1.5 μm room-temperature emission of square-lattice photonic-crystal waveguide lasers with a single line defect

X. Checoury,[a] P. Boucaud, and J.-M. Lourtioz
Institut d'Électronique Fondamentale, UMR 8622 du CNRS, Bât. 220, Université Paris-Sud, 91405, Orsay Cedex, France

O. Gauthier-Lafaye, S. Bonnefont, D. Mulin, J. Valentin, and F. Lozes-Dupuy
LAAS-CNRS, 7 Av. du Colonel Roche, 31077 Toulouse Cedex 4, France

F. Pommereau, C. Cuisin, E. Derouin, O. Drisse, L. Legouezigou, F. Lelarge, F. Poingt, and G. H. Duan
Alcatel Thales III-V Lab, Alcatel Research and Innovation, Route de Nozay, 91460, Marcoussis Cedex, France

A. Talneau
Laboratoire de Photonique et Nanostructures, CNRS, 91460 Marcoussis Cedex, France

(Received 12 October 2004; accepted 3 March 2005; published online 7 April 2005)

Narrow waveguides consisting of a single defect-line (W1) in a square lattice photonic crystal are fabricated on InP using the substrate approach. A single-mode distributed-feedback laser emission is obtained under optical pumping at room temperature. Lasing occurs at the second folding point of the dispersion curve of the fundamental waveguide mode (wave vector $k=0$). The emitted wavelength ranges from 1420 to 1580 nm for a lattice period varying from 460 to 520 nm and a constant air filling factor of ~26%. The highly monomode behavior is explained using two-dimensional plane-wave models. Similar experiments conducted on triangular lattice W1 waveguides do not yield a laser emission. Three-dimensional simulations confirm that triangular lattice W1 waveguides suffer higher losses than their square homologues. © *2005 American Institute of Physics*. [DOI: 10.1063/1.1905810]

Photonic crystals (PhC) are artificial structures that appear to be particularly promising for miniaturized devices in integrated optics. Recently they have been used for the fabrication of ultranarrow-waveguide edge-emitting lasers,[1] which consisted of one row of missing holes (W1) in a perforated membrane. The authors used a small group velocity mode located below the light cone. The membrane approach is known to minimize losses associated with out-of-plane radiation, but is penalized by heating effects and a difficult implementation of electrical excitation. The substrate approach seems in turn to be better adapted to a larger scale integration of photonic devices. However, due to a smaller refractive index contrast between the guiding and cladding layers, it results in a weaker vertical confinement of light than in the membrane approach. Most of the modes are above the light cone thus leading quasiexclusively to leaky modes. To date, lasing in the substrate approach has been reported only for relatively wide waveguides.[2–4] In this letter, we report a single-mode $\lambda=1.5$ μm laser emission obtained at room temperature from narrow waveguides consisting of a single defect-line (W1) in a square lattice photonic crystal using the substrate approach. The lasing is shown to occur at the second folding point of the dispersion curve of the fundamental waveguide mode (wave vector $k=0$). Experiments conducted on similar triangular lattice W1 waveguides do not yield a laser emission in the same conditions. Most of the experimental results are interpreted using theoretical calculations from a two-dimensional plane-wave model. Three-dimensional finite-difference-time-domain (FDTD) simulations are also used for a comparative estimate of W1 waveguide losses in square and triangular lattices.

Photonic crystals consisting of a square lattice of air holes have not been as intensively studied as triangular lattice ones because of their smaller band gap in TE polarization for a given air filling factor. For instance, only a partial TE gap is obtained for an air filling factor of 26% and a refractive index of the dielectric matrix equal to 3.21. In the same conditions, a triangular lattice PhC exhibits a full TE gap. However, an absolute band gap is not mandatory for achieving an in-plane mode confinement. Moreover, out-of-plane radiations also need to be considered to evaluate the overall waveguide performances. This is particularly true in the substrate approach where most of the dispersion curves of guided modes lie above the light line. Vertical radiation losses critically depend on the PhC pattern, the waveguide orientation and the wave vector amplitude. For instance, it has been shown that vertical losses can cancel at the Γ point ($k=0$) for some modes above the light cone.[5,6]

As for the triangular case, narrow waveguides (W1) in a square lattice are obtained by omitting one row of holes. Figure 1 shows the band diagram of guided modes for such a W1 waveguide oriented in the ΓX direction. Calculations are performed using the supercell method. The thick black lines represent the dispersion curve of the lowest order guided mode, which is mainly of refractive nature, as the lowest order mode of the triangular lattice W1 waveguide.[7] As seen, almost all the modes are above the light curve even at the X point. This contrast with the membrane approach, where several lossless guided modes can exist below the light line. A very favorable situation for a laser emission occurs at the two

