CONFINED BAND GAP IN AN AIR-BRIDGE TYPE OF
TWO-DIMENSIONAL ALGAAS PHOTONIC CRYSTAL

N. Kawai, K. Inoue, N. Carlsson, N. Ikeda, Y. Sugimoto, K. Asakawa and T. Takemori

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

N. Kawai and K. Inoue

Research Institute for Electronic Science, Hokkaido University, Sapporo 060-0812, Japan

N. Carlsson, N. Ikeda, Y. Sugimoto, and K. Asakawa

The Femtosecond Technology Research Association, Tsukuba 300-2635, Japan

T. Takemori

Institute of Material Science, University of Tsukuba, Tsukuba, Ibaraki 300-2635, Japan

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.

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 air-holes in an epitaxially grown $Al_{0.1}Ga_{0.9}As$ core layer of 270 nm thickness with a 2.0-μm-thick $Al_{0.8}Ga_{0.2}As$ clad-

ding 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
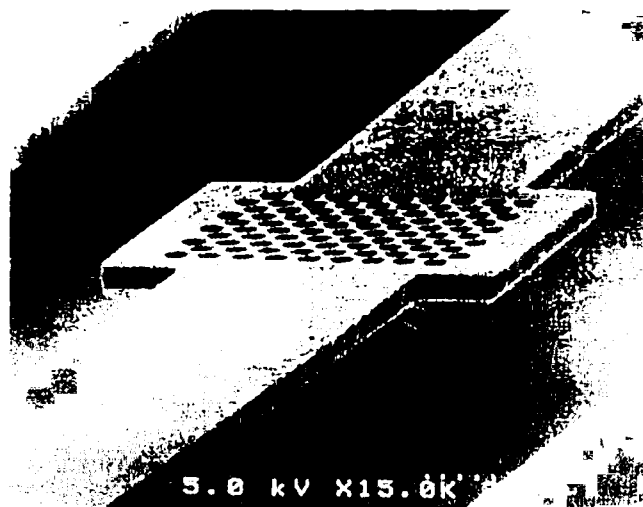

FIG. 1.   A SEM image of a photonic crystal sample with air-bridge structure.

PHYSICAL REVIEW

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CONDENSED MATTER
AND MATERIALS PHYSICS

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Transmittance and time-of-flight study of $Al_xGa_{1-x}As$-based photonic crystal waveguides

N. Kawai and K. Inoue

Research Institute for Electronic Science, Hokkaido University, Sapporo 060-0812, Japan

N. Ikeda, N. Carlsson, Y. Sugimoto, and K. Asakawa

The Femtosecond Technology Research Association, Tsukuba 300-2635, Japan

S. Yamada and Y. Katayama

The Center of Tsukuba Advanced Research Alliance, The University of Tsukuba, Tsukuba 305-8577, Japan
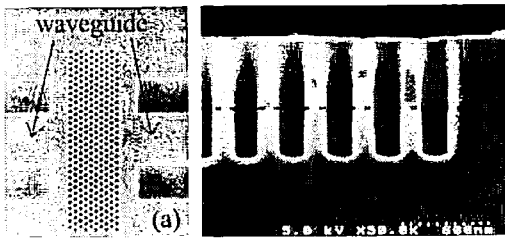
FIG. 1. Scanning electron microscope images of the top view pattern (a) and the cross section (b). The dotted line in (b) shows the interface between the core and the cladding layers.

