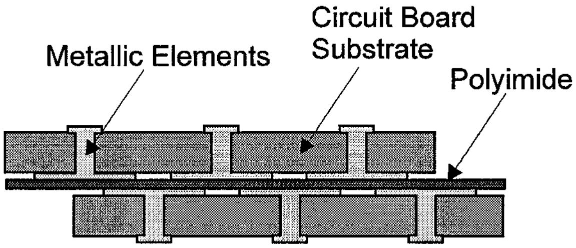

Figure 2: Circuit boards are pressed together, separated by layers of polyimide, which forms the insulator for the capacitors. Metal plated vias allow vertical connections between horizontal traces on the surface.

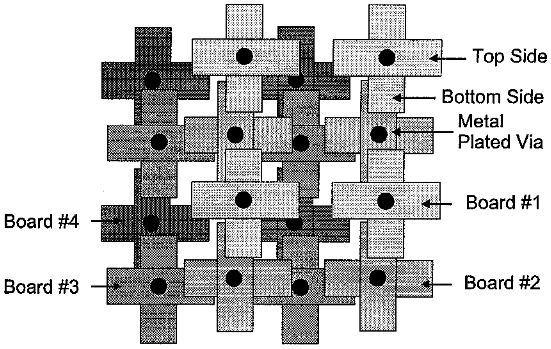

Figure 3: A diagram of our metallodielectric photonic crystal with <001> orientation. The pattern repeats every 4 layers, and our experimental structure was 13 layers thick. The capacitance of this structure is 0.5pF, and the lattice constant is 3.7mm.

BULK PROPERTIES

We studied the bulk properties of our photonic crystals using plane wave transmission measurements. A complete analysis of the bulk properties of this structure, along with a comparison to theory using a finite-difference time-domain technique, is described in [3]. We found that this structure has a bulk band gap

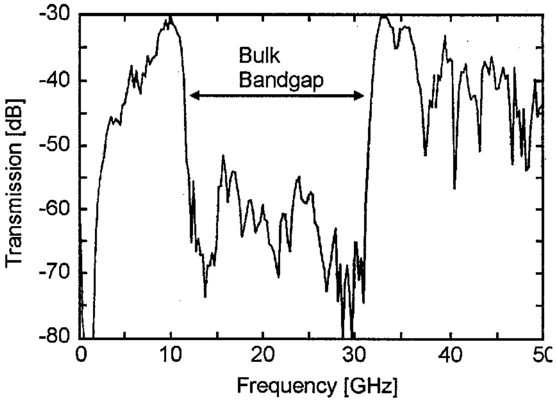

Figure 4: Transmission vs. Frequency for a <001> oriented, metallodielectric photonic crystal with diamond geometry, measured using monopole probe antennas, showing a bulk band gap spanning 12 - 30 GHz.

spanning 12 - 30 GHz. We verified that the band gap is omnidirectional by using monopole probe antennas, consisting of a short metal pin extending from the center conductor of a coaxial cable. A representative plot of transmission versus frequency is shown in figure 4.

SURFACE PROPERTIES

Within the band gap, these structures behave much like metals, in that they forbid the propagation of electromagnetic radiation through their bulk. Like metals they also support surface modes, or surface currents. [1,12,13] We can measure these modes by launching a wave across the surface with either a monopole probe, or a parallel plate waveguide structure. Strong transmission indicates coupling to a surface mode. In the case of the parallel plate waveguide, the plates are flared outward in a triangular shape, so that a wave that begins at the small end will approach a flat wavefront at the flared end, as shown in figure 5.

A typical surface wave measurement for our <001> oriented structure is shown in figure 6. Due to the low symmetry of the top surface, the frequency of the surface modes depends strongly on the angle of propagation. After testing all angles, we determined that this structure does *not* have a band gap for surface currents.

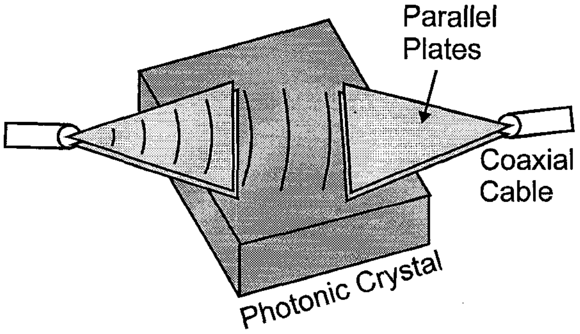

Figure 5: One method of measuring surface modes on photonic crystals. The flared parallel plate waveguide launches a surface wave across the photonic crystal.

