Quantized State in a Single Quantum Well Structure of Photonic Crystals

著者	宮崎　博司
journal or publication title	Physical review. B
volume	63
number	15
page range	153316-1-153316-4
year	2001
URL	http://hdl.handle.net/10097/35669

doi: 10.1103/PhysRevB.63.153316

PHYSICAL REVIEW B, VOLUME 63, 153316

Quantized state in a single quantum well structure of photonic crystals

S. Yano and Y. Segawa
Photodynamics Research Center, The Institute of Physical and Chemical Research (RIKEN), Sendai 980-0868, Japan

J. S. Bae and K. Mizuno
Research Institute of Electrical Communication, Tohoku University, Sendai 980-8577, Japan

H. Miyazaki
Department of Applied Physics, Graduate School of Engineering, Tohoku University, Sendai 980-8577, Japan

K. Ohtaka and S. Yamaguchi
Department of Applied Physics, Faculty of Engineering, Chiba University, Chiba 263-0022, Japan

(Received 16 November 2000; published 30 March 2001)

A quantum well structure was fabricated using two kinds of photonic crystal. The transmittance spectra were measured in the millimeter wavelength range for various well thicknesses, and numerous sharp peaks due to quantized states were observed in the high reflective frequency region of the barrier crystal. To discuss the symmetry of observed quantized states, the electrical field patterns in the well crystal were measured. Even and odd modes were observed alternately in each fine peak. The results of analysis showed that the observed fine peaks were quantized states of a photonic band in a single quantum well.

DOI: 10.1103/PhysRevB.63.153316 PACS number(s): 42.70.Qs

Much interest has been shown in photonic crystals characterized by spatially periodic dielectric structures that create band structures for photons.[1–3] Full three-dimensional (3D) photonic crystals would be able to exhibit much more profound effects, such as a much stronger confinement effect and stop-band characteristics over a broader range of angles or even in all directions of light, like electronic band gaps in semiconductors. However, the impurity states of photonic crystals are expected to control the radiation field of light in the band gap.[4–6] An impurity state is fabricated by making an ‘‘irregularity’’ in an ordered lattice, such as a distortion or defect. This state has been observed and found to explain the localized mode of the radiation field.

Periodic arrays of dielectric spheres provide us with prototypical photonic crystals. The photonic band effect in such systems has been studied both theoretically[7–12] and experimentally.[13–17] In a spherical system, accurate theoretical analysis is possible using group theory and the spherical vector expansion method for a photonic crystal system consisting of a dielectric sphere. Experiments have been performed in the millimeter-wave region, and the results showed good agreement with the results of theoretical analysis.[17]

Recently, the concept of the photonic quantum well, which consists of a quantum well structure similar to that in a semiconductor, has been proposed.[18,19] In these studies, sharp peaks in the stop band were calculated and considered as the effects of the bound state or resonant tunneling. The calculated peaks were not explained as the quantized state of the photonic bands but as impurity states of the photonic crystal. But, in this photonic quantum well, the quantization of the photonic band will occur like the quantization of the electron band in semiconductors. However, no experiments on the quantum well structure using a photonic crystal have been performed.

The aim of this study was to observe and determine the symmetry of the quantized state of a photonic band. For this purpose, we measured the transmittance spectra and the intensity of electrical fields in a crystal containing a single quantum well structure fabricated in a photonic crystal arranged in millimeter-sized Si_3N_4 spheres. The quantization of photonic bands is discussed in comparison with a semiconductor quantum well.

