Observation of light propagation in photonic crystal optical waveguides with bends

T. Baba, N. Fukaya and J. Yonekura

Light propagation is investigated in two-dimensional photonic crystal waveguides with bends, which were composed of closely-packed holes formed in a GaInAsP thin film. Wavelength and polarisation dependence on propagation characteristics were observed in the wavelength range 1.47–1.60µm.

Photonic crystals can be used as omni-directional mirrors with high reflectivity due to the photonic bandgap (PBG). One of the suggested potential applications is for a waveguide with strong optical confinement, in which photonic crystals are used as claddings. Low loss propagation through waveguides with sharp bends, branches etc., has been theoretically estimated [1, 2], and some experimental demonstrations have been presented involving the use of a large crystal for millimetre waves [3]. However, experiments are much more difficult for lightwaves. Light propagation in straight waveguides has been recently investigated [4]. Still, the effect of photonic crystal claddings was not made clear, since the waveguide was as short as several micrometres. In this Letter, we report the first observation of light locus in such waveguides with bends.

In this study, a GaInAsP film epitaxially grown on InP substrate was used as the waveguide material. The thickness and bandgap wavelength were 0.35 and 1.38µm, respectively. It was bonded using a thin epoxy onto a host substrate, the surface of which was covered with a 3µm thick SiO_2 film. The first InP substrate was then removed by selective wet etching. Thus, the GaInAsP film acts as a slab waveguide with upper air and lower SiO_2 claddings. Before the bonding process, a two-dimensional (2D) photonic crystal was formed in the GaInAsP film by electron beam lithography and dry etching. It was composed of closely packed holes. The designed diameter and hole pitch were 0.5 and 0.6µm, respectively. According to 2D photonic band calculations, full PBG is realisable in the wavelength range λ = 1.5–1.6µm when the refractive index of the semiconductor is 3.38 [5]. A channel waveguide was composed of a single line of defects of the crystal, i.e. a GaInAsP corrugated stripe with 0.7µm minimum width. The photonic crystal pattern includes straight waveguides 25µm in length with 60° or 120° bend. Fig. 1 shows the crystal before the bonding process. Holes just beside the waveguides became 20–30% smaller than the designed hole due to nonuniform exposure during the lithography process, while other holes were almost the same size as the designed one. After the bonding process, however, the waveguide width was expanded to 2.4µm, since the dry etching did not pierce the smaller holes.

