Two-dimensional photonic crystal at THz frequencies constructed by metal-coated cylinders

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Two-dimensional photonic crystals with photonic bandgaps (PBGs) in the terahertz (THz) frequency regime have been constructed by arraying metal-coated cylinders. PBGs were observed at 2.2 and 4.7 THz for the samples with lattice constant of 140 and 70 μm, respectively. Experimental results show that the PBGs were realized with only a small number of layers ($\leqslant$10 periods) and they are robust against positional disorder (about 14%). Thus, metal-coated cylinders provide us with a promising approach to create robust PBGs in the THz frequency range. © *2003 American Institute of Physics.* [DOI: 10.1063/1.1573338]

There has been great interest in the terahertz (THz) frequency region due to the potential applications in medical imaging, chemical detection, and analyses, etc.[1–3] The recent realization of a THz laser[2] will undoubtedly benefit these potential applications. Photonic band gaps (PBGs), a fundamental property of photonic crystals (PCs), provides the ability to manipulate the propagation of electromagnetic (EM) waves, leading to applications in photonic components such as filter, polarizer, and reflector.[4–7] Although most experimental studies of PC materials focused on the microwave,[7–9] infrared,[10,11] and visible light[12,13] regions, PCs in the THz range have been fabricated by laser rapid prototyping[14] and other methods.[6,15] Metallic photonic crystals (MPCs) have been studied intensively recently because they have the advantage over dielectric PCs in creating larger PBG in a small number of lattice periods.[16–19] However, some recent results indicate that the PBG in MPCs can be easily destroyed by disorder,[15,20] which would hamper their applications. This communication describes a new construction of two dimensional (2D) PCs with metal-coated silica cylinders which facilitate not only the formation of PBGs but also demonstrate robustness against positional disorder.

The 2D PCs were constructed with Ni-coated silica cylinders in air background, whose diameter is 50 μm. Metal coating was introduced to help to create the PBGs. The cylinders were confined and aligned between two parallel brass meshes and formed a linear lattice structure which can be repeated to form a 2D PC structure [shown in the inset of Fig. 1(a)]. The distance between two neighboring mesh holes is 70 μm. Then the lattice constant a is 70 or 140 μm realized by mounting the cylinders in every or every other mesh hole, corresponding to a filling ratio f of 40% or 10%, respectively.

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Since the diameter of the cylinders is smaller than the size of the mesh hole, it is unable to keep the cylinder exactly at the center of each mesh hole. Thus a can not be exactly uniform. The fluctuation in the lattice constant, however, is less than 10 μm for both samples with $a=140$ and 70 μm, corresponding to a positional disorder of 7% and 14%, respectively. Transmission measurements were performed by using a Fourier transform infrared (FTIR) spectrometer. Both $\langle 10\rangle$ and $\langle 11\rangle$ directions, the principal symmetry directions of 2D square lattice, can be measured in normal incidence as indicated in the inset of Figs. 1(a) and 1(b). The spectra in the principal symmetry directions can reveal the property of complete PBG to some extent.[16,19,21]

It is well known that the EM wave can be decomposed into transverse magnetic (TM) (E along the axis of the cylinders) and transverse electric (TE) polarization modes for a 2D structure. A band gap exists for a 2D PC only when band gaps in both polarization modes are present and they overlap each other.[21] TM and TE polarization modes and total transmission spectra have been measured with normal incidence similar to measurement method used in Refs. 19 and 20. Figure 1(a) presents the results along the $\langle 10\rangle$ direction for a PC constructed of two layers of metal-coated cylinders with $a=70$ μm. Both the spectra of TM and TE polarization modes have an obvious minimum in transmission and they overlap each other. A band gap will be located in this overlapping frequency region. Therefore, a total transmission spectrum without polarization has been measured and an obvious PBG has been detected as shown in Fig. 1(a). The PBG along $\langle 11\rangle$ direction has also been observed as shown in Fig. 1(b). In general, a square lattice of dielectric cylinders in air does not give rise to the complete PBG. However, it helps to create the complete PBG by introducing metal into the square lattice.[16,21] Therefore, the existence of PBG in our samples should be ascribed to the metal coating.