To fabricate the single quantum well structure, two kinds of 3D photonic crystal were prepared. They were made with a layered 2D periodic array of Si_3N_4 beads of millmeter size as constituent spherical dielectric particles. The 2D periodic array is a close packed hexagonal lattice and stacked to make a hexagonal crystal. The building block for the 3D photonic crystal we used was spherical balls of Si_3N_4 with a diameter $d=1/8$ in. Si_3N_4 has a fairly high dielectric constant ($\varepsilon=8.67$) in the millimeter wavelength region investigated. Figure 1 shows illustrations of two types of single quantum well structure, (a) and (b), made with photonic crystals. The photonic band gap can be controlled by changing the air gap of layered three-dimensional photonic crystals. Here, A is the barrier crystal and B is the well crystal. As shown in the figure, the air gap of $A(D_b)$ is different from that of $B(D_w)$. Therefore, the frequency region of the band gap of the barrier is different from that of the well due to the different air gaps. The photonic band of the well crystal overlaps the band gap of the barrier crystal, and is confined and quantized. Both figures corresponded to a quantum well crystal of four layers. The reason that we consider these configurations to correspond to four-layered quantum well crystals will be discussed later. It is expected that sharp transmitted peaks corresponding to the quantized photonic band in the band gap of the barrier crystal will be observed.

The transmittance spectra and the intensity of the electrical field in the air gap of the photonic crystals were measured

0163-1829/2001/63(15)/153316(4)/$20.00

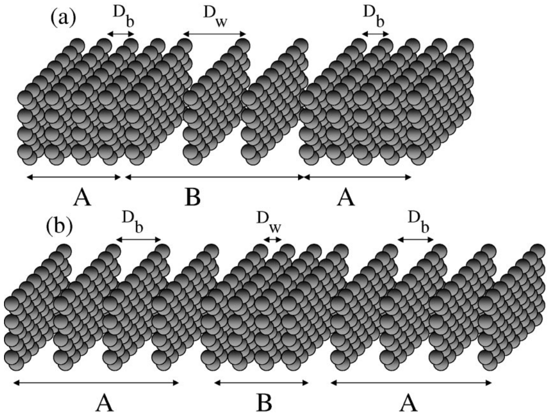

FIG. 1. Illustrations of a quantum well structure using two kinds of photonic crystal, *A* and *B*. Here, we changed the size of the air gaps between *A* and *B*, D_b and D_w. (a) and (b) represent two cases, $D_w > D_b$ and $D_b > D_w$, respectively.

as a function of millimeter wavelength for normal incidence by using a network analyzer (Wiltron 360B). For measurement of transmittance, two horn antennas were used to produce a probe electromagnetic (EM) wave and to detect the transmittance. We used two lenses ($f = 300$ mm) to make an incident EM plane wave and to focus its transmitted component. A semirigid cable of 0.8 mm in diameter was used to probe the electrical field in the air gaps of the well crystal.

Figure 2 shows the transmission spectra when the number of layers in the quantum well crystal is 3–9, D_w is 3.2 mm, and D_b is 1.1 mm. Figure 2(a) shows the experimental transmittance spectra and Fig. 2(b) shows the results of theoretical calculations. The lowest spectrum is for a well width of three layers, and the highest is for nine layers. The number of well layers is represented on the right-hand side of the figure as, e.g., $3L$. If the photonic crystals of both the barrier and the well are perfect crystals, they will have band gaps in different frequency regions. The range of the band gap of the well crystal is 29–32 GHz, and that of the barrier crystal is 33.5–40 GHz. Horizontal arrows show the range of each band gap. Therefore, in our experiment, the photonic band of the well crystal in the range of 33.5 to 40 GHz is confined by the band gap of the barrier crystal. Based on theoretical calculations, the confined photonic band corresponds to the third photonic band [see Fig. 4(a) below]. As shown in Fig. 2(a), some sharp peaks appear in the band gap of the barrier crystal. In the case of a four-layered crystal, whose shape corresponds to that shown in Fig. 1(a), three peaks are observed at 33.9 GHz, 36.5 GHz, and 38.4 GHz. It is thought that these structures correspond to the quantized states of photonic bands in the well crystal. The quantized wave number of the quantized states is determined as follows. As for the quantized states in a semiconductor quantum well, if the lattice constant of the unit cell is a and the width of the quantum well is $l = na$, n is the number of one atomic layer. The wave number of the Brillouin zone boundary is $\pi/a = k_B$, and the quantized wave number of the first quantized state is $\pi/l = \pi/na = k_B/n$. That is, if the well width is four layers, the wave numbers of all quantized states are $\frac{1}{4}k_B$, $\frac{2}{4}k_B$, and $\frac{3}{4}k_B$. Therefore, the second quantized level of four layers, the third of six layers, and the fourth of eight layers should have the same quantized wave number and quantized energy. The first (second) level of three layers, the second (fourth) of six layers and the third (sixth) of nine layers will appear at the same positions. Thus, the wave numbers of the observed quantized levels are shown in the figure by dotted lines and fractions such as 2/4. The number of layers (L) was four for the spectra of $L = 4$ and so on. Therefore, the boundary layers of D_w and D_b in Fig. 1 are considered to belong to the well crystal.

