Near-infrared photonic band gap of two-dimensional triangular air-rod lattices as revealed by transmittance measurement

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(Received 16 May 1995; revised manuscript received 24 August 1995)

Optical transmission measurement on two similar two-dimensional (2D) triangular lattices of air rods with different lattice constants of the order of 1.0 μm has revealed that the central frequencies of photonic band gaps show a reasonable shift relative to each other. The respective gap frequencies observed in the 1.02-μm lattice are found to be consistent with the theoretical ones. These two facts provide firm evidence for the existence of a common gap for *H* polarization in the entire 2D Brillouin zone.

Since the idea[1] of creating gaps in the photon density of states by employing a periodic dielectric structure or photonic band structure was first proposed, a number of theoretical results on the existence of such a forbidden photonic band gap (PBG) has been reported. The occurrence of band gaps is sensitive to the ratio of the relevant dielectric constants, and volume fraction of each material, as well as the symmetry of the lattice structure. Both three[2,3] (3D) and two-dimensional[4,5] (2D) photonic band structures have been examined. Experimentally the existence of the gaps in both the 3D (Refs. 6,7) and 2D (Refs. 8–10) structures has recently been demonstrated only in the millimeter-wave region, where fabrication of such lattices is feasible, except our previous one.[11] Those lattices with a band gap are expected to open the door to a new field in quantum optics, which includes the inhibition of spontaneous emission,[12,13] the modification of basic properties of atomic and molecular systems,[14] and so on. For these purposes, development of a lattice with the gap energy at optical wavelengths is inevitably important. However, those lattices are technically very difficult to fabricate at present.

In this paper, we report a comparison of the PBG profiles between two similar 2D air-rod lattices fabricated with the respective lattice constants of 1.02 and 1.17 μm (abbreviated lattice *A* and *B*, respectively); a preliminary result for the latter has already been reported.[11] Transmission spectra in the near-infrared region relevant to the gap have revealed that the respective nontransmission wavelength regions are observed with the expected relative shift between two lattices, for *H* and *E* polarization for which electric or magnetic vector is parallel to the rods, respectively, in the particular directions, i.e., the Γ-*M* and Γ-*K* directions, where *M* and *K* are high-symmetry points in the relevant 2D Brillouin zone, with the respective wave vectors of $\pi/a\ (1,\sqrt{1/3})$ and $\pi/a\ (\frac{4}{3},0)$. Furthermore, the result in lattice *A* has enabled us to compare unambiguously, unlike the previous one *B*, the nontransmission regions observed, with the calculated ones, indicating a good agreement. These results indicate that the observed nontransmission regions arise from PBG, and thus a common gap exists for *H* polarization.

The present sample is a 2D triangular lattice consisting of a parallel array of air-rod cylinders with a dielectric constant ε_1 of 1 in a background material of PbO glass with $\varepsilon_2 = 2.72$. Two kinds of similar samples were prepared with the different lattice constants as described above. Those were fabricated by means of the technology for producing microchannel plates.[11] First, special optical fibers[15] were arrayed in the hexagonal form, and then the hexagonal pieces were heated up in vacuum to an appropriate temperature and at the same time pulled and elongated parallel to the fiber axis until a desired lattice constant was attained; each hexagon has a distance of 64 mm separating opposite faces. In this procedure the small gaps among the fibers were filled in. Next, many small hexagons thus produced were placed together to form a quasioctagonal bundle, which was supported outside by PbO glass similar to the clad; the size of the bundle is of the order of 1.5 mm with respect to the longest distance, and the length along the fiber axis is 1.0 mm. Finally, the core glass was dissolved with HCl. Direct inspection of the sample with use of an optical microscope reveals that the performance is satisfying enough, as is shown in Fig. 1: the regularity as well as uniformity of the air rods are perfect except the boundary array of holes being in contact with the support glass. We measured the lattice constant *a* and the air-hole diameter *R* by using an optical microscope and an electron microscope, respectively: *a* and *R* of two kinds of lattices are 1.17 ± 0.03 and 1.02 ± 0.06 μm, and 0.90 ± 0.08 and 0.69 ± 0.08 μm, respectively. Independently, *a* was also determined from the reflected angles of the Bragg spots emerging when a specimen was irradiated at normal incidence by a parallel light beam; for this, two polished specimens were prepared with the flat surfaces of the lattice with the normal parallel to either the Γ-*M* or Γ-*K* directions. Depending on the wavelength, the Bragg-reflected spots from one to three were observed on one side of the 0th-order spot. For lattice *A*, for example, the first- and second-order spots were observed at 26.1° and 60.9°, respectively, with a 880-nm light beam incident parallel to the Γ-*K* direction. From the diffraction angles, *a* can be evaluated as 1.02 and 1.04 μm, respectively, ensuring the value of 1.02 μm measured by an optical microscope. We have also estimated directly the refractive index of the background PbO glass as 1.65 ± 0.03 at 5000 cm^{-1} in the relevant region, from adjacent fringe distances of an interferometric pattern for a thin plane-parallel plate prepared with the same glass.

