Experimental and theoretical results for a two-dimensional metal photonic band-gap cavity

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We demonstrate, by both microwave experiments and numerical simulation, that a two-dimensional lattice of *metal* cylinders can form a complete photonic band-gap (PBG) structure. The band structure exhibits a single broad PBG extending from zero frequency to a threshold frequency, above which all modes may propagate in some direction. A single cylinder removed from the lattice produces a defect mode localized about the defect site, with an energy density attenuation rate of 30 dB per lattice constant. The frequency dependence of the transmission through a finite thickness of this structure is also calculated in good agreement with the measurements. We suggest that the defect mode resonant cavity when formed by appropriate low loss metals may be advantageous for use in PBG high energy accelerator structures that we are evaluating.

The search for high-Q structures that localize electromagnetic energy in the optical regime has led to the concept of photonic band-gap (PBG) cavities.[1] The PBG cavities considered involve a periodically modulated dielectric medium into which is introduced a local defect. The periodic medium produces regions of propagating modes (the pass bands), separated by regions where all modes are evanescent (the band gaps). The defect in the medium allows for localized electromagnetic modes with frequencies that occur in the band-gap regions, such that the energy density can be highly localized about the defect. Much of the research reported since Ref. 1 has focused on dielectric structures that have a complete PBG in three dimensions, because the defect modes introduced may be potentially useful as high-Q optical cavities.[2]

While it is desirable for high-Q optical applications to have a structure that confines photons without using any metal, the fundamental concept of the PBG cavity can be extended to frequency regimes where metals may be advantageously incorporated into the structure, particularly in two dimensions (2-D).[3,4] In this letter we consider a PBG resonant cavity constructed by removing a single cylinder from a two-dimensional lattice of metal cylinders, bounded on top and bottom by flat metal plates. The spacing of the plates is chosen such that we can restrict the polarization of the electric field to be parallel to the cylinder axes.

In performing the numerical simulations, we used a real space finite difference method that previously has been shown to be reliable for calculating both band structures[5] and transmission spectra[6] of photonic lattices. We discretize the spatial coordinate of the wave equation in 2-D so that there is a distance l between points, obtaining

$$E_{i,j+1}+E_{i,j-1}+E_{i+1,j}+E_{i-1,j}-4E_{i,j} = -\frac{l^2\omega^2}{c^2}\,\epsilon_{i,j}E_{i,j}. \quad (1)$$

Equation (1) is equivalent to the well studied tight-binding model used in the electronic localization case.[6] The transfer matrix method (TMM) has been successfully used for solving Eq. (1). In that method, the transfer matrix, T, relates the electric fields on the $j-1$ and j slices of the material with those of the $j+1$ slice. So, for a finite system the reflection and transmission coefficients can be found by knowing the transfer matrix of the system. In addition, the band structure of an infinite periodic system can be found by diagonalizing the transfer matrix of a slice corresponding to the unit cell of the system.

In Fig. 1 we present a calculated photonic band structure for a two-dimensional array of perfectly conducting metal rods. The electric field is polarized parallel to the cylinders, and the propagation constant **k** is in the plane of the cylinders. The band structure of Fig. 1 confirms a single complete photonic band gap, which starts at zero frequency and extends to a cutoff frequency f_c.

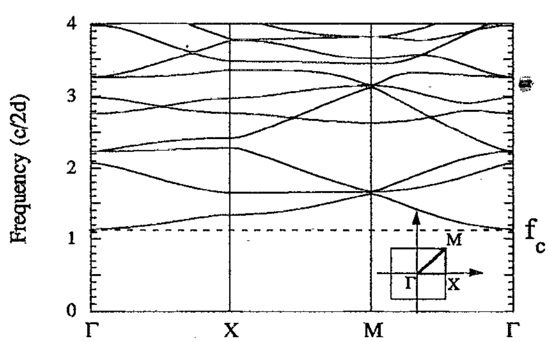

FIG. 1. Photonic band structure for a periodic lattice of perfectly conducting metal cylinders. The band structures has been plotted for values of **k** along the irreducible octant of the first Brillouin zone for the square lattice (inset). The ratio of the cylinder radii to the lattice constant for the calculation was 0.187. The band frequencies have been expressed in units of $c/2d$, where d is the lattice constant. The dashed line at $f=f_c$ indicates the position of the cutoff frequency, below which no propagating modes exist in any direction; the frequency region below f_c is thus a complete photonic band gap.