The experimental transmittance was compared with the theoretical calculations shown in Fig. 2(b). The results of calculation agree well with the experimental results in terms of the frequency of sharp peaks, although the transmitted intensity of the sharp peaks is not unity in the experiment. This discrepancy is due to the loss of electromagnetic energy in the case of a thick sample. Because our sample was slightly distorted, it is thought that the loss occurred by the scattering or diffusion of the EM wave on the 2D lattice plane. It is therefore difficult to observe sharp peaks such as those seen in the spectra of a large well, for example, seven to nine layers.

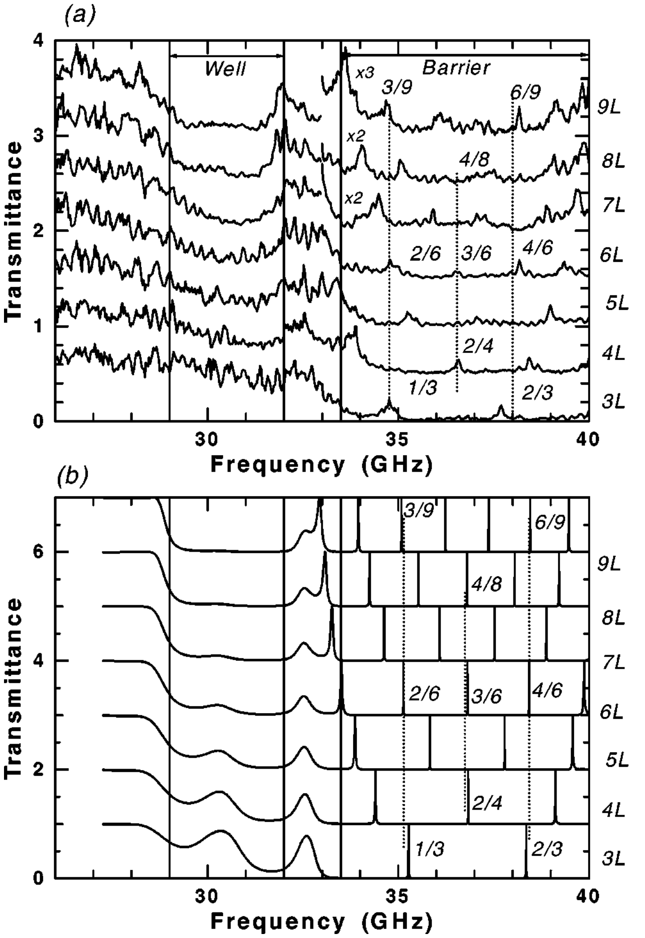

FIG. 2. The transmittance spectra when the air gap of the well crystal (*B*) was 3.2 mm and that of the barrier was 1.1 mm. The well is 3–9 layers. (a) and (b) show the experimental and theoretical transmittance results, respectively. The regions shown by the horizontal arrows give the photonic band gaps of well and barrier crystal when the crystal is infinitely large.