The transmission spectra were observed with use of a FT-IR spectrometer (JASCO, FT/IR-MW7900) in a similar

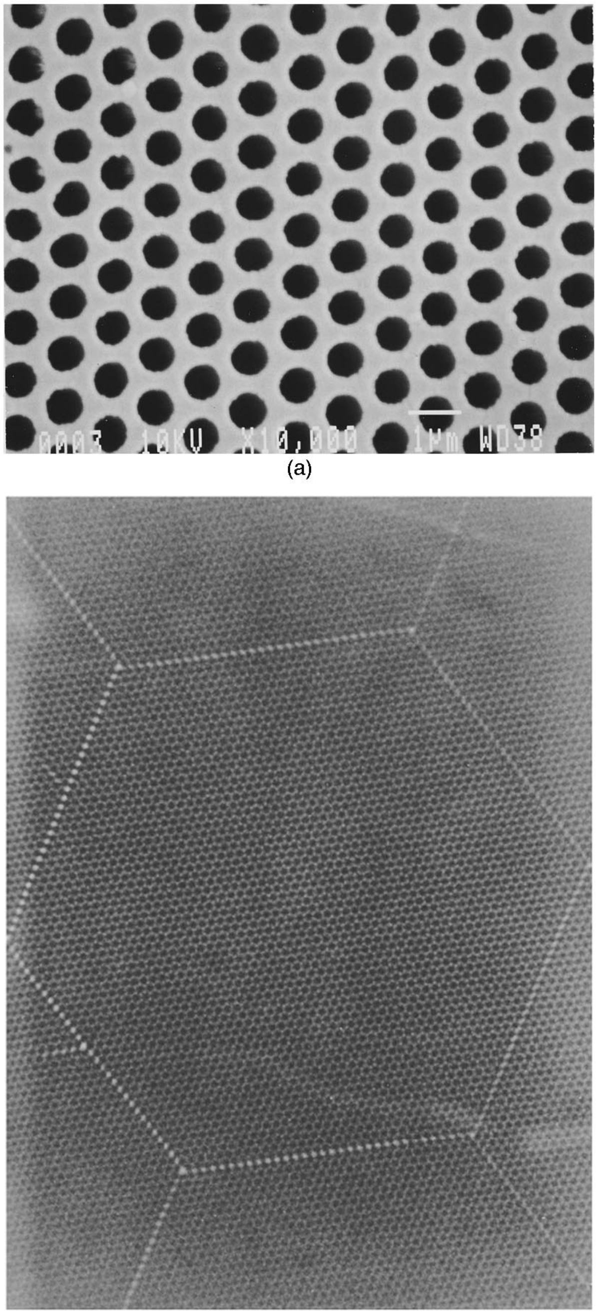

FIG. 1. Top views of a two-dimensional air-rod lattice observed by (a) an electron microscope and (b) an optical microscope ($\times$1000).