The transmittance characteristics were measured for each sample in a range from 0.85 to 1.10 μm in such a way that light from a wavelength-tunable Ti-sapphire laser was coupled to the PC through the input waveguide by using a polarization-preserving optical fiber. Similarly, the signal from the output waveguide was collected by using another identical fiber and measured by a photodetector. An infrared vidicon was employed for attaining best optical alignment and also monitoring the scattering of light out of plane. For calibration of T, a nominally identical sample but without a PC was used. First, we describe the results observed in the Γ-M direction. Examples of transmittance spectra are presented for two samples in Figs. 2(a) and 2(b); the spectra were obtained for incident light with polarizations corresponding to TM-like and TE-like modes, respectively. For comparison, PBS's are also presented in Figs. 2(a) and 2(b), that are assumed to correspond approximately to the present PC's; the assumption is made considering that for samples with both N and f values small, e.g., $N \leq 10$ and $f \leq 0.35$, quasiguided modes may be treated approximately as TE- and TM-like modes in the case of a symmetric PC waveguide.[17] These PBS's were calculated by using the plane-wave expansion method for an infinitely long air-rod 2D PC, embedded , a background (core) material, and assuming an effective refractive index of 3.39, instead of 3.52 for the homogeneous case; the value was estimated from the dispersion relation for uniform slab waveguides. First, we would like to state that overall features of the TM-like spectra observed for many samples can be explained rather well in terms of the above PBS. More concretely, the relative energy shift of the PBS corresponds well within 5% to the observed spectrum in each case. It is seen in both Figs. 2(a) and 2(b) that T drops significantly at a PBG for TM-like polarization, as indicated; notice that the attenuation amounts to at least 15 dB for (a) and 39 dB for (b). Note that T in the case of $N=5$ in (a) is more than 80% in a range corresponding to the second-lowest band for TM-like polarization. Concerning the TE-like spectrum, the result is also reasonable, aside from the absolute transmittance. A moderate drop of T observed in both (a) and (b) arises not from a PBG, which is not expected to exist in the observed range from the PBS, but from the characteristics of the third-lowest band. This band is known to have poor coupling to an external wave of wave-vector parallel to Γ-M due to wave-vector mismatching,[18] so that T should drop to some extent in this region, as is actually observed. Considering the small amount of ambiguity of the
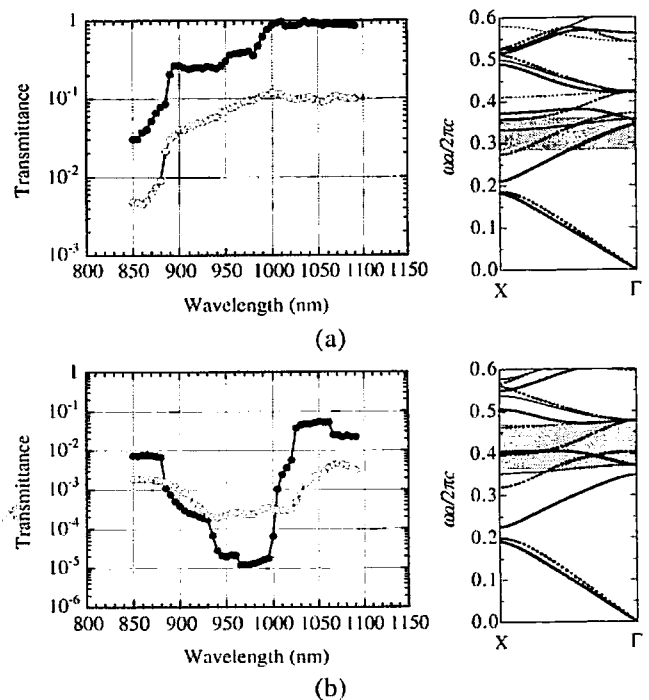

(a)

(b)

FIG. 2. Examples of the transmittance spectra and the corresponding PBS for samples (a) $a=320$ nm, $f=0.30$, $N=5$ and (b) $a=400$ nm, $f=0.41$, $N=10$. The closed and open circles in the spectra represent the data points for TM-like and TE-like incident light, respectively. In the PBS, the solid and dotted lines indicate the bands for TM- and TE-like polarization, respectively, with the thick and thin lines being the coupled and uncoupled bands, respectively. The energy region observed is shown by a hatched area.

parameters, the correspondence between the observed and calculated results is good. However, the absolute T value is recognized to be small; we will discuss this later. Next, we briefly mention the results (not shown) observed in the Γ-K direction. A similar calculation of the PBS indicates that in the present energy region there is no PBG, but an uncoupled band for both TM-like and TE-like modes. Experimentally, a moderate drop of the transmittance is indeed observed due to the uncoupled band for both cases. So the result is again reasonable.

Now we proceed to the time-of-flight measurement, which was performed to get information about R and pulse-propagation characteristics. When a light pulse of 200 fs from a mode-locked Ti-sapphire laser was made to impinge on the input edge of the stripe waveguide by using an objective lens with a 0.5 numerical aperture, a series of reflected pulses appeared. These were observed in such a way that the cross-correlation signal between the reflected pulse and the original (reference) one was measured as a function of the relative time delay; the measurement was made by adopting the so-called up-conversion method. Examples of reflection spectra in the time domain are shown in Fig. 3. The spectra (a) and (b) were observed at 890 nm for the same samples as were used for Figs. 2(a) and 2(b), respectively; the wavelength corresponds to the band edge for (a) and the PBG for (b). The spectrum (c), observed for another sample with a