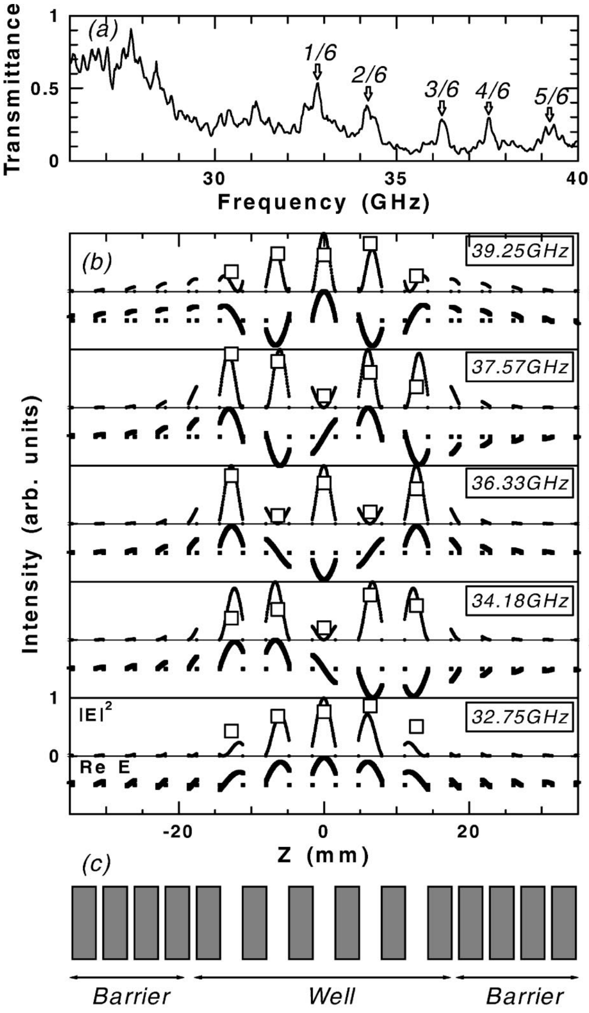

FIG. 3. (a) Transmittance spectra when the air gap of the well crystal is 3.2 mm and that of the barrier crystal is 1.1 mm, and the well consists of six layers, which corresponds to that shown in Fig. 2(a) for $L=6$. (b) Intensity of the electrical field in the air gaps as a function of the distance from the surface. The large squares show the experimental results and the broken lines show the results of theoretical calculations. (c) Diagram of the measured quantum well structure. The gray boxes show the plane of the 2D lattice.

The intensity of the electrical field in the air gap of the well crystal was measured in order to study the symmetry of each quantized structure. The results are shown in Fig. 3, where the air gap of the well is 3.2 mm, and that of the barrier is 1.1 mm, and the number of wells is six layers. The transmittance spectrum is shown in the upper part of the figure. Although the observed sharp peaks are slightly different from those in Fig. 2(a) for $L=6$, five sharp peaks are observed in the spectrum, at 32.75, 34.18, 36.33, 37.57, and 39.25 GHz. The difference was caused by slightly changing the photonic band gap of the barrier crystal toword the low frequency region in order to clearly observe the 1/6 state. The transmittance spectrum observed with a probe in the air gap was almost the same as the spectrum without the probe. The bottom of the figure shows the structure of the measured quantum well. The gray boxes show the plane of the 2D lattice. The intensity of the electrical field in the air gap was measured and calculated. The calculated intensities are plotted in the middle of the figure as a function of the distance from the surface of the Si_3N_4 beads. The theoretical calculations are shown by broken lines for $\mathrm{Re}\,E$ and $|E|^2$. $\mathrm{Im}\,E$ is omitted as it has the same symmetry as $\mathrm{Re}\,E$. In our measurement, the square of the intensity of the electrical field was observed. The experimental results are plotted with the calculated $|E|^2$ as large squares. As shown in Fig. 3, the experimental results are in good agreement with the theoretical calculations for $|E|^2$. Moreover, the symmetry of the sharp peaks will be discussed. From the calculation of $\mathrm{Re}\,E$, one can see the symmetry, that is, the first, third, and fifth quantized states are even modes, and the second and fourth are odd modes. The intensity at the third air gap, which is at the center of the well crystal, is almost zero for the second (34.18 GHz) and fourth (37.57 GHz) peaks, but it is nonzero for the first, third, and fifth states. Considering that the center is a loop for even parity and a node for odd, the experimental results clearly show that the mode of the sharp peaks changes alternately between even and odd parity. This indicates that the envelope function of the quantized electromagnetic wave

