Band structure of terahertz metallic photonic crystals with high metal filling factor

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The excitation of resonant eigenmodes in two-dimensional metallic photonic crystals by incident terahertz pulses is both experimentally and numerically investigated. Transmission experiments are in excellent agreement with numerical calculations of the crystals’ photonic band structures and internal electromagnetic field patterns. The structures show large photonic band gaps in the terahertz spectral range and are highly polarization selective. At the resonant frequencies, transmittance is extraordinarily high despite the high metal filling factor. © 2008 American Institute of Physics. [DOI: 10.1063/1.2929376]

Photonic crystals have incited considerable interest over the past few decades.1–13 Such periodic media can be individually designed to meet specific requirements as to their interaction with electromagnetic radiation. Furthermore, they may exhibit optical properties which cannot be observed in natural materials, such as negative refraction1 and left-handed transmission,5 phenomena which may be utilized in the development of flat lenses.6,14 Photonic crystals operating at terahertz frequencies are particularly interesting, since terahertz radiation offers many fields of practical application in science and technology, for which optical components functioning in this spectral range are required. Besides, investigating the transmission mechanisms of photonic crystals in the terahertz range allows easy fabrication of samples, as the wavelengths are comparably large (1 THz corresponds to 300 µm). Metal constituents are particularly suitable for the construction of photonic crystals in the terahertz range, as the losses caused by the finite conductivity of the metal are small at these relatively low frequencies.5 Moreover, past publications indicate that terahertz transmission through structures composed of metallic objects can be enhanced by surface plasmon resonances. This has been reported for dense nonperiodic media composed of subwavelength particles,15,16 as well as rows of metallic cylinders which are in direct contact to each other.17–19 In this letter, the excitation of resonant modes in two-dimensionally periodic arrays consisting of steel cylinders is investigated. The distance between the constituents is kept as small as possible in order to obtain a high metal filling factor. Although two-dimensional arrays of metallic cylinders have been extensively studied in the past,5,7–13 the regime of photonic crystals with a metal filling fraction of larger than 50% has remained largely unexplored so far.

The photonic crystals are assembled using 50 mm wide aluminum holders with periodically spaced holes in which 50 mm long steel cylinders are positioned. Transmission measurements are made for three values of the cylinder diameter $d$ (1.0, 1.5, 2.0 mm), different sample thicknesses (two to ten layers of cylinders, i.e., 2–20 mm), and two different patterns (square and hexagonal lattice, see Fig. 1). The average distance left between the cylinders is less than 10 µm (i.e., less than 1% of the cylinder diameter and less than 5% of the terahertz wavelength). The metal filling factor of the structures is 78% and 90% for the square and the hexagonal cylinder array, respectively. To investigate the samples’ spectral properties, a terahertz time domain spectroscopy setup is used. Generation and detection of the terahertz radiation is done by a pair of photoconductive switches. With this setup, broadband terahertz pulses of approximately 1 ps length are created. The bandwidth of the pulses is 1.5 THz, centered at 0.6 THz (wavelengths between 0.2 and 3 mm). The samples are placed in a collimated terahertz beam which is approximately 30 mm in diameter. Progression of the terahertz pulses is measured in time domain, then transformed into frequency domain with a fast Fourier transform. By dividing the spectrum of the transmitted pulse by that of a reference pulse measured without any sample in the beam, the photonic crystals’ amplitude transmittance is obtained as a function of frequency. The pulses are measured over a time period of 200 ps. That corresponds to a spectral resolution of 5 GHz. In addition to the experimental investigations, numerical calculations are performed with the commercial software CST Microwave Studio®, which uses the finite integration technique to numerically solve Maxwell’s equations. In the calculations, the photonic crystals are modeled as arrays of infinitely long, perfectly conducting cylinders in vacuum. The periodicity of the samples is taken into account by using periodic boundary conditions in the plane perpendicular to the propagation direction.

FIG. 1. (Color online) Schematic of the two cylinder patterns under investigation. Also depicted are the structures’ brillouin zones as well as the direction and polarization of the incident terahertz radiation. The structures’ unit cells are highlighted. Note that the unit cell of the hexagonal array contains two separate cavities.
According to theory, an incident electromagnetic wave can excite an eigenmode of a photonic crystal if it matches that mode’s frequency and the component of the wave vector parallel to the crystal surface. The electromagnetic eigenmodes are obtained from

\[ \nabla \times \left[ \frac{1}{\varepsilon(r)} \nabla \times \mathbf{H}(\mathbf{r}) \right] = \left( \frac{\omega}{c} \right)^2 \mathbf{H}(\mathbf{r}), \]

