Experimental Demonstration of High Coupling Efficiency Between Wide Ridge Waveguides and Single-Mode Photonic Crystal Waveguides

P. Sanchis, J. García, J. Martí, W. Bogaerts, P. Dumon, D. Taillaert, R. Baets, V. Wiaux, J. Wouters, and S. Beckx

***Abstract*—The experimental demonstration of a high efficiency coupling technique based on setting a single defect within a photonic crystal (PhC) taper is reported. The samples were fabricated on a Silicon-on-insulator substrate and a 3-μm-wide ridge waveguide was used to couple the light into and out of a single-mode PhC waveguide. Transmission efficiencies higher than 70% for wavelengths at 1.55 μm are demonstrated which sharply improves the transmission efficiency achieved with butt-coupling and conventional PhC tapers.**

***Index Terms*—Coupling losses, photonic crystals (PhC), tapers.**

I. INTRODUCTION

PHOTONIC CRYSTALS (PhC) have been the subject of an increasing research effort in order to develop microscale photonic integrated circuits [1]. However, a highly efficient coupling from an external medium (dielectric waveguide or fiber) is mandatory to ensure their optimum performance. Coupling losses between conventional waveguides and line-defect PhC waveguides are originated due to the mode mismatch in both kinds of waveguide. Furthermore, the existence of coupling to radiation modes in the vertical direction (out-of-plane losses) can also contribute to the degradation of the coupling efficiency in planar PhC. Therefore, a large variety of coupling techniques for efficient interfacing conventional waveguides with PhC waveguides have been proposed. PhC tapers have shown high coupling efficiencies and small coupling lengths [2]. Recently, different configurations of PhC tapers have been experimentally demonstrated. Transmission efficiencies from 50% to 90% have been reported for PhC tapers based on progressively varying holes radii [3], [4], continuous tapering and lattice distortion [5], and by removing some air holes from the original PhC waveguide [6]. However, those experiments were all carried out in III–V composites in which the width of the ridge access waveguides was only about 1–2 μm and multimode single-line defect PhC waveguides were used. Recently, it was proposed that higher transmission efficiencies between wide dielectric and PhC waveguides can be achieved in a broad and flat transmission spectrum by appropriately inserting localized defects within a PhC taper [7]. In this letter, the experimental demonstration of this coupling technique by using an air-hole PhC structure fabricated in a Silicon-on-insulator (SOI) substrate is presented. SOI is a promising approach to develop PhC-based microscale integrated circuits and very low propagation losses have been recently reported [8]. High-index contrast in the vertical direction is used in SOI structures while low-index contrast is used in classic III–V heterostructures. Scattering in defects (such as cavities, bends, etc.,) is much higher in the former than in the latter [9]. Therefore, the performance of a certain coupling technique may be very different in both kinds of structures. On the other hand, a 3-μm-wide ridge access waveguide has been used and single-mode transmission in the PhC waveguide has been ensured by using a line-defect PhC waveguide of reduced width [10].

II. SIMULATIONS

The structure considered is formed by an input dielectric waveguide coupled to a line-defect PhC waveguide. The bulk PhC is a two-dimensional (2-D) triangular array of air holes in a dielectric background of Silicon. We use the effective index approximation ($n_{\text{eff}} = 2.8$) for the vertical direction and a hole radius of $R = 0.3a$, where a is the lattice constant. The effective index was calculated for a thickness of the Silicon layer of 220 nm in agreement with the fabricated structure. This approach allows us to design the fabricated structure by means of 2-D finite-difference time-domain simulations [11]. However, discrepancies between experimental and 2-D simulation results may occur, especially because out-of-plane losses, which can only be evaluated by means of three-dimensional (3-D) simulations, are not taken into account.

A line-defect PhC waveguide of a reduced width of $0.6W$, where W is the width of the single-line missing-hole defect waveguide, was chosen in order to obtain single-mode transmission [10]. A lattice constant of $a = 435$ nm has been used for transmission in the wavelength band of 1.55 μm. The width of the dielectric waveguide is 3 μm with a surrounding medium of

---

Manuscript received February 20, 2004; revised May 14, 2004. This work was suppoted in part by the Spanish Ministry of Science and Technology under Grant TIC2002-01553, in part by the Generalitat Valenciana, and in part by the European IST-PICCO Project. The work of P. Sanchis was supported by a grant from Spanish Ministry of Education, Culture and Sport. The work of W. Bogaerts and P. Dumon was supported by a specialization grant from the Flemish Institute for the Industrial Advancement of Scientific and Technological Research (IWT).

P. Sanchis, J. García, and J. Martí are with the Fiber-Radio Group, Valencia Nanophotonics Technology Center, Universidad Politécnica de Valencia, 46022 Valencia, Spain (e-mail: pabsanki@ntc.upv.es).

W. Bogaerts, P. Dumon, D. Taillaert, and R. Baets are with the Department of Information Technology, Ghent University-IMEC, B-9000 Ghent, Belgium.

V. Wiaux, J. Wouters, and S. Beckx are with the IMEC vzw. Silicon Processing Technology Division, B-3001 Leuven, Belgium.