[a]Electronic mail: xavier.checoury@ief.u-psud.fr

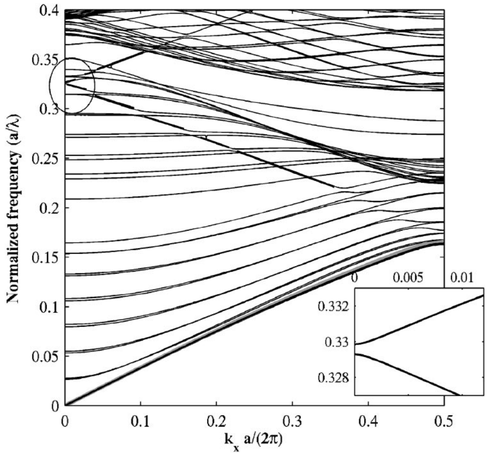

FIG. 1. Band diagram calculated for a square lattice W1 waveguide with an air filling factor of 26% and a dielectric refractive index of 3.21. The supercell size comprises 1×14 periods of the PhC lattice. Inset zoom of the second folding of the fundamental mode. The dispersion curve of the fundamental guided mode is represented in thick line. The light curve (*superimposed on the first branch of the fundamental mode*) is represented in gray.

edges of the Brillouin zone (X and Γ points) since the group velocity is very low and the modal gain is strongly enhanced.[8] However, laser oscillation of modes within the light cone is more probable at the Γ point since vertical radiation losses are smaller at this point: indeed, it is known from previous works on DFB lasers[9,10] that radiation losses can be cancelled out by interference effects at the second folding of the fundamental mode.

In the present work we explore the laser emission around the second folding of the fundamental mode at the Γ point which occurs at the normalized frequency $a/\lambda=0.326$ for an air filling factor of 26% and a dielectric refractive index of 3.21. The inset of Fig. 1 shows the existence of a ministop band around this normalized frequency. However, the calculation of the *H* field shows that only one of the two modes defining the minigap is well localized inside the waveguide (see Fig. 4 hereafter). The other mode spreads in the whole supercell used for the calculation. As a consequence, its normalized frequency depends on the boundary condition and varies with the size of this supercell. For quantifying the mode confinement, we can define the side-lobe intensity suppression ratio (SLISR) as the ratio of the mean intensity outside the guide to the peak intensity in the guide core. The SLISR calculated from the *H*-field distribution is represented for the two dispersion branches in Fig. 2. The SLISR is nearly independent of *k* (~ -10 dB) for the unconfined mode while a strong evolution with *k* is obtained for the confined mode. In this latter case, a *k* variation of $10^{-3}\ \pi/a$ [i.e., a frequency change of only $\Delta(a/\lambda)=1.9\times 10^{-6}$] leads to a SLISR change of ~ 30 dB. All these observations are in agreement with those reported in Refs. 9 and 10. The very low SLISR obtained near $k=0$ for the confined mode (~ -70 dB) means small diffraction effects at the lattice holes and low losses for this mode. In contrast, the losses strongly increase as soon as the mode frequency varies.

Experimentally, the PhC waveguide lasers were fabricated in an InP/InGaAsP/InP laser structure including six quantum wells with a TE polarized emission near 1550 nm. Different lattice periods were used ranging from 320 to 540 nm by steps of 20 nm. The holes were etched around 4 μm deep through the whole semiconductor

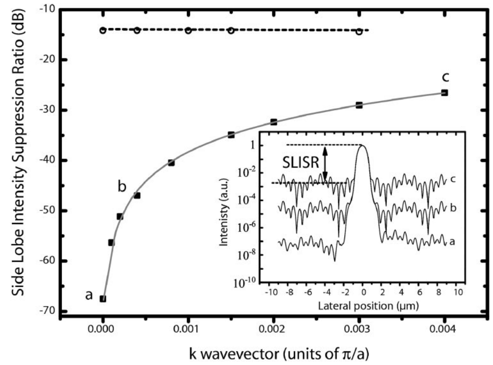

FIG. 2. Side lobe intensity suppression ratio (SLIRS) vs *k* wave vector for the low (black squares) and high (gray open circles) frequency DFB modes. Inset: intensity profiles of the confined mode corresponding to the points *a*, *b*, and *c* of the main figure. In each case, the mode intensity is averaged over one period along the propagation axis.

