Transmission Measurement of Tapered Single-Line Defect Photonic Crystal Waveguides

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Abstract—Two-dimensional tapered single-line defect photonic crystal (PC) waveguides were fabricated with coupled ridge waveguides in InP–InGaAsP and optical transmission characteristics measured. Three different taper designs that optimized both mode size match and impedance match between the accessing ridge waveguides and the PC waveguides were fabricated and characterized. An ~8-dB improvement of coupling efficiency was observed for the tapered structures over untapered.

Index Terms—Integrated optics, photonic crystals (PCs), waveguides.

I. INTRODUCTION

PHOTONIC crystal (PC) waveguides are currently under investigation, with promises of low-loss guiding around sharp bends, slow group velocities, and large dispersion, as well as enhancement of nonlinear phenomena [1]–[4]. In view of all these possibilities, these structures are good candidates for application in highly integrated photonic circuits. A great amount of work has been devoted to reducing transmission losses in the PC waveguides, and recently, propagation loss on the order of 1 dB/mm has been achieved [5]. Future integrated circuits will require integration of low-loss PC waveguides with other types of passive and active integrated photonic structures like lasers, switches, etc. Therefore, the efficient coupling of light into and out of PC waveguides from fibers and integrated waveguides is a critical requirement.

Coupling the light into a single line defect PC waveguide, either from air or butt-coupled waveguides, is especially difficult. To avoid substantial coupling losses, the propagating signals should be matched both in real space and in momentum space. This latter requirement pertains to the use of PC “delay lines” where slow wave propagation in PC waveguides has shown a reduced group velocity to less than 0.01c [6]. In order to enhance the coupling into and out of the PC waveguides, various coupling techniques have been proposed, such as tapered waveguides [5], [7], evanescent coupling [8], or PC taper structures [9]–[13]. The PC taper structures are typically more compact and, therefore, good for integration. Several PC taper designs have been tested [12]–[15], but systematic investigation of various taper schemes is still in demand. In this work, InP-based single-line-defect membrane PC waveguides with and without tapers were designed, fabricated, and tested. Coupling of light into and out of the membrane PC waveguides was realized by butt-coupled access ridge waveguides. Three different kinds of PC taper structures were investigated to try to improve the coupling efficiency between the access ridge waveguides and PC waveguides. This work is an initial step toward incorporation of PC into standard photonic integrated circuits at 1550 nm.

II. DEVICE FABRICATION

The two-dimensional (2-D) PCs consist of a triangular array of holes etched into a 350-nm-thick InGaAsP slab. A lattice constant of $a = 400$ nm was chosen to place the fundamental gap-guided mode at around 1550 nm. The holes were defined by electron beam (E-beam) lithography and etched into the InP–InGaAsP by reactive ion etching using methane-hydrogen-argon [16]. The etching was done at 55 mT, with MHA 420/10 sccm, bias at 500 V, with frequent oxygen cycling to ensure a good sidewall profile. The InP substrate was removed in a subsequent step by selective wet etching to create the thin membrane with air cladding for vertical optical confinement. A PC channel waveguide $W_1$ is created by omitting “n” line of holes along the $\Gamma$K direction from 2-D PCs. $W_1$ PC waveguides integrated with a 1-$\mu$m ridge waveguide were fabricated. The 1-$\mu$m ridge waveguide is further tapered to 3 $\mu$m for a better coupling to a lensed fiber. The sample was thinned and cleaved, and antireflection coating was applied on the cleaved facets to prevent Fabry–Pérot fringes.