To investigate the influence of periodicity along cylinder layers, on the formation and characteristics of the PBGs, nor-

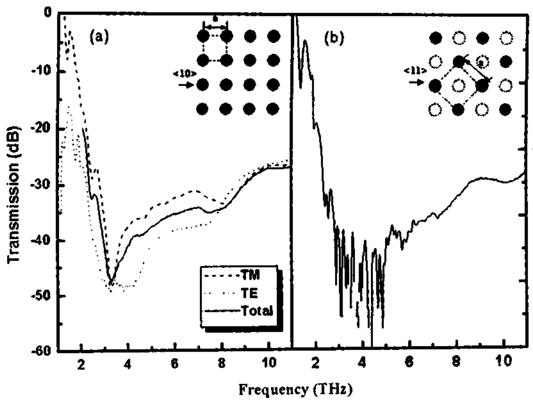

FIG. 1. Spectra propagation along the two principal symmetry directions of ⟨10⟩ and ⟨11⟩. (a) Dash, dot, and solid lines represent the TM polarization, TE polarization, and total (without polarization) transmission spectra along the ⟨10⟩ direction for PC constructed of two layers of metal-coated cylinders with lattice constant of 70 μm, respectively; (b) total (without polarization) transmission spectra along the ⟨11⟩ direction for PC constructed of eight layers of metal-coated cylinders with lattice constant of 99 μm.

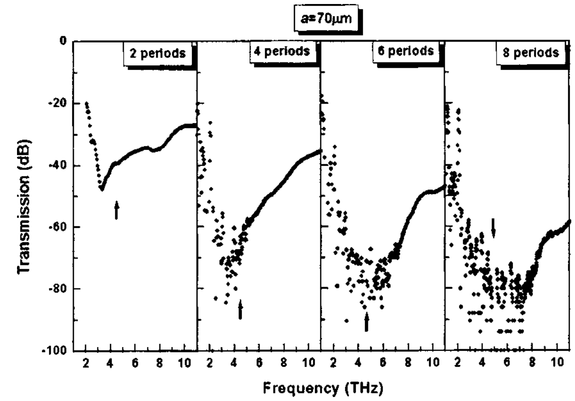

FIG. 3. Measured transmission spectra for PCs constructed of two, four, six, and eight layers (periods) of metal-coated cylinders. Lattice constant $a = 70$ μm, filling ratio $f = 40\%$. The calculated center frequencies of PBG are indicated by arrows.

mal incident transmission was measured for various PCs by varying the lattice periods from one to ten with $a = 140$ μm, and from two to eight layers with $a = 70$ μm. Figure 2 presents the measured results of PCs with $a = 140$ μm and one, three, and ten periods. For a single row the structure resembles a linear grating filter with cylinders, which should exhibit a minimum in transmission at the frequency where the wavelength is equal to the cylinder-to-cylinder spacing. The minimum of transmission was found near the frequency of 2.2 THz (corresponding to a wavelength of 138 μm, very close to the lattice constant of 140 μm) showing good agreement with this simple rule of thumb.[9] As the sample thickness increases to three layers, the frequency of the transmission dips remains unchanged while its amplitude decreases from -34 to -42 dB. It indicates the effect of increasing the sample thickness, showing that the EM waves have been modulated by the periodicity of dielectric constant and experienced at least partial Bragg scattering. For the crystal with ten layers of Ni-coated cylinders, the PBG centered at 2.2 THz is almost completely realized.

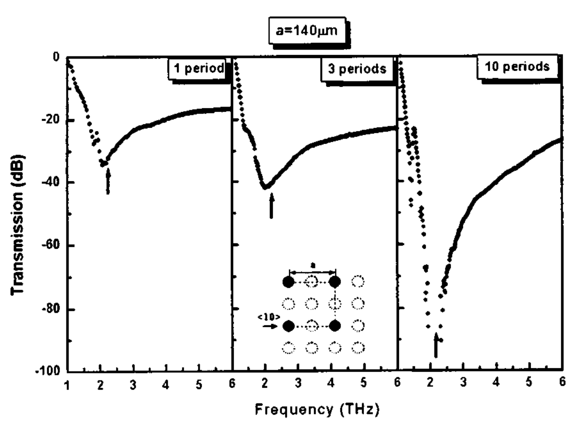

FIG. 2. Measured transmission spectra for PCs constructed of one, three, and ten layers (periods) of metal-coated cylinders. Lattice constant $a = 140$ μm, filling ratio $f = 10\%$. The calculated center frequencies of PBG are indicated by arrows.

