Confined Band Gap in an Air-Bridge Type of Two-Dimensional AlGaAs Photonic Crystal

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The transmittance spectrum for an air-bridge type of AlGaAs photonic crystal (PC) slabs successfully fabricated was measured. It is found that the observed spectrum is consistent with both the theoretical band structure and the calculated one. Moreover, the transmittance due to the modes below the light line is found to be almost 100%, indicating that the guided modes should exist. The respective stop bands are observed in the Γ-M direction for TM-like and TE-like modes, implying that a photonic band gap should exist for the TE-like guided modes. The present PC is very suited for controlling the radiation field.

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Recently, two-dimensional (2D) photonic crystals (PCs) have attracted an increasing interest for controlling the radiation field and light propagation [1,2]. Among 2D structures, waveguide-based PC slabs with periodically arranged air-rods, made of semiconductor heterostructures are most attractive, because those are particularly suited for developing remarkably miniaturized planar photonic circuits. Up until now, a few kinds of such samples have been proposed from the viewpoint that light must be practically confined also in the vertical direction [1,3–7]. For all cases the radiation loss, i.e., the radiation escaping from the plane due to intrinsic origin (leaky modes) is an important problem [1,6]. In this respect, PC of the air-bridge type (a perforated membrane freely suspended in air) should be very promising, since it may be easier to create a clear and wide photonic band gap (PBG) for the guided (nonleaky) modes [6]: hereafter we use the term PBG only for an omnidirectional gap in the 2D plane and otherwise the term stop band (SB). However, for this type of PCs the fundamental characteristics such as the transmission spectrum has not been experimentally studied yet, although fabrication of such a sample was reported by two groups [8,9]. In this Letter we report on the characteristics of the transmittance versus wavelength, of an air-rod PC with air-bridge structure, which was successfully fabricated from an AlGaAs waveguide. We find that the respective stop bands exist in the Γ-M direction for incident light with the electric field perpendicular (TM) and parallel (TE) to the PC plane, and that the transmittance in an energy region where only the guided modes exist, is very good, as is expected. The result implies that a PBG should exist for the TE-like guided modes.

We describe briefly the fabrication procedure of our samples. First, we fabricated a triangular lattice of airholes in an epitaxially grown $Al_{0.1}Ga_{0.9}As$ core layer of 270 nm thickness with a 2.0-μm-thick $Al_{0.8}Ga_{0.2}As$ cladding layer on a GaAs substrate by using electron-beam lithography and Cl_2-based reactive-ion-beam etching. Thus, the sample was formed in such a shape as equipped with a 3.0-μm-wide and 0.4-mm-long stripe waveguide on both sides of the PC. The PC is aligned such that the Γ-M direction of the corresponding 2D Brillouin zone is parallel to the waveguides. Finally, the cladding layer was dissolved by using buffered HF as a selective wet chemical solvent; the thickness d of the membrane is essentially the same (270 nm) within 5 nm with the original thickness. Various samples of 10 rows or 5 periods (Ns) were prepared with different parameters, i.e., with the lattice constant a in a range of 400–450 nm and the air-filling factor f of 0.47–0.64. Figure 1 shows a SEM image of a typical sample.

Optical transmission spectra were directly measured in a range from 850 to 1100 nm by using a cw Ti-sapphire laser [10]. A spherical-lensed polarization-preserving optical

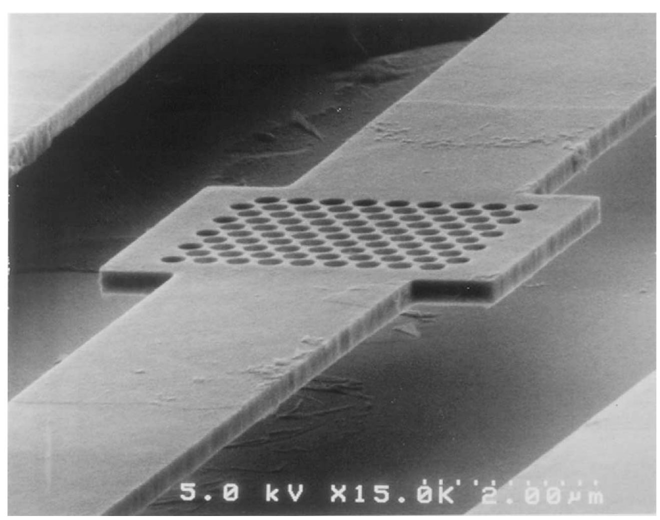

FIG. 1. A SEM image of a photonic crystal sample with air-bridge structure.

fiber was employed to couple light to the stripe waveguide. Similarly, the transmitted light from the other waveguide was collected using another identical fiber and detected with a photodetector.

