APPLIED PHYSICS LETTERS VOLUME 77, NUMBER 18 30 OCTOBER 2000

Low-loss channel waveguides with two-dimensional photonic crystal boundaries

C. J. M. Smith
Optoelectronics Research Group, Glasgow University, Glasgow G12 8LT, Scotland

H. Benisty,[a] S. Olivier, M. Rattier, and C. Weisbuch
Laboratoire Physique de la Matière Condensée, Ecole Polytechnique, 91128 Palaiseau Cedex, France

T. F. Krauss
School of Physics and Astronomy, St. Andrews University, St. Andrews KY16 9SS, Scotland

R. M. De La Rue
Optoelectronics Research Group, Glasgow University, Glasgow G12 8LT, Scotland

R. Houdré and U. Oesterle
IMO, Ecole Polytechnique Fédérale de Lausanne, CH-1025 Lausanne, Switzerland

(Received 11 July 2000; accepted for publication 6 September 2000)

We have used transmission measurements to estimate the propagation loss of submicron channels defined in two-dimensional photonic crystals patterned into a Ga(Al)As waveguide. The measured propagation loss of the fundamental mode is indistinguishable from the material absorption, setting an upper limit of 50 cm^{-1} (2 dB per 100 μm). We also find that, provided the etching is deep enough, propagation losses of these photonic crystal waveguides are lower than those of ridge waveguides etched in the same run.
[S0003-6951(00)04144-9]

Photonic crystals (PCs) are a promising platform for the realization of ultracompact photonic circuits due to their high reflectivity for a few periods.[1] In the band gap of a PC, the absence of propagating modes prevents small scatterers due to irregularities within the crystal from radiating. This feature is very attractive for waveguides: conventional guides defined by a deeply etched ridge suffer from roughness-induced scattering losses reaching the cm^{-1} range only for, e.g., optimized, InP-based guides at $\lambda = 1.55\ \mu$m.[2] For a PC as a waveguide boundary, scattering due to roughness should be *inhibited*, reducing propagation losses for the same fabrication tolerances. There is limited experimental evidence of guiding by the sole photonic band gap effect at optical wavelengths, apart from the photonic crystal fiber.[3] Waveguides and sharp bends have, however, been demonstrated in three-dimensional structures[4] at microwave frequencies. But, on a submicron scale, due to fabrication difficulties, the main focus has been to pattern two-dimensional (2D) PCs into a dielectric waveguide, leading to confinement in PC cavities[5–7] and photonic bandgap lasers.[8,9] As for PC waveguides, Refs. 10 and 11 implemented the single missing row scheme, whereas Ref. 12 showed evidence for Bloch modes outside the band gap, along the ideas of Ref. 13.

The propagation losses have not been clearly quantified in the earlier work. Quantitative data are nevertheless crucial because the third dimension represents, in a 2D PC, a very plausible loss channel. Only Floquet–Bloch modes below the ''light line'' for the cladding material are, ideally, lossless.[13,14] As soon as translational invariance is broken (e.g., with bends), losses become unavoidable and their degree establishes the performance of all other optical elements such as resonators and demultiplexers.

In this letter, we report on spectral transmission measurements of straight channel guides with 2D PC boundaries. We find that such guides with different widths and lengths show transmission levels comparable to, or even higher than, those measured for conventional ridge waveguides of identical width etched in the same fabrication run. The guides defined by three missing rows, are multimode. We show, however, from the analysis of a minigap related to the periodic nature of these guides, that our measurement scheme isolates the transmission of the fundamental mode.

Electron-beam lithography and reactive-ion etching were used to define both ridge waveguides and PC channels (PC–WGs) in a GaAs-based heterostructure (400-nm-thick $Al_{0.8}Ga_{0.2}As$/220 nm GaAs core/310 nm $Al_{0.8}Ga_{0.2}As$ top cladding, with an effective index of 3.4 at 955 nm).[15,16] Various periods ($a = 240$, 260, and 280 nm) of the PC triangular lattice were used to ''lithographically tune'' across the 2D in-plane TE photonic band gap.[17,18] The air filling factor was about 38% (hole diameter $d = 168$ nm for $a = 260$ nm) and the etch depth was 1 μm in the large trenches. The PC–WG was defined as three missing rows in a PC of length from $15a$ to $240a$ [Fig. 1(a)]. The width of the ridge guides is equal to the physical width of the PC–WG [Fig. 1(a)], $w = 2\sqrt{3}a - d$ (e.g., $w = 802$ nm for $a = 280$ nm).