which is directly derived from Maxwell’s equations. The eigenvectors \( \mathbf{H}(\mathbf{r}) \) of this eigenvalue problem are the magnetic field patterns of the modes, the eigenvalues \( (\omega/c)^2 \) relate to their frequencies \( \omega \). The discrete translational symmetry of the problem leads to a discrete set of eigenmodes. Besides, in the case of our two-dimensional photonic crystals, the eigenmodes separate into two independent sets according to the polarization angle of the fields with respect to the plane of periodicity. The two polarizations are transverse electric (TE) (electric field perpendicular to the cylinder axes) and transverse magnetic (TM) (magnetic field perpendicular to the axes). In our samples, the electromagnetic field is concentrated in the cavities between the metallic cylinders. Depending on the cylinders’ arrangement, the eigenmodes of the photonic crystals are similar to those of a waveguide with square or triangular cross section. Figure 2 shows some of the modes which our cylinder arrays can support. Note that the fields of all TM modes are zero at the points of contact between the cylinders. This is due to the fact that the electric field has to be perpendicular to the metallic surfaces and the gaps between the cylinders are small compared to the wavelength. Therefore, TM-polarized modes cannot enter the gaps. Neighboring cavities are entirely independent of each other, and the modes cannot propagate through the crystal. Propagating TE modes, however, are possible, as their fields are maximal at the points of contact. This leads to strong coupling between the cavities. In the hexagonal array, there is a splitting of the TE eigenmodes because the structure’s unit cell contains two triangular cavities (cf. Fig. 1). That means that for each mode of the triangular cavity, the hexagonal cylinder array can support a symmetric and an antisymmetric mode, with the eigenfrequency of the latter being higher.

Figure 3 shows numerical calculations of the band structures of a hexagonal and a square cylinder array compared to experimentally determined transmission spectra. Only zeroth-order amplitude transmittance is shown, higher orders of diffraction are not detected. It can be clearly seen that transmission occurs only at the frequencies where there are eigenmodes with wave vectors parallel to that of the incident radiation (shaded areas). The bands relate to the field patterns of the TE modes shown in Fig. 2(a). Subscripts \( s \) and \( a \) mark symmetric and antisymmetric modes, respectively.

FIG. 2. (Color online) Numerical calculations of the first TE and TM eigenmodes in the cavities of square and hexagonal cylinder arrays.

FIG. 3. Transmission measurements and numerically calculated band structures of (a) the six-layer hexagonal array and (b) the five-layer square array of cylinders with \( d=2.0 \) mm. Transmission bands exist where there are eigenmodes with wave vectors parallel to that of the incident radiation (shaded areas). The bands relate to the field patterns of the TE modes shown in Fig. 2(a). Subscripts \( s \) and \( a \) mark symmetric and antisymmetric modes, respectively.
transmission through the structures, Fig. 4 shows numerical simulations of the field patterns inside a square array of cylinders. When a TE-polarized plane wave with frequency within a photonic band hits the surface of the array [Fig. 4(a)], it excites a resonant eigenmode inside the cavities of the structure. Because of the high field amplitude in the cavities, the coupling between neighboring unit cells is strong, and the wave is transmitted through the crystal. When the plane wave’s frequency lies in a photonic band gap, the fields decay rapidly inside the crystal [Fig. 4(b)]. However, if the sample is very thin, transmission can take place even if there is no resonant excitation inside the crystal [Fig. 4(c)].

In any of our samples, the average distance left between the cylinders is less than 1% of the cylinder diameter. Thus, by purely geometrical considerations, no more than 1% of an incident wave’s intensity (10% of the field amplitude) is predicted to pass through a single layer of cylinders. Accordingly, the amplitude transmittance of an n-layer cylinder array would be less than 0.1^n. The actual measured amplitude transmittances exceed these values by far. The peak transmittance of our thinnest samples (two layers) is 22% for the square and 18% for the hexagonal array. Even for samples consisting of ten layers (20 mm thickness), the peak value is still 6%. The decrease in transmittance for thicker samples is mainly caused by the damping that is introduced by irregularities in the samples. When the structures’ periodicity is not perfect, the cavities between the cylinders differ in size and shape (and thus in resonance frequency) at different locations inside the structure. That means that incident radiation at a given frequency in a photonic band is not necessarily resonant in the whole crystal and therefore decays with the distance it travels through the sample. Comparing measurements with different diameter cylinders show that the damping is stronger for thinner cylinders. This is because the small irregularities of the structures’ cavities have a greater influence when the unit cell is smaller.

In summary, we have demonstrated that the excitation of resonant eigenmodes in the cavities of two-dimensional photonic crystals consisting of steel cylinders leads to extraordinary transmission of incident terahertz radiation at frequencies in the photonic bands. Each transmission band corresponds to a specific field pattern in the crystals’ cavities. The fraction of the incident radiation that is transmitted through the samples is extraordinarily large compared to the very small area fraction of the openings in the structures. Because the gaps between the cylinders are very small compared to the wavelength, only TE-polarized radiation is transmitted through the samples. At frequencies in photonic band gaps, the radiation rapidly decays inside the crystals. Therefore, nonresonant transmission is very low and can only be observed with very thin samples.