III. CHARACTERIZATION AND RESULTS

The photonic band structure was calculated by using the MIT photonic band program [17]. Lattice constant $a = 400$ nm, membrane thickness $h = 350$ nm, and refractive index $n = 3.4$ were used in the calculation. The air hole size used here was such that $r/a = 0.35$, as measured from the scanning electron microscope (SEM). For the transverse-electric (TE)-like mode, bulk PCs like this will open a photonic bandgap between $a/\lambda \approx 0.258$ and 0.373. $W_1$ PC waveguides were created by omitting one line of air holes along the $\Gamma$K direction from 2-D PCs. The band diagram is plotted in Fig. 1(a). The shaded region indicates the bandgap region of the corresponding bulk PC, extending from 0.258 to 0.373 in normalized frequency, or 1550–1072 nm in wavelength. The solid line in the graph is the light line, above which all modes are leaky. Nonleaky waveguide modes can be found within the photonic bandgap from $a/\lambda \approx 0.261$ to 0.273, (corresponding to wavelengths between 1532 and 1465 nm). These are zeroth order, symmetric modes, into which coupling is desired. In the region between 0.255 and 0.261, which corresponds to 1532–1566 nm in wavelength, no confined modes exist.
The waveguides were characterized by transmission measurements using an external source. Light from a tunable laser source was TE polarized and coupled into the device under test with a lensed fiber. The output beam was collected with an infinity-corrected high-numerical aperture (NA = 0.75) microscope objective and the spectrum recorded using an HP Wavelength-Domain Component Analyzer. With this set up, an alignment error of less than 1.5 dB from device to device was achieved, which is critical for a meaningful comparison of coupling loss between different devices. The measured transmission spectra of the waveguides were normalized to the spectrum, plotted in Fig. 1(b), of a conventional 1-μm-wide ridge-waveguide fabricated on the same sample.

Fig. 1(b) shows the spectrum obtained from measurement of a simple W1 waveguide. The sharp increase in transmission at \( \lambda \sim 1530 \text{ nm} \) can be correlated with the onset of the nonleaky waveguide mode band. The relatively small transmission for wavelengths longer than \( \lambda \sim 1565 \text{ nm} \) is related to the lossy slab modes in the dielectric band of the PCs. The extremely low transmitted power for wavelengths between \( \lambda = 1530 \text{ nm} \) and \( \lambda = 1565 \text{ nm} \) is correlated with the stopband on the band diagram, where no modes exist below the light line.

Even though there is a good agreement between theory (band diagram) and experiment, the transmitted power through the W1 guide was observed to be about 8 dB lower than that of the reference waveguide. We believe that the main reason for this loss is the slow coupling between the 1-μm ridge waveguide and the W1 PC waveguide. The large coupling loss results from the mode mismatch between the W1 PC waveguide and the 1-μm index-guided ridge waveguide. In the W1 PC waveguides, a typical mode size is about \( 0.4 \times 0.3 \text{ μm}^2 \), which is much smaller than the mode size in the 1-μm ridge waveguide. The spatial mode-mismatch between the index-guided waveguide and the PC waveguide results in a large coupling loss. There is an additional mismatch in the propagating modes: At the long wavelength region near the band edge of the W1 PC waveguide mode, there is a greatly reduced propagation speed. We must, therefore, also account for the impedance mismatch caused by the large group velocity difference between the conventional 1-μm index-guided waveguide and the PC waveguide.

In order to enhance the coupling efficiency, different taper structures were investigated. The large spatial mode-mismatch can be improved by introducing a more gradual spatial accommodation between index guided and PC waveguides. To improve the mismatch in group velocities between the conventional and the slow wave PC structure, gradually varying PC radii \( r \) can be used. If the lattice constant \( a \) is held constant, the increase in \( r \), and hence \( r/a \), results in a reduced effective refractive index of the slab, thus shifting the photonic bands toward higher frequencies. Thus, for light propagating at a fixed frequency \( \omega_0 \), the effect of gradually increasing the hole-size along the direction of propagation, is to change the position of \( \omega_0 \) on the dispersion curve. The net result is a gradual matching of the group velocity [18].

Devices with the three different taper designs were fabricated, consisting of 80-μm-long W1 waveguides with tapered ends and 1-μm-wide accessing ridge waveguide on both sides. The nontapered W1 PC waveguide is shown in Fig. 2(a). The lattice constant \( a \) is 400 nm, the same as for the previously described waveguide; however, a smaller \( r/a \) ratio of 0.31 was used to ensure a wider range of the nonleaky waveguide mode, both in the normal group velocity region and the low group velocity region, can be covered by the tunable laser.