Representative transmittance spectra are shown in Figs. 2(a) and 4, where the solid (TM) and open (TE) circles denote the data points observed with the electric field of incident light perpendicular and parallel to the slab plane, respectively. The spectra were observed for two samples with different f values but otherwise almost the same parameters including a. The absolute transmittance is determined by normalizing the transmission with use of a reference measured with a nominally identical waveguide without PC. The corresponding photonic band structures (PBS) were calculated by a method to solve the Maxwell's equations using an admixture of the plane-wave expansion and the real space decomposition [11]. In Figs. 2(b) and 2(c) are shown those corresponding to TM-like and TE-like modes, respectively, where the solid and open circles represent the modes of odd and even symmetry, respectively, with respect to the electric field about the mirror plane in the middle of the slab; dominant bands are shown by thick lines, while unimportant bands of higher-order modes by thin lines, which are usually not excited, as will be discussed later. The modes below and above the light line correspond to the guided and leaky modes, respectively.

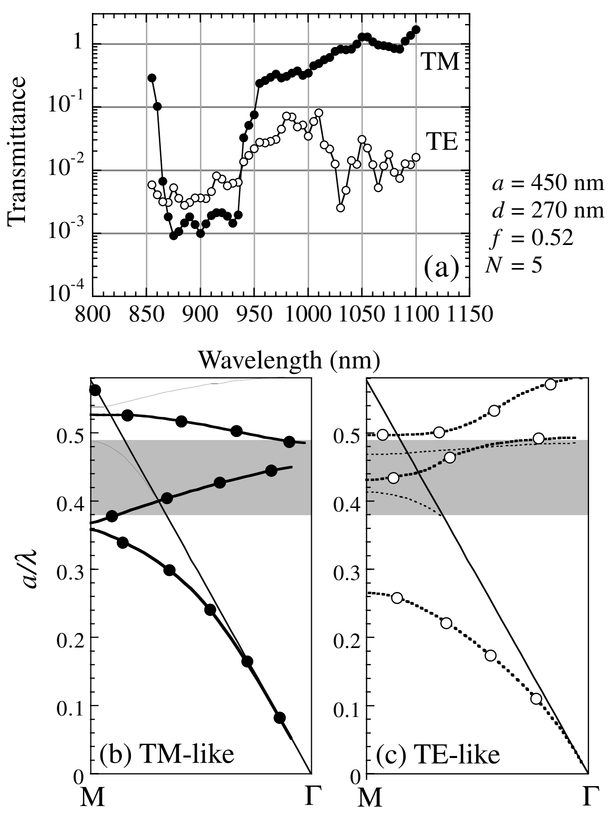

FIG. 2. (a) An example of transmittance spectra. The corresponding photonic band structure, (b) TM-like (solid line), and (c) TE-like (dotted line) modes; the solid and open circles indicate the modes of odd and even symmetry, respectively. Dominant bands are shown by thick lines, whereas higher-order bands (modes) are shown by thin lines. The oblique line denotes the light line.

Now let us see first the TM spectrum in Fig. 2(a). It is seen that a deep drop of the transmittance manifests itself from 860 to 950 nm and importantly, the absolute transmittance reaches almost 100% above 1020 nm. From now on, we interpret the spectrum in terms of the PBS with the dominant bands, unless otherwise noted. The opaque region is interpreted as arising from a SB between the second- and third-lowest TM-like bands of odd symmetry in Fig. 2(b). From a comparison of the gap width between the observed and the calculated results, it is reasonable to consider that the width is practically determined not by the guided modes, but by the relevant bands including the leaky modes for the reason described later. Under this postulation, a slight (8%) energy shift of the PBS to the higher energy side agrees nicely with the observed opaque region; for clarity, in Figs. 2(b) and 2(c) the measured region shown by a hatched area is inversely shifted by 8% to the lower energy side. This shift is reasonable, since an inaccuracy of 10% or less should be involved for each sample parameter. The transmittance of almost 100% indicates that the radiation loss is small enough, if any. This is reasonable because only the guided mode is present in the lower energy region. As for the TE spectrum, it is not straightforward to interpret it as compared to the TM one. The transmittance of this spectrum is less than 10% over the observed region. For TE-like modes, theoretically the transmittance should be quite small in the wavelength region longer than 1040 nm and also shorter than 990 nm. The former is caused by the lowest SB of even symmetry, whereas the latter by the second-lowest one only for the guided modes; in other words, the transmittance should become large only in a narrow energy region due to the second-lowest guided band, assuming that this band above the light line is leaky enough. That the transmittance in the above narrow region remains $5 \sim 10\%$ is not necessarily strange, because experimentally it should usually become large only when the relevant wavelength is far from the gap.

In Fig. 3 is shown the calculated transmittance spectra for the exactly same sample by using the finite-difference-time-domain (FDTD) method. The correspondence between the observed and calculated is very good, both qualitatively and quantitatively. This fact reveals the validity of the present interpretation including the assumption. Thus, the overall features of the observed spectra can be well explained.