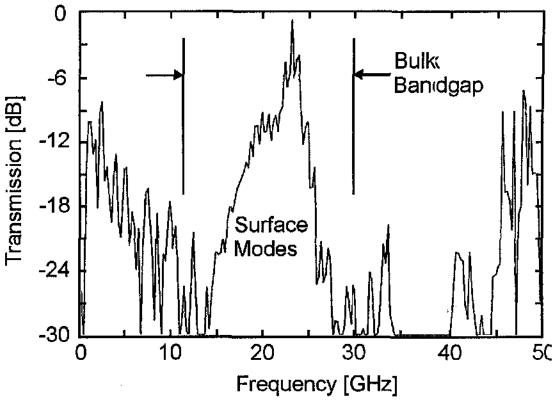

Figure 6: Surface mode measurement for a <001> oriented metallodielectric photonic crystal, measured in the <110> direction across the surface using flared parallel plate antennas. The large peak represents coupling to a surface mode.

<111> SURFACE ORIENTATION

The properties of photonic crystals can be engineered by adjusting various parameters such as the crystal geometry, the surface orientation, and termination. [1] The surface modes cannot be eliminated, but they can be pushed to frequencies outside the band gap by a proper choice of the surface geometry. Since a <111> termination yeilds a surface with much higher symmetry, we chose this geometry for our next structure, shown in figure 7.

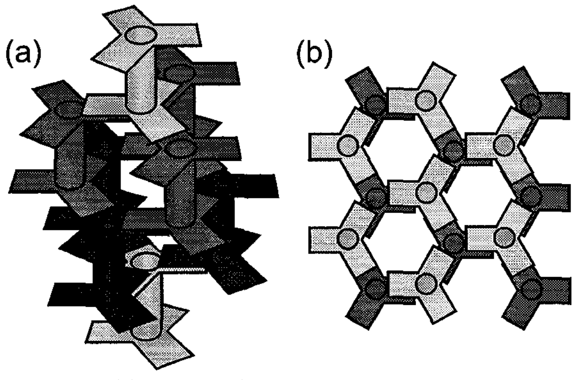

Figure 7: (a) Perspective view of our <111> oriented metallodielectric photonic crystal. The repeat unit is 3 layers in this orientation, and the experimental structure was 12 layers thick. Each capacitor is 0.3pF, and the lattice constant is 2mm. (b) View of the surface of our structure, showing the triangular symmetry.

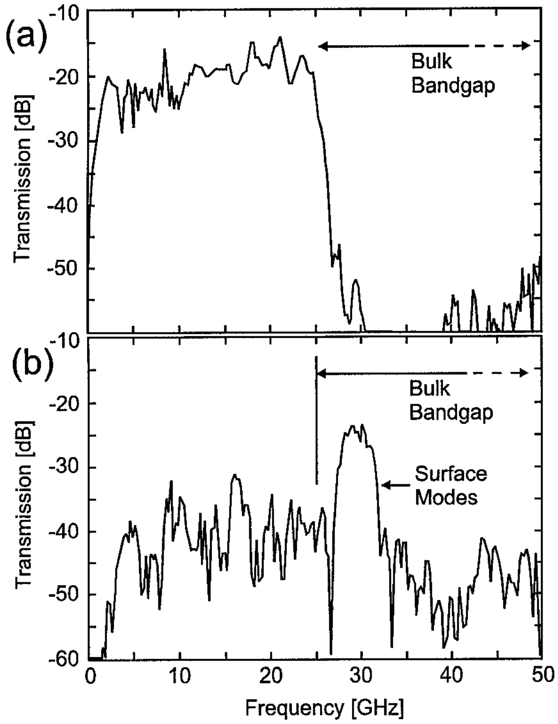

Figure 8: (a) Bulk transmission measurement reveal a band gap spanning from 25 GHz to greater than 50 GHz. (b) The surface waves are localized to narrow frequency band near the lower band edge.

Figure 8 shows the bulk and surface measurements of this new metallodielectric photonic crystal which has a <111> surface termination. The bulk band gap begins at 25 GHz, and our measurement capabilities were limited to 50 GHz. The surface waves on this structure are confined to a narrow band between 25-32 GHz. Due to the high symmetry of this surface geometry, the frequency of the surface modes is independent of direction, to within the limits of our measurement capabilities. The band gap for surface modes partially overlaps the bulk band gap, beginning at 32 GHz, and extending beyond 50 GHz.

CONCLUSION AND APPLICATIONS

We have demonstrated a metallo-dielectric photonic crystal which has a band gap for surface currents that overlaps the bulk band gap over a broad range of frequencies. This new type of photonic crystal is unique in that it expels electromagnetic waves just like a metal, but without the unwanted surface waves. With this property, photonic crystals could provide an alternative to metals for antenna ground planes. Since the surface properties involve only the last few layers of the crystal, the same effect may be achievable with only a thin skin of photonic crystal structure above a regular metal surface.

ACKNOWLEDGEMENTS

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