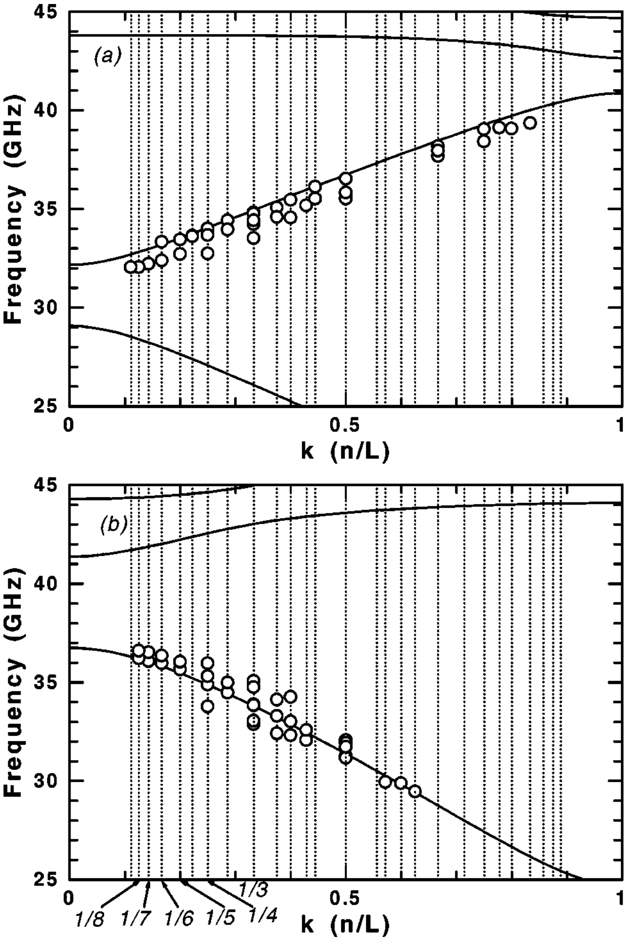

FIG. 4. The dispersion relation of photonic bands. The solid lines show the results of theoretical calculation. The frequency of observed fine structures is plotted by the circles as a function of wave number $k=n/L$. Here, n represents the quantum number and L is the number of well layers. Air gap of well is (a) 3.2 mm and (b) 0.3 mm. Vertical dotted lines were guidelines of the wave number.

is given by $\sin(n\pi/L)$. Thus, the difference of the electrical field pattern for the sharp peaks is well explained by the various even and odd quantized states in the quantum well.

Next, the quantized state of the photonic bands is considered. In Fig. 4, the frequency of the observed sharp peak is plotted as a function of wave number $k=n/L$. The calculated photonic bands ($\Gamma - X$) are shown by solid lines. Figure 4(a) shows the third photonic band for an air gap of 3.2 mm, and Fig. 4(b) is the second photonic band for an air gap of 0.3 mm. Here, n represents the quantum number as assigned in Fig. 2, and L is the number of well layers. The experimental results for different barrier crystals are also plotted in the figure. The experimental data for the same wave number of different quantized states, for example, 1/2 and 2/4, overlap. Therefore, multiple circles are plotted at the same wave number. The experimental results agree well with the calculated photonic bands. Thus, these agreements indicate that the idea of quantized photonic bands is a good model.

Our experiment was performed in the frequency region where the band structure was simple. So the photonic crystal can be considered as 1D multistack dielectric layers. Therefore, the observed peaks may also be explained by the coupling of the impurity states in the multistack dielectric layers because the air gaps of the well crystal are considered as irregular lattices. For example, in the case of four layers (see Fig. 1), there are three air gaps of the well crystal. Therefore, the number of impurities is three and the number of sharp peaks is simply expected to be 3. This expected number agrees with the experimental result [see Fig. 2(a) $4L$]. Thus, it is thought that these impurity states are coupled and split. However, in the higher frequency region, the phenomenon cannot be explained by the idea of multistack dielectric layers, because the photon state (photonic band) is more complicated from the effect of the 3D crystal. In contrast, in the quantum well model, one can estimate the frequency and the number of transmission modes in all frequency regions from the band structures of well and barrier crystals and the thickness of the well crystal. Therefore, the idea of a ''quantized state'' in the quantum well structure is more helpful than that of a ''coupled impurity state'' in multistack dielectric layers.