The characterization technique is similar to that of Ref. 16: the photoluminescence (PL) of InAs quantum dots (QDs) embedded in the GaAs core was excited and their guided PL was used as a probe [Fig. 1(b)]. The three planes of QDs were grown with a large size distribution in order to give a broad PL spectrum (960–1050 nm). The excitation point was typically at 20 μm from the PC–WG entrance. The TE guided signal was collected at the cleaved facet [top image of

---

[a] Electronic mail: hb@pmc.polytechnique.fr

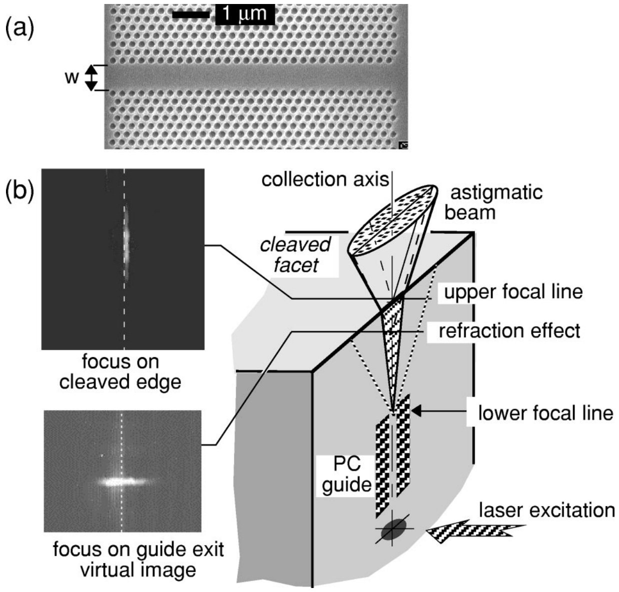

FIG. 1. (a) Micrograph of a straight PC waveguide consisting of 3 missing rows, and of length 30a, for a PC period $a=260$ nm; $w=802$ nm is the physical width. (b) Geometry of the guide transmission measurement using guided photoluminescence as a probe. The insets show video images obtained at the cleaved edge and at the indicated focusing depth.

Fig. 1(b), see Ref. 16]. In order to check the absence of spurious light scattered by adjacent patterns, we focussed the collection lens to the PC–WG exit virtual image,[16] at a locus determined by refraction at the facet. This resulted in a beam elongated normally to the facet, on account of the beam astigmatism [bottom image of Fig. 1(b)]. This ensured that the collected light had indeed traveled along the waveguide being probed.

It was straightforward to compare quantitatively the transmission levels of PC–WGs and deep-ridge waveguides with identical dimensions from the ratio of their cleaved edge spectra. Inhomogeneities of the local PL yield, generally below ±20%, were corrected by using the front PL intensity. The *absolute* normalization of guide transmission is a more delicate task. Our former method,[16] based on the guided PL of a nearby unpatterned area as a reference, is inappropriate for a waveguide with unknown input and output characteristics: for example, the internal collection angle θ is here 6.5°. Thus, light diverging beyond θ at the guide exit is not collected. To obtain propagation losses reliably, we rather compared the signals I_1 and I_2 obtained in *identical excitation and collection* geometries but with guides of *different lengths* L_1 and $L_2=L_1+L$. The ratio I_2/I_1 is then of the form $\exp(-\alpha L)$, where α measures the total *extinction* of the guided beam, and contains, in addition to the losses α_{PC} directly caused by out-of-plane scattering, a merely absorptive contribution α_{QD} due to the QDs. We determined separately the modal absorption α_{QD} by taking guided PL spectra of an unpatterned area with the laser spot located at increasing distances x from the cleaved edge: the signal then follows an $\exp(-\alpha_{QD}x)/x$ decay. We found α_{QD} to be around 100 cm^{-1} at 1000 nm.

