Group velocity dependence of propagation losses in single-line-defect photonic crystal waveguides on GaAs membranes

Y. Tanaka, Y. Sugimoto, N. Ikeda, H. Nakamura, K. Asakawa, K. Inoue and S.G. Johnson

Group velocity, v_g, dependence of propagation loss in single-line-defect photonic crystal waveguides on GaAs membranes, and minimum loss as low as 2.5 dB/mm, are presented. When v_g is reduced by a factor of 7, an additional loss is found to be only 5 dB/mm, thus proving a feasible usage of low v_g.

Introduction: Two-dimensional (2D) photonic crystal (PC) waveguides are expected to be one of the significant platforms in future optical communication networks. To date, much effort has been devoted to the light guidance by 2D-PC line-defect waveguides that achieve a 3D optical confinement by use of a combination of the photonic bandgap and total internal reflection [1–5], and small propagation losses were reported [6, 7]. However, discussion on the propagation loss spectrum is limited [7, 8]. On the other hand, a precise tunability for the low group velocity, v_g, of light capable of enhancing the photon density may be one of the key features of the PC waveguides. However, one who intends to use a low v_g to enhance the photon density may suffer an increase in the propagation loss. Therefore, it is of great importance to investigate the v_g dependence of the propagation losses. In this Letter, we describe a fabrication of the 2D-PC waveguides as long as ~1 mm, and show the propagation loss spectrum. We also calculated the theoretical loss spectrum and obtained the v_g dependence of the propagation loss.

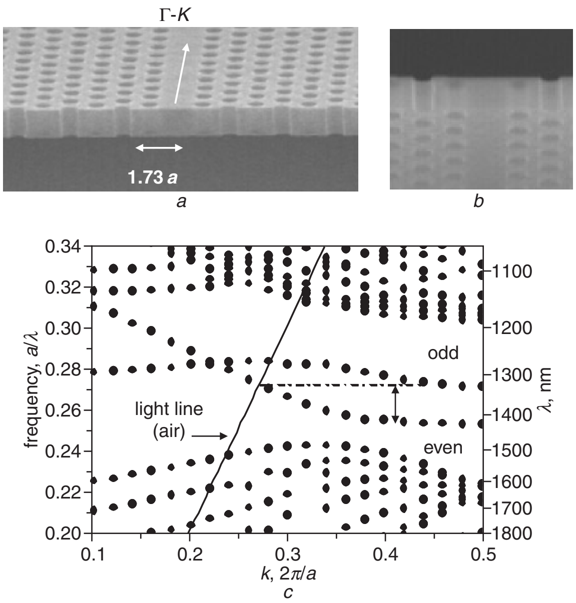

Fig. 1 *SEM photographs of fabricated PC waveguides and band diagram*
a Straight line-defect waveguide *b* Back surface of core layer
c Band diagram

Sample structure and band diagram: The samples were fabricated in epitaxial heterostructures grown by molecular beam epitaxy. A 250 nm-thick GaAs core layer was deposited on top of a 2 μm-thick $Al_{0.6}Ga_{0.4}As$ clad layer on the GaAs substrate. The pattern of the hexagonal triangular lattices of air holes and the single-line-defect waveguide were drawn by electron-beam lithography, and transferred into the core surface by reactive-ion-beam etching. The lower sacrifice clad layer was removed by HF through air holes. The lattice constant *a* and hole diameter were 360 and 220 nm, respectively. Three straight line-defect PC waveguides with lengths of 0.5, 1, and 1.5 mm were prepared by cleaving both ends. The fabricated 2D-PC waveguide is shown in Fig. 1*a*. The back side of the PC core layer is shown in Fig. 1*b*. By varying a fraction of Al content of the clad layer and wet etching duration, a PC core layer with a very smooth back surface has been obtained, which is expected to reduce the propagation loss. The band diagram of the 2D-PC waveguide calculated by the 3D finite difference time domain method is given in Fig. 1*c*. Two waveguide modes for the even and odd symmetries appear within the bandgap of the TE-like mode (electric field in slab plane). There is a singlemode below the light line, as indicated by a bold arrow.