In summary, a quantum well structure was fabricated using two kinds of photonic crystal. The photonic crystals were fabricated from a 2D lattice made of Si_3N_4 spheres. The transmittance spectra were measured in the millimeter wave region in normal incidence for the 2D lattice when the well crystal was 3–9 layers. Numerous sharp transmitted peaks were observed in the band gap of the barrier crystal. Some of these peaks were observed at the same frequency for different well numbers. The intensity of the electrical field was measured in the air gap of the well crystal. An alternating even and odd pattern of electrical field was observed for each peak. These features can be explained by the concept of the quantization of a photonic band, that is, the transmitted peaks are the quantized states of a single quantum well.

This work was supported by Grants-in-Aid for scientific research from the Ministry of Education, Science and Culture of Japan and by Special Coordination Funds for Science and Technology of STA.

---

[1] E. Yablonovitch, Phys. Rev. Lett. **58**, 2057 (1987).

[2] E. Yablonovitch, J. Phys.: Condens. Matter **5**, 2443 (1993).

[3] J. Opt. Soc. Am. B **10**, (1993), special issue on photonic crystals.

[4] D.R. Smith, S. Schultz, S.L. MaCall, and P.M. Platzmann, J. Mod. Opt. **41**, 395 (1994).

[5] E. Özbay, G. Tuttle, J.S. McCalmont, M.S. Galas, R. Biswas, C.M. Souloulis, and K.M. Ho, Appl. Phys. Lett. **67**, 1969 (1995).

[6] K. Sakoda, T. Ueta, and K. Ohtaka, Phys. Rev. B **56**, 14 905 (1997).

[7] K. Ohtaka, Phys. Rev. B **19**, 5057 (1979).

[8] N. Stefanou, V. Karathanos, and A. Modinos, J. Phys.: Condens. Matter **4**, 7389 (1992).

[9] Xindong Wang, X.-G. Zhang, Qingliang Yu, and B.N. Harmon, Phys. Rev. B **47**, 4161 (1993).

[10] T. Suzuki and P.K.L. Yu, J. Opt. Soc. Am. B **12**, 570 (1995).

[11] K. Ohtaka and Y. Tanabe, J. Phys. Soc. Jpn. **65**, 2265 (1996).

[12] K. Ohtaka, H. Miyazaki, and T. Ueta, Mater. Sci. Eng., B **48**, 153 (1997).

[13] E.R. Brown and O.B. McMahon, Appl. Phys. Lett. **67**, 2138 (1995).

[14] I.I. Tarhan, M.T. Zinkin, and J.H. Watson, Opt. Lett. **20**, 1571 (1995); Phys. Lett. **68**, 3506 (1996).

[15] I.I. Tarhan and G.H. Watson, Phys. Rev. Lett. **76**, 315 (1996).

[16] T. Fujimura, K. Edamatsu, T. Itoh, R. Shimada, A. Imada, T. Koda, N. Chiba, H. Muramatsu, and T. Ataka, Opt. Lett. **22**, 489 (1997).

[17] K. Ohtaka, Y. Suda, S. Nagano, T. Ueta, A. Imada, T. Koda, J.S. Bae, K. Mizuno, S. Yano, and Y. Segawa, Phys. Rev. B **61**, 5267 (2000).

[18] H. Miyazaki, Y. Jimba, C.Y. Kim, and T. Watanabe, J. Phys. Soc. Jpn. **65**, 3842 (1996).

[19] Y. Jiang, C. Niu, and D.L. Lin, Phys. Rev. B **59**, 9981 (1998).