heterostructure.[11] The filling factor was kept constant and equal to 26% as in the numerical simulations of Fig. 1. The waveguide was about 800 PhC period long, which represents a guide length of 250 μm (resp. 430 μm) for the shortest (resp. the largest) period. The waveguide lasers were ended with a cleaved facet at one side, and a PhC mirror at the other side. The PhC mirror had the same lattice constant, filling factor and orientation as the PhC matrix. For each period, we realized two series of W1 waveguides: one with antireflecting (AR) coating on the cleaved facet and the other one without particular treatment. The PhC waveguides were optically pumped by a pulsed yttrium–aluminum–garnet laser emitting at 1.06 μm. The pulse duration was fixed to 15 ns and the repetition rate to 10 kHz. A cylindrical lens was used to focus the pump beam to a ~ 10 μm width ~ 2 mm long spot. The laser emission was spectrally resolved at the waveguide output using a monochromator. All the experiments were carried out at room temperature.

Figure 3 shows the superimposition of the emission spectra of four W1 lasers with PhC lattice periods equal to 460, 480, 500, and 520 nm, respectively. The lasers are single mode. The emitted wavelength increases from 1420 to 1580 nm when the lattice period, *a*, is varied from 460 to 520 nm. In each case, the normalized frequency (a/λ) is close to 0.327. From a previous work,[4] we can claim that the discrepancy between the measured and calculated

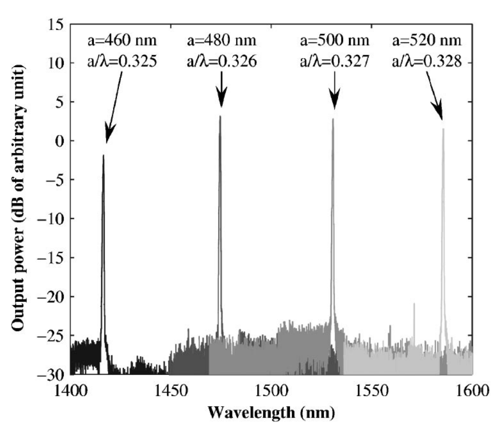

FIG. 3. Superimposition of the emission spectra of four square lattice W1 waveguide lasers with lattice periods of 460, 480, 500, and 520 nm, respectively (from the darker to the lighter gray). For each laser, measurements are performed at pump powers of 1.2 times the threshold.

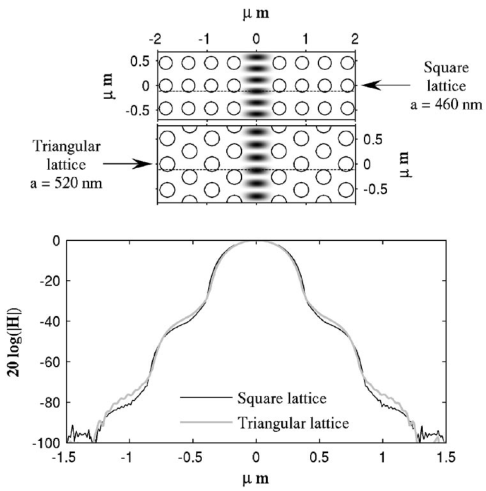

FIG. 4. Top: *H*-field pattern of the fundamental W1 waveguide mode calculated at the frequency of the second folding in the Brillouin zone (Γ point). Upper image: square lattice (PhC period of 460 nm). Lower image: triangular lattice (PhC period of 520 nm). Bottom: mode profiles calculated along the lines of maximum field amplitude (black dashed lines in the top images).

mode frequencies is less than 1%. Since there is only one well-confined mode calculated in the frequency range of interest (Fig. 1, the modes at the X point with similar frequencies are unconfined), we can identify the lasing mode to the fundamental guided mode at the Γ point ($a/\lambda=0.329$ in the calculations). Indeed, the W1 lasers behave like second-order DFB lasers. As expected, the laser threshold depends on the position of the DFB wavelength with respect to that of the gain maximum. The minimum threshold was achieved for the laser emitting at 1530 nm (PhC period of 500 nm), the incident pump power being approximately 1.3 W over a surface of $10\times 400\ \mu m^2$. The thresholds of the lasers with PhC periods of 460, 480, and 520 nm were, respectively, found to be 1.6 and 1.1 times higher than the threshold of the $\lambda=1530$ nm laser. No lasing was observed for periods smaller than 420 nm as the DFB wavelength was too far away from the gain maximum. Even in the case of uncoated samples, no Fabry–Pérot oscillations were detected at the frequencies around the gain maximum, and the side mode suppression ratio was greater than 25 dB whether an AR coating was used or not. This is in agreement with the spectral filtering highlighted by SLISR calculations.

