Photonic-crystal ultrashort bends with improved transmission and low reflection at 1.55 μm

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We propose and demonstrate improved designs in order to increase the transmission level through double 60°-bend photonic-crystal-based waveguides. These bends are defined in a two-dimensional photonic crystal (PC) patterned into a GaInAsP slab on InP substrate. Transmission spectra calculated using a two-dimensional finite difference time domain method that accounts for radiation losses, as well as measurements, demonstrate enhancement of the transmission when moving holes in the corner. As expected a drop in reflection is obtained. The sensitivity to the PC guide width is also evidenced. © *2002 American Institute of Physics.* [DOI: 10.1063/1.1445270]

Due to their photonic band gap, 2D photonic crystals (PC) are promising candidates for waveguiding with strong optical confinement, thus allowing the design of ultracompact bends. Removing rows of holes forms a line defect that localizes light and sustains propagation modes.[1] Propagation through sharp bends has been theoretically assessed,[2] and experimentally observed.[3–5]

Our measurements and simulations concern triangular 2D PC defined by drilling holes through a standard InP-based heterostructure, in order to further integrate active functions at 1.55 μm with PC circuitry for wavelength division multiplexing (WDM) applications. For ultracompact photonic integrated circuits (PIC), ultrashort bends with a high transmission level are a prerequisite. We investigate here the spectral behavior around 1.55 μm of bend channel guides formed by removing 1, 2, or 3 rows of holes—named as W1, W2, and W3. The PC parameters (period $a = 450$ nm, air-filling factor $f = 45\%–50\%$, operating wavelength $\lambda = 1.55$ μm) correspond to operation in the band gap, the band gap being much larger than the WDM band. The choice of hole size and their correlative depth has to be considered with respect to the issue of out-of-plane losses.[6]

The confinement in the vertical direction is provided through total internal reflection in a GSMBE grown 500 nm thick GaInAsP layer, which has a photoluminescence peak at 1.22 μm, and is capped by a 200 nm thick InP protecting layer.[7] The effective index of the guided mode in the unpatterned structure is 3.21. The 2D PC is CH4-based dry etched, the etched depth is limited to 1.1 μm. Channel guides are formed by removing 1, 2, or 3 rows along the ΓK direction. As these passive structures are measured by injecting TE-polarized external light, a reproducible coupling in and out the PC section including the bends is ensured by inserting the PC section between two uniform monomode-TE ridge access guides. The generic double-60° bend is presented in Fig. 1. Together with the bends, an adjacent PC straight guide of equal length is fabricated. Micrographs of the cross section and of the top view are shown in Fig. 1 for a W2-PC guide with three holes displaced at each corner of the double bend.

Measurements are performed using a fiber-to-fiber bench in TE polarization. A constant optical power $P = 0.5$ mW is launched from a tunable source (1500–1590 nm) and collected through microlensed fibers. Transmission spectra through straight PC guides and bends are presented indepen-

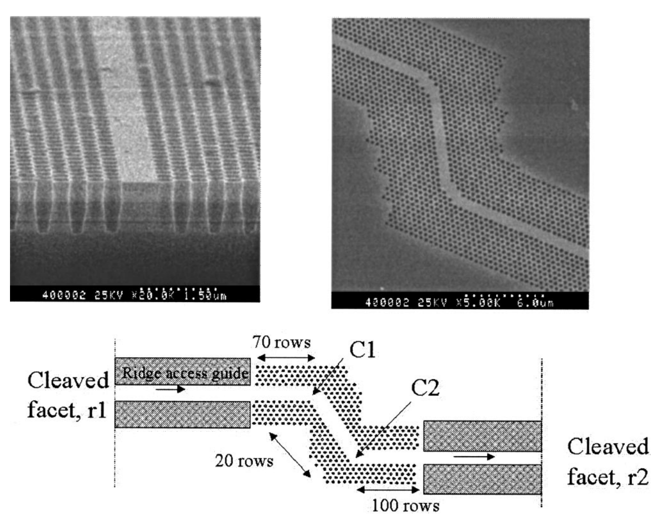

FIG. 1. Cross and top view micrographs of $W2$-PC guide; schematic of the structure measured.