The spectra in Fig. 4 also support the above interpretation. A calculation of PBS reveals that by diminishing the f value from 0.52 to 0.46, the energy position of the above SB for the TM-like modes moves to the lower energy side. Actually, the observed opaque region is found to concomitantly shift by 70 nm, which is quite reasonable since the volume-averaged dielectric constant increases with decreasing f. Another drop of the transmittance is also seen

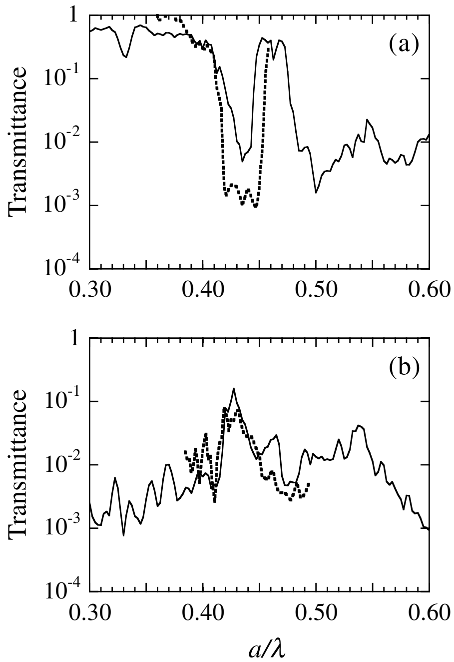

FIG. 3. Comparison of the calculated transmittance spectrum (solid line) with the observed one (dotted line): (a) TM-like spectrum and (b) TE-like spectrum, where the observed one is shifted in energy by 13% and 6% for (a) and (b), respectively.

from 850 to 900 nm. This drop should arise from another SB above the third lowest TM-like band of odd symmetry. It is noted that the guided modes still exist in a narrow range below the light line, corresponding to the observed one. Concerning the TE spectrum, the feature above 900 nm is basically similar to that of Fig. 2(a), if we shift the latter spectrum by 60 nm to the longer-wavelength side. So, the same explanation with the case for Fig. 2(a) holds. Notice that the transmittance above 1060 nm decreases more remarkably due to the first gap. Besides, the transmittance below 900 nm is seen to be very small, which may be explained by invoking that the third band corresponding to this energy region is quite likely to be

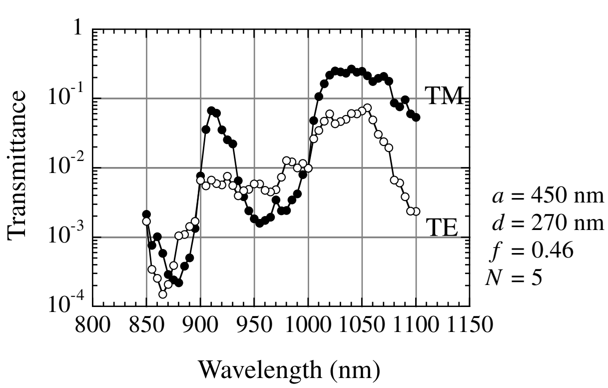

FIG. 4. Another example of the transmittance spectra. The transmittance drop from 935 to 995 nm for TM light corresponds to the deep drop in Fig. 2(a).

more leaky than the second one, as is seen from Fig. 3(b); it is remarked that the portion of the same band below the light line is too flat to practically give rise to a high transmittance. An estimation of Q value for the relevant leaky bands is needed to confirm this.

Here, we would like to emphasize a distinction of the observed transmittance between the leaky- and guided TM-like modes. The transmittance in a leaky-mode region of the second band is always less than 100%, while it always reaches almost 100% in a guided-mode region. This is clearly seen in Fig. 2(a), as already described; only the former is seen in Fig. 4. Furthermore, we mention that a clear distinction is also observed in another spectrum (not shown) for a sample with $f = 0.60$ and $a = 400$ nm, where a narrow but definite transmittance dip due to the lowest SB for TM-like modes is observed, corresponding to the narrow and shallow one around 0.33 in the normalized energy in Fig. 3(a). Importantly, in this case the transmittance is also 100% on the lower energy side (the first band) of this dip, which is, of course, below the light line. A possibility that the distinction might arise from the Fabry-Perot effect is very unlikely because the maximum transmittance should be reached within at largest one-fourth of the entire energy region of the second band, which is 50 nm or so apart from the second-gap edge, considering 10 Fabry-Perot peaks for 10 rows.

Next, in order to see whether a PBG exists or not, the PBS over the entire Brillouin zone is shown in Fig. 5; the portion in the Γ-M direction is the same with Figs. 2(b) and 2(c). In Fig. 5, we describe also the characters of the higher order modes such as the symmetry, which are not shown in Fig. 2 for clarity. From the overall agreement between the observed spectra and the PBS in the Γ-M direction, it follows that a PBG for the TE-like guided modes should exist between the first- and second-lowest bands with even symmetry.