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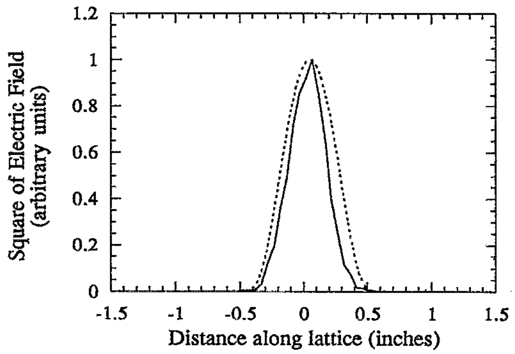

FIG. 2. Spatial map of the defect mode created by removing one cylinder from the center of a lattice of metal cylinders. The lattice consisted of 5 rows by 19 columns of cylinders. The cylinders had diameters of 0.475 cm, and had a repeat distance of 1.27 cm, thus matching the parameters used for the band structure calculation in Fig. 1. The solid curve is the experimental data, while the dashed curve was computed by numerical simulation. Both curves are taken just off a line tangent to the center row of cylinders, along the (10) symmetry axis.

Forming a 5×5 supercell of the metal rods with one missing cylinder, we find a defect mode pushed down into the band gap. In Fig. 2 we present the calculated energy density of this mode. A log plot of the energy density shows that the next highest peak of the electric energy density is three orders of magnitude smaller than the central peak, with a continuing energy density decay of 10^3 per lattice constant.

Our experiments were carried out at microwave frequencies in a waveguide scattering chamber, 1 cm high, 46 cm wide, and 51 cm long.[7] The bottom and side walls of the chamber are machined out of a solid aluminum plate. On both ends of the chamber are standard 8–12 GHz waveguide fittings that can be used to detect or inject microwaves in the chamber through a tapered region integrally machined into the main plate. Alternatively, p-band tapers can be connected to the waveguide fittings so that the range of measurement can be extended (up to 18 GHz). An aluminum cover plate, free to translate laterally, completes the chamber. The scattering lattice is composed of aluminum cylinders 1 cm high positioned by holes accurately spaced in a styrofoam ($\epsilon=1.04$) template. A thick layer of foam microwave absorber is placed between the interior chamber walls and the styrofoam template, which serves to minimize reflections.

In conjunction with an HP model 8756A network analyzer we are able to sweep the microwave frequency and make measurements of the power transmitted through the scattering region. We are also able to map the spatial structure of standing wave modes by weakly coupling to a tuned probe placed through any one of a lattice of small holes drilled in the cover plate for this purpose.

We performed transmission experiments for cylinders with a diameter of $2a=0.475$ cm, and a repeat distance of $d=1.27$ cm. In Figs. 3(a) and 3(b) we present the experimental transmitted power vs frequency for one and three rows of cylinders, respectively, and compare it with the results of the numerical simulations (dotted line). The incident radiation was along the (10) direction of the lattice. Note the onset of