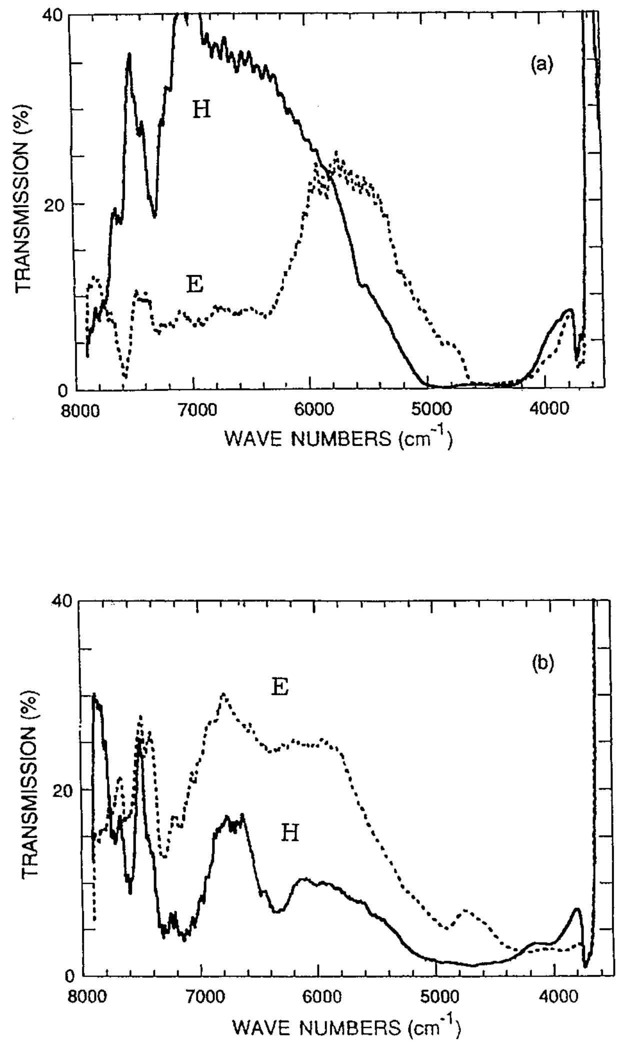

FIG. 2. Transmission spectra of a 2D air-rod lattice with the 1.02-μm lattice constant, observed in Γ-M (a) and Γ-K direction (b) in the 2D Brillouin zone. The spectra were taken separately for E and H polarization. A region between 2500–3700 cm^{-1} is corrected concerning absorption due to a few bands given rise to in elongating the fibers.

way to the previous one.[11] Examples of the spectra observed separately for E and H polarization are shown in Fig. 2. An improved measurement yields better spectra for lattice A than for B (see Fig. 3). Two kinds of plane-parallel plates for each lattice were prepared in such a manner that external light at normal incidence can travel in either Γ-M or Γ-K direction; for this purpose, the portions of the support glass, not the periodic lattice were polished to have optically flat surfaces. In this work, we have been concerned with only the frequency region around the respective lowest-lying band gaps expected between the first and second bands in the 2D Brillouin zone. So, the spectra are shown only in a range from 3500 to 7000 cm^{-1}. Intrinsic absorption bands induced by elongating the background material (clads) arise in a range from 3800 to 2500 cm^{-1}. In fact, in the previous paper[11] unexpected manifestation of this band prevented us from estimating the gap widths. For a similar lattice with a shorter lattice constant, the gap should shift to the higher-energy side, not masked by this band; this is one motivation of the present work. The spectra shown in Fig. 3 reveal that this is indeed the case, although the qualitative appearance is otherwise similar to that of lattice B. The respective spectra in Fig. 2 clearly show each nontransmission frequency region, except for E polarization in the Γ-K direction. From Fig. 2 we can estimate quantitatively the PBG frequencies, which are listed in Table I.

We have also studied theoretically the present photonic band structure. In Fig. 4, the result for lattice A, derived with the relevant parameters substituted, is shown along with the density of states. The calculation was based on the plane-wave method following the one by Phihal *et al.*[4] We used 271 plane waves to solve the eigenvalue problem derived

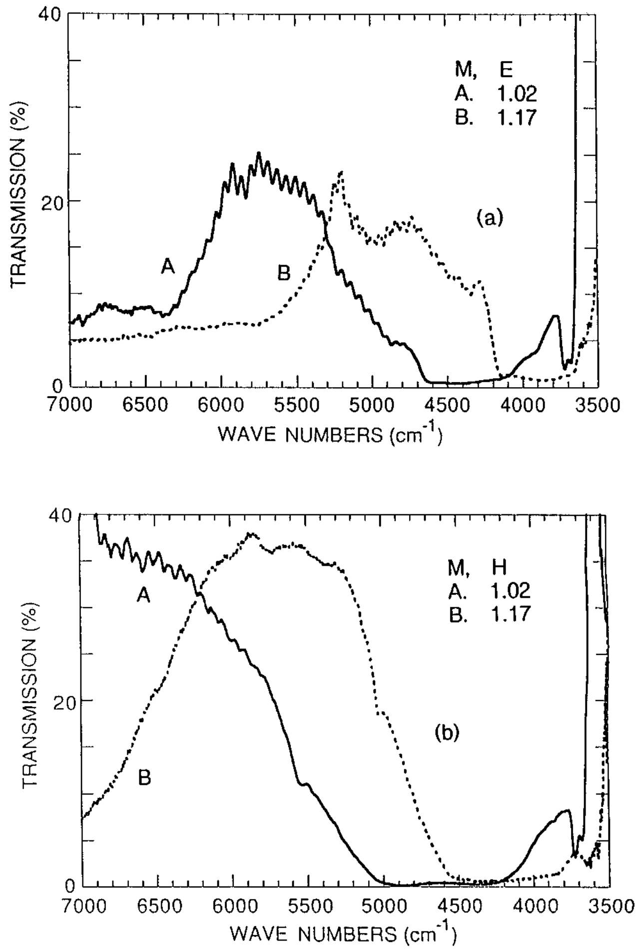

FIG. 3. A comparison of the transmission spectra in the Γ-M direction between two air-rod lattices with the different lattice constants, observed for E polarization (a) and H polarization (b).