Guides with a PC period $a=280$ nm were probed for lengths of 15a, 30a, 60a, 120a, and 240a. All guides had a characteristic minigap of 15–20 nm width, located at about 1060 nm (Fig. 2, raw spectra). This minigap is a signature of the periodic corrugation of the waveguide boundary, which couples the guided modes that ordinarily propagate in the corresponding noncorrugated guides, leading to an anticrossing in their dispersion relations.[19] The analysis of its spectral location for other PC periods (it lies at $\lambda=990$ nm for $a=260$ nm), as well as the strong attenuation encountered in this region for long enough guides ($L\geqslant 120a$) clearly indicate that the fundamental guided mode is the only one being measured, and the only one that survives after long propagation lengths.

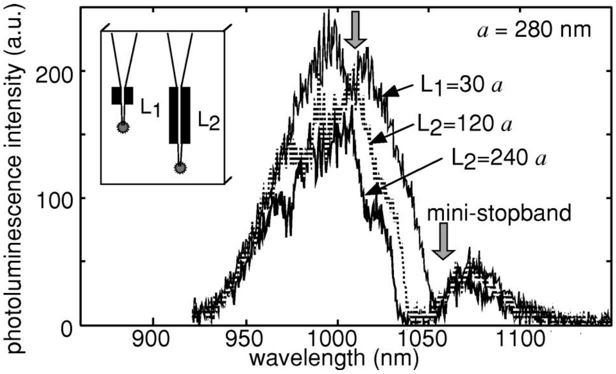

FIG. 2. Raw spectra for the PC guide with three missing rows and period $a=280$ nm for lengths 30a, 120a, and 240a. Arrows indicate spectral regions to be discarded from the analysis, due to the mismatch of the dips.

From Fig. 2, as a first estimate for $a=280$ nm, the attenuation ratio between the $L_2=120a$ and $L_3=240a$ guides is, outside the minigap feature, of the order of 0.75, giving roughly $\alpha\sim 100$ cm^{-1}. To be more precise, one has to form the ratio of $L_2=120a$ and $L_3=240a$ to $L_1=30a$. One can note that the minigaps (arrow at 1060 nm) are not identical for the various guides, due to fabrication variations such as uncorrected proximity effects in the electron-beam lithography. This part of the spectra should be discarded, as well as the region at around 1010 nm due to the feature arrowed on the $L=30a$ sample.

In Figs. 3(a) and 3(b) we show the extinction $\alpha=\alpha_{QD}+\alpha_{PC}$, deduced from the two ratios that correspond to $L_3=240a$ and $L_2=120a$ with $L_1=30a$. The arrows indicate the spurious features discussed earlier. The first main result from this work is the fact that, for both cases, $\alpha(\lambda)$ cannot be distinguished from $\alpha_{QD}(\lambda)$ (also plotted) in the transmission windows. Both extinction ratios are somewhat noisy, but, we can conclude with reasonable confidence that the out-of-plane losses α_{PC} are certainly *less than* 50 cm^{-1} (2 dB per 100 μm). When analyzing the shorter guides (length 15a to 60a and PC periods $a=260$ and 280 nm), we were similarly unable to distinguish α from α_{QD}, $\exp(-\alpha L)$ being then close to unity. In the case of a 240a long, 240 nm period, PC–WG, and only in this case, we could find with the same procedure a clear sign of out-of-plane losses α_{PC} on the order of 40–80 cm^{-1} [Fig. 3(c)]. These higher losses are attributed to the shallower holes upon etching smaller diameter cylinders.

In Fig. 4, we compare the transmission from the same PC–WG (240a long, $a=280$ nm, i.e., $L=67.2$ μm) to that of deeply etched ridge guides with the same physical width, $w=802$ nm, and length. The second main result is that the transmission ratio is on the order of 1.4 in favor of the