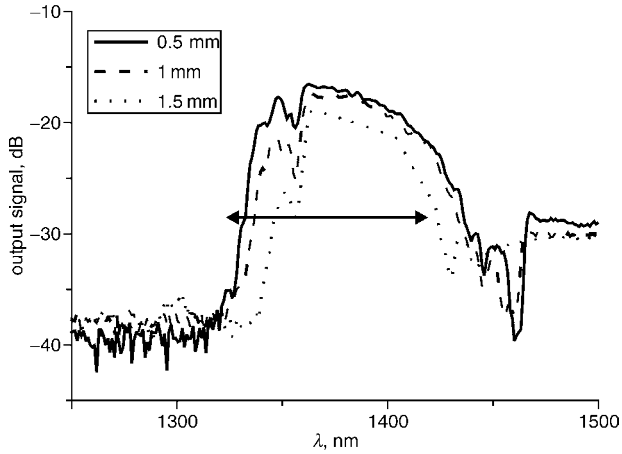

Fig. 2 *Transmission spectra of PC waveguides with different lengths*

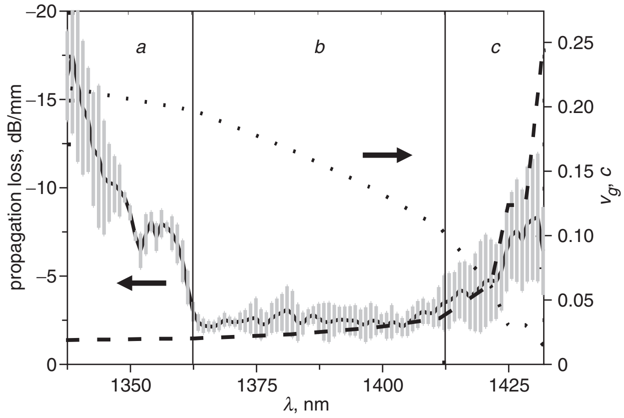

Fig. 3 *Propagation loss spectra and their dependence on group velocity*
a Above light line; *b* below light line and high v_g; *c* below light line and low v_g

Experiments and results: We measured the TE polarisation transmission spectra of the three waveguides. The input signal of the white light source with a wavelength range of 1100 to 1600 nm was directly coupled into the cleaved facet of the PC waveguide using a polarisation-maintaining fibre and aspherical lenses. After being collected by a tapered fibre, the output signal was introduced into a monochromator equipped with a grating with 150 grooves/mm and detected using a cooled MC (512 channels, one-dimensional) InGaAs detector. The measured transmission spectra are given in Fig. 2. Output signals were normalised by the reference signals of the 'fibre to fibre'. The theoretical transmission range is also given by a horizontal arrow, identical to the vertical one in Fig. 1*c*, for reference. A close correspondence between both the wavelength ranges is observed. Furthermore, Fig. 3 shows a propagation loss spectrum (solid line with uncertainty) derived from linear regressions of the transmission spectra of Fig. 2. It is interesting to note that the loss spectrum can be classified into three parts, labelled by *a*, *b*, and *c*. As the region *a* is above the light line (radiative mode), the propagation loss here is intrinsic and large. In the region *b* below the light line where v_g is relatively high, the loss is almost flat, and as low as 2.5 dB/mm. The loss is drastically increased again in the region *c* owing to the very low v_g. To gain a deep insight into the loss spectrum, we also show the v_g spectrum (dotted line in Fig. 3) obtained from derivatives of the dispersion curve in Fig. 1*c* and the theoretical loss spectrum (dashed line) that was calculated using the equation, $\alpha = 2\pi/\lambda v_g Q$, assuming no absorption in this wavelength range [3]. *c* is the speed of light and the quality factor, *Q*, was set at ~70 000. Both the loss spectra agree very well. Note that when v_g is reduced by a factor of 7 from 0.175*c* at 1363 nm to 0.025*c* at 1425 nm, the additional loss is only 5 dB/mm. The result means that the low v_g region can be used with low losses.

Conclusion: We fabricated long PC waveguides and obtained the propagation loss spectrum from their transmission spectra. From comparison with the theoretical one, the v_g dependence of the propagation loss is experimentally obtained and the possible usage of the low v_g is demonstrated.

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