The attenuation of EM waves in this frequency region is larger than 80 dB, beyond the sensitivity of our FTIR spectrometer. It is obvious that introducing metal coating on the silica core facilitates the formation of PBGs. The center frequencies of the PBGs in different structures have been calculated by using the transfer-matrix method (TMM).[22] They agree very well with the experimental results, as indicated by arrows in Fig. 2.

We have also constructed other samples with a lattice constant of 70 μm, just by shortening the distance between the neighboring cylinders. It should be pointed out that the decrease of the lattice constant is accompanied by increasing the filling ratio from 10% to 40%. The experimental spectra for these samples are presented in Fig. 3. A broad dip in transmission centered around 4.7 THz has been observed for all the structures with thickness of two to eight layers. The TMM calculated results are indicated in Fig. 3 by arrows. It is noted that the center wavelength is again close to the lattice constant of the structures. The frequency gap around 4.7 THz is seen to be present with only two layers. The transmission dip becomes deeper with increasing sample thickness. With eight layers, a PBG with attenuation larger than 80 dB was realized.

It is seen from Figs. 2 and 3 that the calculated center frequencies of the PBGs fit the measured dips reasonably well. However, the measured transmission in the upper-pass band is somewhat lower than expected. The difference between measured and calculated transmission in the upper-pass band is attributed to disorder in the structures, similar to the results in Ref. 15. Figure 4 presents the transmission difference (ΔT) as a function of the number of periods for both structures with $a = 140$ and 70 μm. For $a = 140$ μm, ΔT increases in dBs with increasing thickness. It changes from 14 to 37 dB at 4 THz as the thickness varies from one to ten layers. It is almost an increase of 2.6 dB per layer, indicating that the disorder has not affected the exponential growth of attenuation with increasing layers. Similar to the structure of $a = 140$ μm, ΔT for the samples with $a = 70$ μm also shows an increase of 6.3 dB/layer. Again the disorder does not seem to affect the exponential trend. The increasing rate of ΔT for the sample with $a = 70$ μm is al-

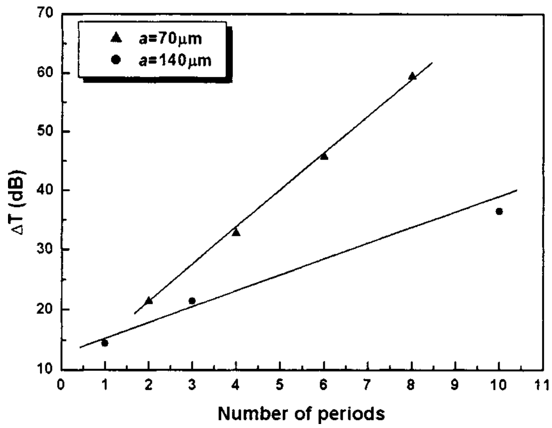

FIG. 4. The difference between measured (with disorder) and calculated (without disorder) transmission (ΔT) in the upper-pass band, as a function of periodicity for both lattice constant of 140 and 70 μm at 4 and 8 THz, respectively. The lines are only to guide the eyes.

most twice as much as that of a sample with $a=140$ μm. This is due to the disorder difference between the structures of $a=70$ and 140 μm. By adding a layer, the amount of disorder introduced into the structure of $a=70$ μm is twice as much as that of $a=140$ μm. Since ΔT ascribes to disorder in the structures, its increasing rate for the former structure is consequently faster than that of the latter. We observed that if the Bragg-like multiple scattering is the dominant mechanism for PBG functions, the PBG should be very sensitive to positional disorder. On the other hand, if the dominant mechanism is the Mie resonances, the PBG may survive even for large amounts of disorder, similar to what the electronic band gap survives in an amorphous semiconductor.[20] With our results, we expect the dominant mechanism for the formation of the PBG to be Mie resonances for the PCs constructed of metal-coated silica cylinders. Therefore, PBG in such structures can be realized with only a few lattice periods, and survives even for a relatively large amount of disorder.

In conclusion, 2D PCs in THz frequencies have been constructed by arraying the Ni-coated silica cylinders in linear lattice structures as well as repeating the layer with $a=140$ and 70 μm. The PBGs were realized in less than ten layers for both structures. They are only slightly influenced by the positional disorder of the structures. With metal-coated cylinders in the construction of PCs, it takes advantage of the metal in creating larger PBG while avoiding the destruction of PBGs induced by disorder effects. Our approach is thus advantageous for fabrication and applications of PCs in the THz frequency regime.

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