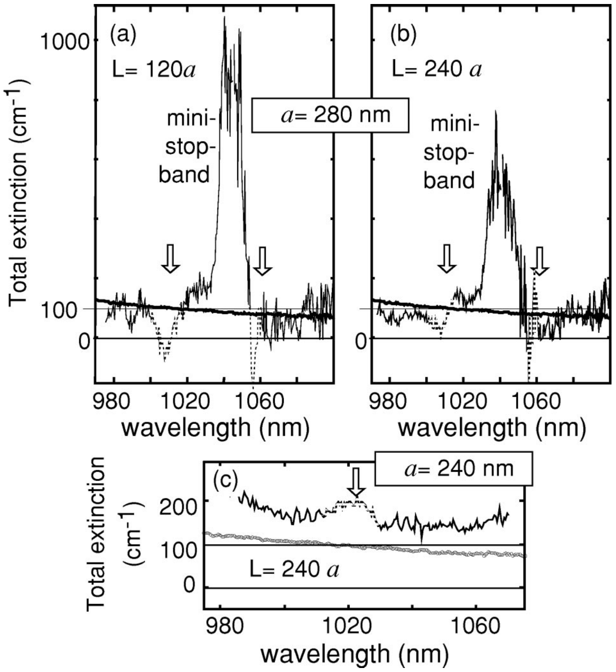

FIG. 3. (a) Thin line: Total extinction $\alpha = \alpha_{PC} + \alpha_{QD}$, (out-of-plane losses +absorption) deduced from the ratio of $L_3 = 240a$ and $L_1 = 30a$. Thick line: α_{QD}, deduced from a separate series of measurements. (b) Same for $L_2 = 120a$. (c) Same for $L_3 = 240a$, but with $a = 240$ nm. Arrows refer to regions discarded from the analysis (see Fig. 2).

PC–WG in the shorter wavelength region. While noise seems to make the measurement uncertain, we have verified on many samples (e.g., at different distances from the cleaved edge, from 50 to 150 μm) and experimental procedures [e.g., collection at the facet focus or at the internal focus, Fig. 1(b)] that the better behavior of PC–WGs is beyond doubt. Of course, the ratio is very small in the minigap, but the attenuation is then related to the coupling to other modes and not to the fundamental mode loss. Hence, with a similar fabrication-induced roughness, the PC guide displays signs of reduced losses compared to the ridge guide. This trend is a striking demonstration that, in their band gap, PCs allow only evanescent waves and therefore very small scattering losses, while the out-of-plane losses could not be measured. As for the ~50 cm^{-1} losses of our ridge guides (estimated by the same method as PC guides), a basic scaling by λ^{-4} (Rayleigh scattering) and by the squared field at the air interface indicates that they should be 7–10 times those of the guides of Ref. 2, i.e., 5–8 cm^{-1}, for the same rms roughness $\langle y \rangle$. Since losses scale like $\langle y \rangle^2$, an increase of $\langle y \rangle$ by a factor ~2.5–3, realistic in our ridges, has to be assumed.

The same experiment was carried out for smaller periods, $a = 260$ and 240 nm ($w = 725$ and 650 nm, respectively), in search of the effect of etch depth on propagation losses. The 260 nm period PC–WG showed again weaker losses outwith the minigap, but by a smaller factor than in the $a = 280$ nm case. The 240 nm period PC–WG showed a transmission level comparable to that of the corresponding ridge guide. This latter result agrees with the measurements of Fig. 3(c) and confirms that insufficient etch depth in that case is detrimental to PC properties.

In conclusion, we have demonstrated that out-of-plane losses are quantitatively low in a waveguide consisting of three missing rows in a 2D PC, below 50 cm^{-1} (2 dB per 100 μm). This is an excellent upper value as many ultracompact PC-based elements can be cascaded in a length of 100 μm (hundred of periods). A shallower etch increases the scattering loss, thereby supporting the quest of high-aspect-ratio PCs. To set a lower bound in sufficiently deep etched structures (PC period $a = 280$ nm), we are presently limited by measurement uncertainties. The propagation losses of PC guides have also been shown to be smaller than those of ridge guides obtained by the same etching method, a trend that we attribute to the PC-induced inhibition of roughness scattering in its band gap.