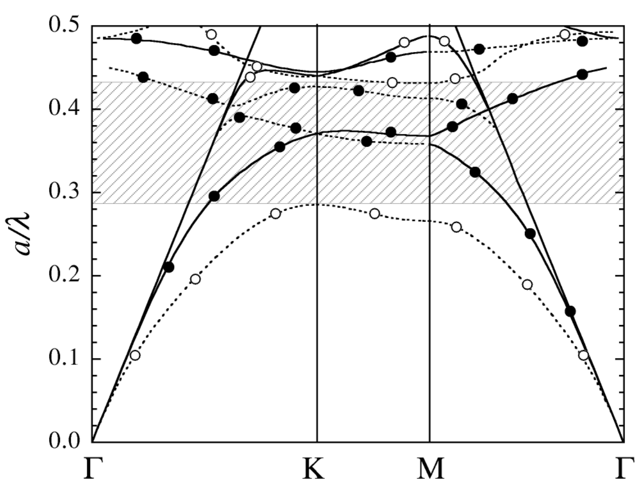

FIG. 5. The photonic band structure over the entire Brillouin zone. The same notation as in Figs. 2(b) and 2(c) is used for lines and symbols. The hatched area shows the PBG for the TE-like guided modes with even symmetry.

Now, let us discuss the obtained results in a bit more detail. First, we would like to discuss what role the leaky modes will play in the transmittance spectrum. We point out that there are the leaky modes with a relatively large Q value above the light line [11–13]; notice that the guided modes are defined for an infinite slab. In the case of a sample with small periods like the present one ($N = 5$), those modes should contribute also to the transmittance, more or less. As already described, the observed gap width for TM light does not agree with a gap calculated for the guided modes, but agrees with that for the relevant leaky modes, indicating that those should have a large Q value. Second, we mention another implication of observation of the transmittance of almost 100%. This observation implies that the quality of the present samples is very good; in particular, the cladding layer is considered to be cleanly dissolved away, otherwise inhomogeneous interface should cause serious loss due to scattering of light. Third, we describe the accuracy of the data points in the present spectra. As already described, the transmission spectrum for an identical sample without PC was used for obtaining the present transmittance spectrum. The former is rather smooth in shape over the observed energy region except for a narrow one below 870 nm, where the transmission drops to a considerable extent. In any case, the accuracy is considered to be predominantly governed by that of this transmission spectrum. The accuracy of the data points is estimated to be 20% or so above 870 nm, but 50% or even more below it. This is the reason that the transmittance around 1050 nm apparently exceeds 100%. The above transmission drop below 870 nm is likely to arise either from the intrinsic absorption of the core-layer material, or from involvement of higher-order modes. In this connection, it is remarked that although in the present air-bridge waveguide there exists only the lowest-energy TE(TM) mode for each even or odd symmetry above 870 nm, the second-lowest TE(TM)-mode of even symmetry starts appearing around 870 nm. This statement also explains that the higher-order modes in PC do not practically contribute to the transmittance above 870 nm.

Finally, we describe the significance of the present outcome. There are two other ways to practically confine light in the vertical direction. One is to perforate both the core and cladding layers for the conventional semiconductor waveguide [5,7]. This method is advantageous for fabrication of a compact but complicated circuit on the basis of PC. However, it is necessary to perforate deeply enough the cladding layer, which is technically very difficult to attain at present. More importantly, a limitation for practical use should exist, i.e., such a PC could be used only with small N, since the radiation loss should be more serious as N becomes larger. The other is to replace the cladding layer of, e.g., $Al_{0.35}Ga_{0.65}As$ with different material of much smaller refractive index than that of the core-layer material [14]. This makes sense, since there exist the guided modes in this case. However, as far as fabrication of GaAs-based PC is concerned, it is not necessarily easy to fabricate such a PC. Furthermore, it is noted that the gap width becomes narrower in most cases as compared to the air-bridge PC. So, the air-bridge type of PC is considered to be most suited for creating a wide PBG for vertically confined light, as compared to the other two types, as has already been pointed out theoretically [6]. However, in developing a compact device or circuit on the basis of this type of PC, the coupling of light between the waveguides with and without the cladding layers becomes a problem [15].

In conclusion, we have experimentally proved that an air-bridge type of 2D AlGaAs-based PCs show the respective SBs for TM- and TE-like guided modes. This result indicates that a PBG should exist for TE-like guided modes. We have also found that the transmittance corresponding to the guided modes is satisfying enough, indicating that the radiation loss should be absent. The present work will open the door to developing a new type of optoelectronic devices or circuits working in the wavelength range below 1.1 μm.

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