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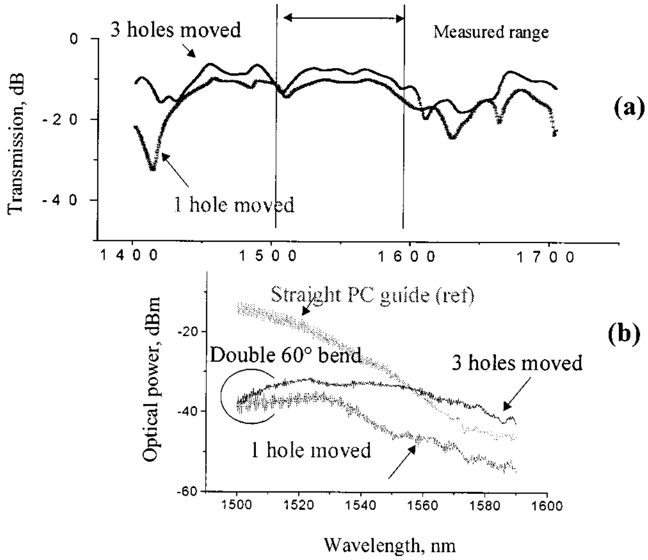

FIG. 2. Three missing lines PC guide (a) simulated transmission for a double-60° bend; (b) measured spectra for a double-60° bend.

dently rather than taking their ratios or smoothing them as will be justified below.

Figure 2 presents the transmission spectra for a W3-PC double-60° bend. The top spectra are the simulated ones, and the bottom are the measured ones. The calculated transmission is obtained through the numerical solution of Maxwell's equations, carried out by means of a 2D finite-difference time-domain (FDTD),[8] implemented with Liao boundary conditions.[9] The fundamental guided mode of the PC guide is excited by an external TE polarized[10] pulse with a field profile devised for optimal coupling. Two line detectors, covering the whole cross section of the PC guide, integrate the incident and outgoing instantaneous Poynting vectors. For the line detector located between the source and the guide at the entrance of the PC guide, a first run is performed without any PC structure, hence without reflection. The other detector is located at the exit of the PC guide after the double bend. Eventually, the Poynting vectors are fast Fourier transformed into the frequency domain. Their ratio yields the transmission spectrum of the bent PC guide. An imaginary part is included for the dielectric constant of the air holes to account for radiation losses.[6] This method has been validated for straight guides.[11] One can wonder how valid this approach is to predict out-of-plane losses at the bend. Since Ref. 2 describes a bend as a potential well, it may be argued that these losses are controlled by the residence time in the well, or, in other words for a bend, by the degree of resonance experienced upon turning. Rattier *et al.*[12] have validated the complex index approach for in-plane PC-based resonant cavities. Both arguments taken together indicate that the present approach should be fairly valid at bends. Namely, large out-of-plane losses at a bend are caused by the time spent "bouncing" against the walls of the bend, i.e., the holes with a complex epsilon.

The measured transmission level between the ridge access guide and the straight PC guide has been previously measured and found to be better than 95%.[13] The straight PC guide spectrum exhibits a dip (ministopband) at large wavelengths (only one side is seen here) that we could attribute to a mode coupling mechanism of the fundamental mode.[14] The double-60° bend with no hole displaced had too poor a transmission (of the order of the photodiode sensitivity: −73 dBm) and is not plotted. Clearly, displacing one and three holes in the corner greatly improves the measured transmission, in agreement with the FDTD simulations. The best fit of the measured spectra is obtained for an air-filling factor of 50%, and an imaginary part of the dielectric constant $\varepsilon''=0.22$. Obviously, these figures point to rather high losses that we attribute to the limited hole depth. The best transmission level (outside the ministop band) leads to losses of 3 dB/bend at 1540 nm, in fair agreement with the simulation prediction.

We now turn to an estimate of bend reflection, an important requirement for use in integrated optics being a low reflection level. Narrow fringes of the measured spectra are associated to a set of weakly interacting cavities. The optical paths of the different cavities are revealed on the Fourier transformed spectrum: the peak with the largest path is related to the total cavity (both ridge access guides +PC guide), the next peak is related to the cavity defined by the left cleaved facet and corner $C1$, and the third one corresponds to the cavity between the right cleaved facet and $C2$. Facet reflectivities $r1$ and $r2$, as well as propagation losses in the ridge access guide α_r and in the PC guides α_{pc} have been measured.[13] Thus, the fringe contrast u (the ratio of minimum to maximum transmitted light intensity) allows to estimate the modal reflection amplitude $r(C1)$ of the PC corner $C1$ [$r(C2)$ for $C2$]:

$$\ln[r1^*r(C1)]-\alpha_r L_r-\alpha_{pc}L_{pc} =\ln[(1-u^{1/2})/(1+u^{1/2})].$$

We assume that $r(C1)$ is not wavelength dependent, which is reasonable as our measured wavelength range lies within the very large PC band gap. The measured reflection in the case of one hole moved, is $r(C1)=0.495$, but drops to a mere $r(C1)=0.126$ in the case of three holes moved, thus considerably reduced. This reflection reduction is also visible on the 2D FDTD simulated field patterns in Fig. 3; a single