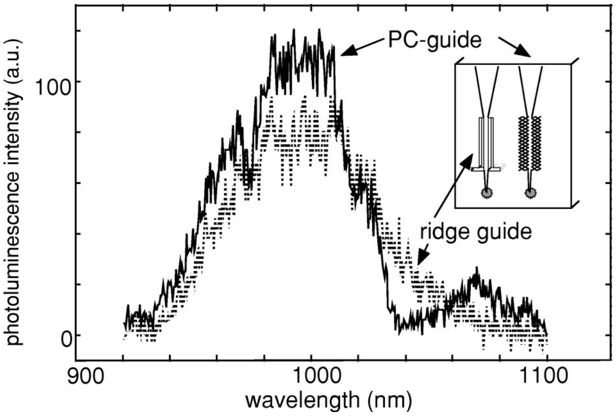

FIG. 4. Transmitted intensity from the 240a PC guide of Fig. 2 ($a = 280$ nm) and from a ridge guide of identical length and width, etched in the same run on the same sample, as depicted in the inset.

[1] J. D. Joannopoulos, R. D. Meade, and J. N. Winn, *Photonic Crystals* (Princeton University Press, Princeton, NJ, 1995).
[2] C. G. P. Herben, X. J. M. Leitens, F. H. Groen, and M. K. Smit, ECIO 99, Torino, 13–16 April 1999.
[3] R. F. Cregan, B. J. Mangan, J. C. Knight, T. A. Birks, P. S. Russel, P. J. Roberts, and D. C. Allan, Science **285**, 1537 (1999).
[4] S. Y. Lin, E. Chow, V. Hietala, P. R. Villeneuve, and J. D. Joannopoulos, Science **285**, 274 (1998).
[5] R. K. Lee, O. J. Painter, B. D'Urso, A. Scherer, and A. Yariv, Appl. Phys. Lett. **71**, 1522 (1999).
[6] P. Pottier, C. Seassal, X. Letartre, J. L. Leclercq, P. Viktorovitch, D. Cassagne, and C. Jouanin, J. Lightwave Technol. **17**, 2058 (1999).
[7] C. J. M. Smith, T. F. Krauss, R. M. De La Rue, D. Labilloy, H. Benisty, C. Weisbuch, U. Oesterle, and R. Houdré, Electron. Lett. **35**, 228 (1999).
[8] O. Painter, R. K. Lee, A. Scherer, A. Yariv, J. D. O'Brien, P. D. Dapkus, and I. Kim, Science **284**, 1819 (1999).
[9] J.-K. Hwang, H. Y. Ryu, D.-S. Song, I.-Y. Han, Y. H. Lee, and D. H. Jang, Appl. Phys. Lett. **76**, 2982 (2000).
[10] T. Baba, N. Fukaya, and J. Yonekura, Electron. Lett. **35**, 654 (1999).
[11] M. Tokushima, H. Kosaka, A. Tomita, and H. Yamada, Appl. Phys. Lett. **76**, 952 (2000).
[12] M. D. B. Charlton, G. J. Parker, and M. E. Zoorob, J. Mater. Sci.: Mater. Electron. **10**, 429 (1999).
[13] P. S. J. Russell and T. A. Birks, in *Photonic Band Gap Materials*, edited by C. M. Soukoulis (Kluwer, Dordrecht, 1996), p. 71.
[14] S. G. Johnson, S. Fan, P. R. Villeneuve, J. D. Joannopoulos, and L. A. Kolodziejski, Phys. Rev. B **60**, 5751 (1999).
[15] D. Labilloy, H. Benisty, C. Weisbuch, C. J. M. Smith, T. F. Krauss, R. Houdré, and U. Oesterle, Phys. Rev. B **59**, 1649 (1999).
[16] D. Labilloy, H. Benisty, C. Weisbuch, T. F. Krauss, R. Houdré, and U. Oesterle, Appl. Phys. Lett. **71**, 738 (1997).
[17] C. C. Cheng, A. Scherer, V. Arbet-Engels, and E. Yablonovitch, J. Vac. Sci. Technol. B **14**, 4110 (1996).
[18] T. F. Krauss and R. M. De La Rue, in *Photonic Band Gap Materials*, edited by C. M. Soukoulis (Kluwer, Dordrecht, 1996), p. 427.
[19] C. J. M. Smith, H. Benisty, M. Rattier, S. Olivier, T. F. Krauss, R. M. De La Rue, R. Houdré, U. Oesterle, and C. Weisbuch, PECS, Sendai, 3–8 March 2000.