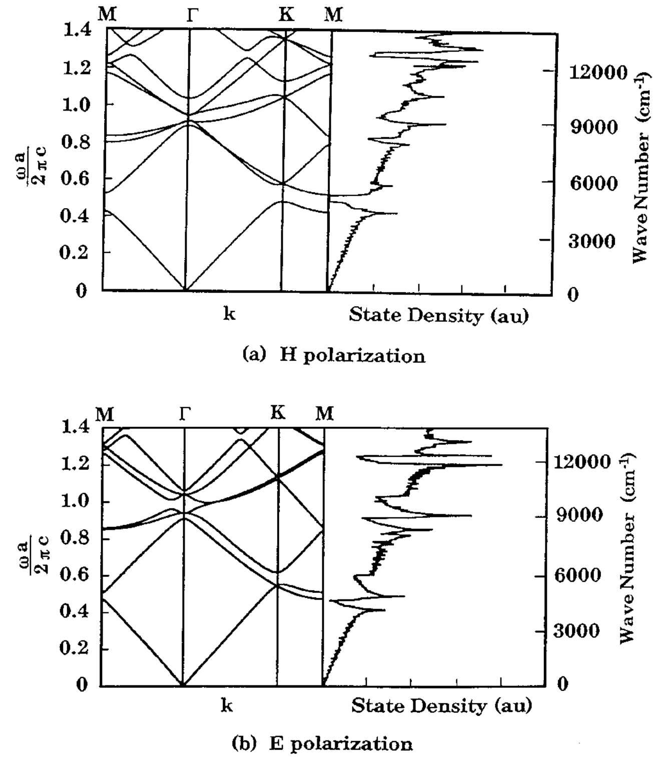

FIG. 4. The photonic band structure calculated for the two-dimensional air-rod lattice with the lattice constant a of 1.02 μm and the density of photonic states (right). The frequency is given in units of $2\pi c/a$, where c is the light velocity.

from Maxwell's wave equations, and calculated the eigenfrequencies for 28 800 wave vectors distributed uniformly over the 2D Brillouin zone to obtain the density. The result indicates that a common gap exists between the first and second bands for H polarization, but for E polarization the degeneracy of those two bands at the K point prevents the gap from opening. The calculated result on the respective gaps is shown in Table I.

Let us discuss the results in more detail. First, Table I shows that the agreement between the observed and the calculated is essentially good, if we take into account the ambiguity of the parameters involved in calculation. While the agreement is excellent for H polarization in the Γ-K direction, a small discrepancy of around 10% is recognized in the Γ-M direction, for both E and H polarizations. In addition to large ambiguity of the filling factor f of air rods, the value of ε_2 adopted for the calculation, 2.72 for bulk PbO glass, may be responsible for it. The true value of the clads is likely to diminish to a certain extent by elongation. As this discrepancy is small, by inspecting the band structure in Fig. 4, the observed results provide evidence for the existence of a common gap for H polarization.

TABLE I. Comparison of the nontransmission energy region between the observed and the calculated.

Direction	Polarization	Expt.	Calc.
Γ-M	E	4100–4650	3730–4210
	H	4200–5060	3790–4680
Γ-K	H	4300–5100	4310–5170

Next, we remark on the transmission profiles other than the nontransmission region. The observed profiles have a tendency of being smaller as the wavelength is shorter. This feature might arise partly from nonideal interfaces between the lattice and the support glass, and partly from some sorts of imperfections such as slight fluctuations of the lattice periodicity. Whether this feature is still left or not for a specimen with ideal interfaces is an open question. In this connection, the calculated result[16] for a thin model sample with ideal interfaces reveals that the transmittance is normal[17] except for the gap region, although many interference fringes appear due to the finite lattice (14 periods) adopted.

Finally, a calculation[16] reveals that the second-lowest band in the Γ-K direction cannot couple to an external wave by symmetry. From the band structure shown in Fig. 4, a nontransmission region should apparently exist for E polarization in this direction with the energy range almost superposed with that due to PBG for H polarization. That the transmission of the observed spectrum in question diminishes considerably around the relevant energy region may be explained as being caused by this uncoupled band. However, the transmittance does not go down to zero and besides the minimum energy range seems to be somewhat lower than the calculated. The reason for these quantitative disagreements is not clear to us at present. The problem of the interfaces is again likely to be responsible for that. Measurement to confirm this statement by making use of a similar specimen without hexagonal pieces is in progress.[17]

The authors express sincere thanks to the Hamamatsu Photonics Co. Ltd. for kindly fabricating the samples. Thanks are also due to Professor J. W. Haus of Rensselaer Polytechnic Institute for valuable discussions.

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