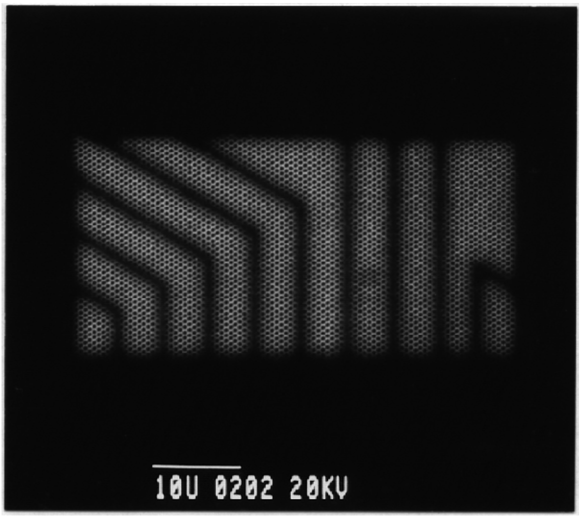

Fig. 1 *Top view of formed photonic crystal with defect waveguides*

In the measurement, a tunable laser with λ = 1.47–1.60µm was used as a light source. The light was focused on a cleaved facet of the sample. The light locus was observed from the top of the surface using an infrared TV camera. For the film without the photonic crystal and unexpected defects, the light locus was not observed due to the small surface scattering of light. Light propagation in the slab waveguide was confirmed over the above wavelength range from the scattered light at some cracks of the film, which might be caused by the residual tension in the epoxy. We considered that it was a guided mode in the GaInAsP, not a cladding mode in the SiO_2, since the calculated propagation loss of the cladding mode was as large as 43–45dB/mm for arbitrary polarisation. For a channel waveguide, we confirmed the light propagation, as shown in Fig. 2. The straight light locus was seen for the straight waveguide. We consider that the scattering of the guided mode at the core/cladding boundaries caused the locus. The strong light output was seen at a deep crack near the right hand side in Fig. 2. The distance of the crack from the waveguide end was 93µm. The width of major light intensity at the crack was 25µm. We consider that the light propagates from the waveguide end to the crack as a Gaussian beam and the width at major intensity is the full width at $1/e^2$ of its maximum. Assuming an equivalent refractive index of 3.0 for the slab waveguide, the spot diameter at the waveguide end was calculated to be 2.4µm. This value is the same as the waveguide width, as mentioned above.

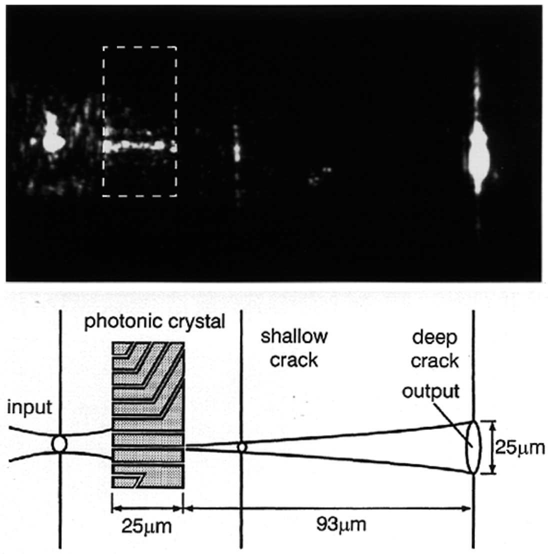

Fig. 2 *Near field image and schematic diagram of waveguide surface*
– – – – position of photonic crystal

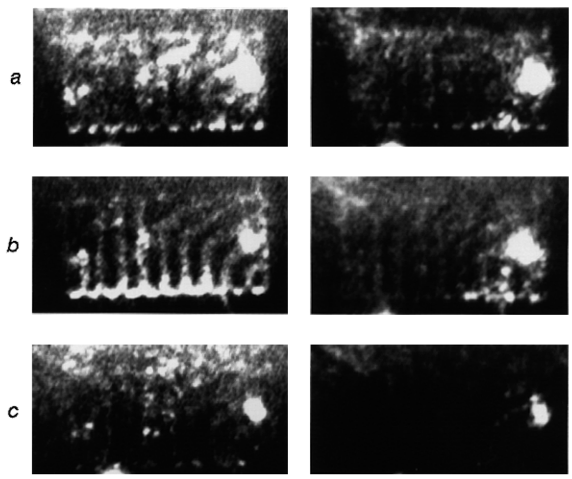

Fig. 3 *Near field images of waveguide surface*
a λ = 1.49µm
b λ = 1.53µm
c λ = 1.58µm
Left: TE polarisation
Right: TM polarisation

Fig. 3 shows the light locus when the light was widely inserted at the end of the photonic crystal. For the transverse electric (TE) polarisation, the locus changed significantly with wavelength. For λ = 1.51–1.56µm, the locus was clearly seen for waveguides. The light propagates even in waveguides with bends. Outside this range, the light almost passed through the crystal; over the photonic crystal area, the scattering was enhanced at λ < 1.51µm, while being suppressed at λ > 1.56μm. This indicates that a PBG exists at λ = 1.51–1.56μm. For the transverse magnetic polarisation (TM), a locus for waveguides was barely observed at λ = 1.51–1.53μm. However, it was more indistinct than for TE polarisation. It might be caused by a narrow PBG for TM polarisation which was expected from the photonic band calculations [5].

In conclusion, we have fabricated thin film channel waveguides with 2D photonic crystal claddings of closely packed holes, and successfully observed light propagation at λ = 1.51–1.56μm. In this study, we only used a 2D calculation, not a 3D calculation for the design. Nevertheless, the evaluated PBG roughly agreed with the expected result. In the future, we shall investigate the propagation characteristics and the correspondence to 3D theory.

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