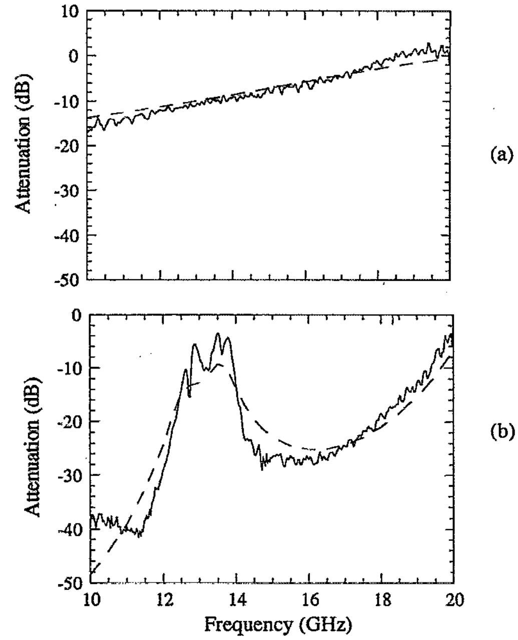

FIG. 3. Transmitted power through one row (a) and three rows (b) of metal cylinders. The lattice parameters are the same as in the previous figures. The solid line is an experimental sweep, while the dashed line is the computed transmission.

the propagating region that occurs at $f_c\sim12.5$ GHz; this behavior is consistent with the calculated band structure of Fig. 1, which predicts that no propagating modes should occur until the threshold frequency f_c. The dip commencing at ~14 GHz is due to the next band gap [along the (10) direction], also in agreement with the simulations. The higher frequency band gap, however, is associated only with the particular direction of propagation, and is not a complete PBG.

To create a resonant defect mode, a single cylinder was removed from the center row of the 3×19 array of cylinders. Figure 4 shows the appearance of a resonance corresponding to the defect mode. The sharpness of the peak is indicative of the strongly localized nature of this mode, despite the rather narrowly defined boundary of only one row on either side.

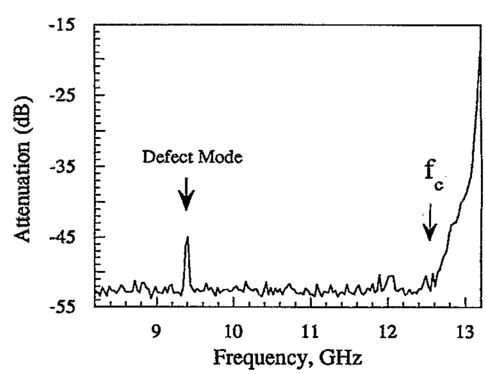

FIG. 4. Transmitted power through three rows of cylinders with one cylinder removed from the center row. Arrows indicate the resonance due to the defect mode, and the onset of the propagation region.

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We further performed a point-by-point mapping of the energy density of the defect mode along a path just off the sides of the cylinders. These data are shown as the solid line in Fig. 2. It was necessary to perform the mapping just past the edge of the cylinders, because the polarization fields between the cylinders and the plate were sensitive to the small holes in the plate, and perturbed the measurement significantly. Probing the field density away from the cylinders yielded a stable measurement which, as can be seen, agrees well with the numerical simulation data.

We have demonstrated that a 2-D PBG-defect cavity composed entirely of metal, may readily be simulated and fabricated for use at microwave frequencies. The advantage of this cavity over standard metal cavities, and even previously proposed PBG-defect cavities,[3] is that it has only one resonant defect mode, the mode has an extraordinarily high localization length (10^3 per lattice constant), and all frequencies above f_c are propagating (thus can be damped by suitable absorber around the circumference of the finite structure). These properties may make the all metal structure advantageous for applications where losses to higher order modes can be a problem, although we have yet to investigate the possibility of partially damped resonances that may occur in practice.

In calculating the properties of the all metal 2-D PBG-defect cavity, we have used real space computational techniques recently introduced, and found the resulting numerical simulations to be very reliable for predicting the experimental results. We suggest that one may now thoroughly investigate the entire range of 2-D potential PBG-defect structures for a variety of technical applications. In particular we have determined the r/Q_0 (r is the shunt impedance) for the metal PBG cavity mode to be 0.92 that of the r/Q_0 for a TM_{010} mode of the standard pill box cavity at the same frequency.

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