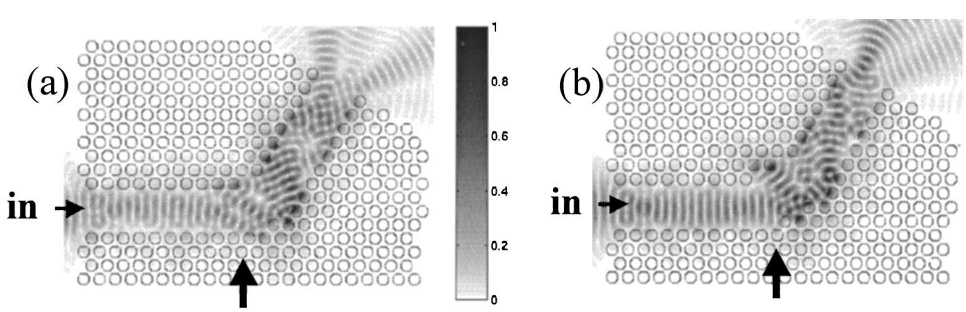

FIG. 3. Field pattern for one 60° bend (a) one hole moved; (b) three holes moved.

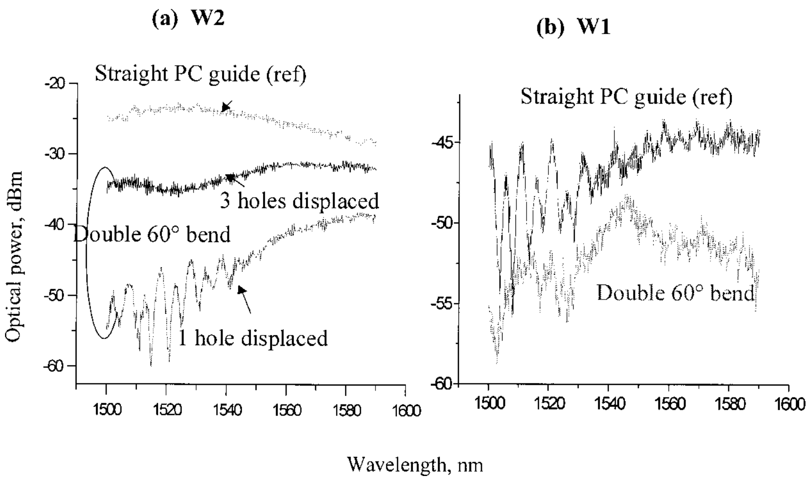

FIG. 4. (a) Two missing lines PC double-60° bend; (b) one missing line PC double-60° bend.

60° bend is considered here. The field in the arrowed region at the entrance of the bend is cleaner in case (b), three moved holes. We can also notice in both corner designs the mode conversion towards higher order modes responsible for the washing out of the ministopband clearly visible on the measured transmission of Fig. 2.

In the case of a two-missing-rows guiding configuration $W2$, we again measured the transmission spectra [Fig. 4(a)] in the three cases zero, one, and three moved holes, but again do not plot the case with no hole moved. The losses are reduced here to 2.25 dB/bend at 1580 nm. In the case of a single-missing-row guiding structure $W1$ and 1 hole moved [Fig. 4-(b)], losses are further reduced to 1.5 dB/bend at 1545 nm.

Moving holes in the corner of a PC bend is found, thus, to be very efficient in increasing the transmission, as corroborated by FDTD simulations. This improvement is stronger in the case of $W2$ than $W3$, as $W2$ is a narrower PC guide, thus supporting a lower number of modes. Obviously, the narrowest PC guide—$W1$—leads to the lower bending losses, as in this case conversion to higher order mode is very limited. As far as absolute transmission levels are concerned, one has to consider that the hole depth is relatively modest, as confirmed by the effective simulated loss parameters $\varepsilon''=0.22$. This can lead to important coupling to substrate modes. A great effort is currently undertaken for improving the etching technique. A first estimation of the reflection coefficient at the corner has demonstrated that this severe drawback of basic PC bends can be substantially reduced in the improved designs, while not being small enough. Improved designs are under investigation for further reducing these reflections and limiting mode conversion.

We measured and simulated ultrashort double-60° bends defined on 2D PC guiding structures patterned on a GaInAsP slab on InP substrate. Reflections at the corner have also been measured, and optimized designs have been measured and simulated to reduce these reflections. Also, the effect of the PC waveguide width is clearly demonstrated. The narrower the PC guide, one missing row, the lower the bending losses.

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