The previous experiments were repeated with triangular lattice PhC W1 waveguides. For this purpose, a second series of devices was fabricated with the same substrate approach, the same lattice periods (from 320 to 540 nm by step of 20 nm) and the same hole diameter, thus leading to an air filling factor of ~30%. However, no laser emission was observed, neither at $k=0$ nor at $k=\pi/a$. The fact that the dispersion curve of the fundamental mode is always above the light curve certainly explains our unsuccessful attempts compared to the recent results obtained in the membrane approach.[1] Besides, for a given lattice period, triangular lattice W1 waveguides are narrower than their square lattice homologues, thereby leading to a lower confinement of the guided modes. Figure 4 compares the field distributions of the fundamental mode calculated at the second folding point in the Brillouin zone, for the two types of waveguides in the particular case where the guides have approximately the same width (square lattice of 460 nm period and triangular lattice of 520 nm period). Although the field distributions are similar, a slightly better confinement is achieved in the square lattice case. Three-dimensional FDTD simulations have been carried out for a comparative estimate of the W1 waveguide losses in the two lattices. The FDTD model used is basically the same as the one described in Ref. 12, while it is extended to simulate periodic waveguides in the substrate approach. The correct implementation of the numerical model has been verified by reproducing recent results reported in Refs. 7 and 12. The model has then been used to compare the losses of a square lattice waveguide with 460 nm period to those of a triangular lattice waveguide with 520 nm period in the substrate approach. The comparative study revealed that the propagation losses near the Γ point were about ten times lower for the square lattice case than for the triangular lattice case. Simulations also indicated that the losses at the Γ point were ten times lower than those calculated at the X point in the range of frequencies between 0.22 and 0.33.

In conclusion, narrow waveguides consisting of a single defect-line (W1) in either square or triangular lattice photonic crystals have been fabricated using the substrate approach on InP. Lasing has been demonstrated from square lattice photonic crystal W1 waveguides under optical pumping. We have shown that these lasers behave as second-order DFB lasers. Side-mode rejection ratios larger than 25 dB were obtained over a wavelength range from 1420 to 1550 nm. Calculations from a two-dimensional plane wave model have confirmed the strong confinement of the fundamental mode at the Γ point. Three-dimensional FDTD simulations have revealed that losses at this point are one order magnitude smaller for the W1 square lattice waveguide than for its triangular homologue.

This work is supported by the French RNRT CRISTEL project.

[1]A. Sugitatsu and S. Noda, Electron. Lett. **39**, 213 (2003).
[2]T. D. Happ, M. Kamp, A. Forchel, J. L. Gentner, and L. Goldstein, Appl. Phys. Lett. **82**, 4 (2003).
[3]S. Mahnkopf, M. Arlt, M. Kamp, V. Colson, G.-H. Duan, and A. Forchel, IEEE Photonics Technol. Lett. **16**, 353 (2004).
[4]X. Checoury, P. Boucaud, J.-M. Lourtioz, F. Pommereau, C. Cuisin, E. Derouin, O. Drisse, L. Legouezigou, F. Lelarge, F. Poingt, G. H. Duan, D. Mulin, S. Bonnefont, O. Gauthier-Lafaye, J. Valentin, F. Lozes, and A. Talneau, Appl. Phys. Lett. **85**, 5502 (2004).
[5]P. Paddon and J. F. Young, Phys. Rev. B **61**, 2090 (2000).
[6]T. Ochiai and K. Sakoda, Phys. Rev. B **63**, 125107 (2001).
[7]L. C. Andreani and M. Agio, Appl. Phys. Lett. **82**, 2011 (2003).
[8]K. Sakoda, *Optical Properties of Photonic Crystals, Opt. Express* (Springer, Heidelberg, 2001).
[9]C. H. Henry, R. F. Kazarinov, R. A. Logan, and R. Yen, IEEE J. Quantum Electron. **21**, 151 (1985).
[10]R. F. Kazarinov and C. H. Henry, IEEE J. Quantum Electron. **21**, 144 (1985).
[11]F. Pommereau, L. Legouézigou, S. Hubert, S. Sainson, J.-P. Chandouineau, S. Fabre, G.-H. Duan, B. Lombardet, R. Ferrini, and R. Houdré, J. Appl. Phys. **95**, 2242 (2004).
[12]Q. Chen, Y.-Z. Huang, W.-H. Guo, and L.-J. Yu, Opt. Commun. (in press).