The Type 1 taper provides a less abrupt spatial mode match, together with a better impedance (velocity) matching. As shown in Fig. 2(b), light is first coupled from the accessing ridge to a seven-period-long W3 PC waveguide and then into the W1 waveguide by a progressive increase (over eight periods) of \( r \) of the two inner lines of holes. Note that the effective index change is, therefore, confined to the periphery of the waveguide. The total taper length is approximately 6 μm.

The Type 2 taper, as shown in Fig. 2(c), attempts to create a better, more gradual spatial mode matching, and is formed by lattice distortion: Starting from a W1 PC waveguide, each row of holes is shifted outwards in steps of 10 nm along its 15 periods, the defect width finally matching that of the 1-μm access ridge waveguide. In this fashion, a smoother mode-size conversion is expected. There is no deliberate variation of hole size.

Finally, the Type 3 taper [Fig. 2(d)] attempts to achieve better mode matching both spatially and with respect to velocity. Similar to the Type 2 taper, the lattice is distorted along a 15-period region by shifting each row of holes outwards, accompanied by a row-by-row variation in \( r \), so that the \( r/a \) ranges from 0.28 to...
0.31. In this case, a gradual change in effective index applies to the broader lateral region surrounding the PC waveguide.

Fig. 3 shows a comparison of the transmission spectra of these four waveguides. The transmission through an untapered PC waveguide introduced a loss of about 8 dB over that of a 1-μm-wide conventional ridge waveguide. In the short-wavelength region, the loss is believed to be due primarily to the mode-mismatch between the W1 PC waveguide and the 1-μm access waveguide. The Type 1 taper yielded a transmission enhancement of about 4 dB over that of the untapered W1 in the long-wavelength (>1600 nm) region; however, there is no improvement at shorter wavelengths. We believe the improvement results from better impedance matching between the W1 and W3 guides at longer wavelengths approaching the band-edge due to the progressive increase of r of the two inner lines of holes. For the shorter wavelengths, losses are mostly due to spatial mode-mismatch, since the taper is rather abrupt.

With the Type 2 taper, a maximum transmission close to unity was observed, corresponding to an enhancement of about 8 dB compared to the untapered W1 waveguide. This improved coupling, however, happened mostly in the short-wavelength region, while at wavelengths near the mode cutoff the improvement is actually less than that achieved with the Type 1 taper. In this design, the coupling enhancement is mostly due to a better spatial matching of the ridge mode profile to that of the PC waveguide. Since there was no alteration of r/a, the impedance matching close to the band-edge is not very effective.

With the Type 3 taper, at the short-wavelength region, the transmission shows the same features as the Type 2 taper waveguide, with a transmission improvement at both the shorter wavelengths, and at longer wavelengths, near the mode cutoff. The Type 3 taper yields a further improvement of coupling efficiency of about 3 dB, as compared to the Type 2 taper.

The problems for the Types 2 and 3 taper structures are clearly the periodic minima in transmission, even though the overall transmission of the PC waveguide was enhanced by ~8 dB at most wavelengths. We believed that those deep dips are most likely due to the multimode nature of the taper. Because of the increased channel width in the taper region, there are higher order modes available in the taper section which might cause mini gaps at certain wavelength [19]. More work is needed to clearly identify the nature of those resonance dips and to optimize the taper structure to ensure a flat transmission versus wavelength of the PC waveguide.

IV. SUMMARY

We have designed, fabricated and characterized single line defect PC waveguides on InP-based material. Three types of taper designs were fabricated and characterized: spatial mode-match, group velocity matched, and combined spatial-velocity matched. With proper taper design, an overall coupling efficiency enhancement of ~8 dB was achieved. Further optimization of the taper structure is needed to ensure a flat transmission versus wavelength of the PC waveguide.

REFERENCES