Digital Object Identifier 10.1109/LPT.2004.833915

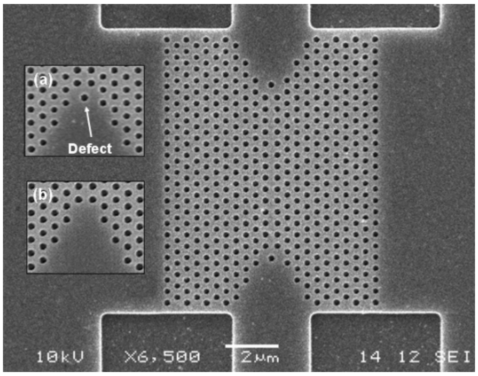

Fig. 1. Scanning electron micrograph of the fabricated structure. The insets show a detailed view of the PhC taper (a) with and (b) without the defect.

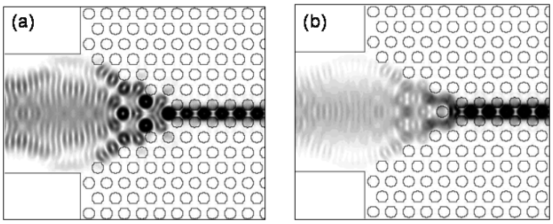

Fig. 2. Magnitude of the Poynting vector for the PhC taper structures (a) without and (b) with defect for the wavelength of 1.55 μm.

air. The PhC taper considered is shown in Fig. 1. The insets show a detailed view of the PhC taper [Fig. 1(a)] with and [Fig. 1(b)] without the optimized defect. In order to design the optimum parameters of the defect, we follow the approach reported in [7]. In a first step, the defect position along the waveguide axis within the PhC taper was obtained. Then, the optimum defect radius at the previously calculated optimum position was calculated. Thereby, a transmission efficiency of 72% was obtained by inserting within the PhC taper a defect with radius $r = R$ at $z = 3.9a$, with $z = 0$ the first column of holes that form the PhC taper. The introduction of the defect significantly improves the transmission efficiency regarding the PhC without taper, in which the transmission efficiency is only 44%, and the butt-coupled case, in which the transmission efficiency is 36%. The introduction of the defect within the PhC taper alters the modal properties of the modes so that mode matching is achieved. This can be seen in Fig. 2 which shows the magnitude of the Poynting vector for the PhC taper structure with and without defect. In Fig. 2(a), it can be seen that resonant states are excited within the PhC taper which increase coupling losses. Resonant states are eliminated with the introduction of the defect [see Fig. 2(b)] improving, thus, the coupling efficiency.

On the other hand, the optimum parameters of the defect were designed to achieve the highest transmission for the wavelength of 1.55 μm. Fig. 3 shows the simulated transmission spectra as a function of the wavelength for the butt-coupled and the PhC taper structures without and with the optimized defect of a finite length PhC waveguide. A length of $24a$ and $14a$ was considered for the butt-coupled and PhC taper structures, respectively, in agreement with those used in the fabricated structures. The transmission spectra have also only been plotted between 1500 and 1600 nm to compare with experimental results. From the results presented in Fig. 3, it can be seen that the transmission spectrum for the PhC taper with defect significantly improves the other two cases.

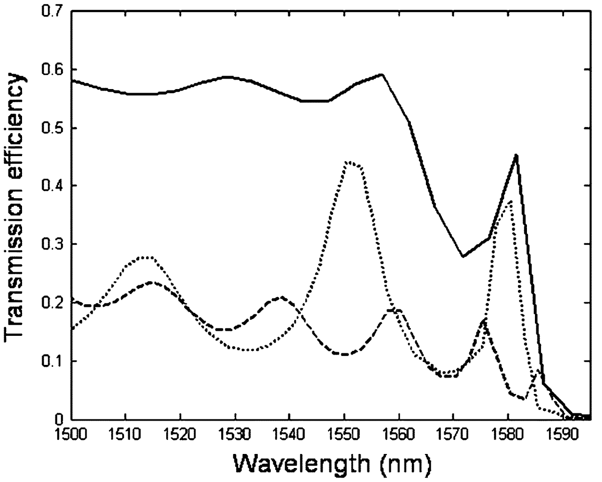

Fig. 3. Simulated transmission spectra as a function of the wavelength for a PhC waveguide of finite length. The dashed, solid, and dotted lines represent the butt-coupled and PhC taper structures with and without the optimized defect, respectively.

III. EXPERIMENTS

The samples were fabricated on an 8$''$ SOI wafer using 248-nm deep ultraviolet lithography [12], [13]. A top Silicon layer with a thickness of 220 nm on a silica layer with thickness of 1 μm was used. The illumination conditions were varied for each die to obtain repetitions of the same designs with different hole radius. In this case, only the Silicon film was etched in order to reduce propagation losses due to roughness. The transmission as a function of wavelength was measured using an end-fire technique. Light from a tunable laser source was coupled in the ridge waveguide using a lensed fiber. The output power of the laser was 1 mW (0 dBm). The output light was collected by an objective onto a power detector. A polarizer selecting the transverse-electric polarization and a diaphragm to collect only the output light from the ridge waveguide were used before the power detector.

The butt-coupled and PhC taper structures with and without the optimized defect structures were fabricated and measured. A 3-μm-wide ridge waveguide was used to couple light into and out of the PhC waveguide. In principle, the optimum waveguide width to achieve the maximum transmission with butt-coupling is 1.5 μm, however, even in this case the transmission efficiency is still of 60%. On the other hand, an efficient coupling from a wider dielectric waveguide implies a reduction of the conversion ratio in the horizontal direction needed to couple from a fiber, which typically has a thickness between 8 and 10 μm, allowing the design of compact spot size converters. In this case, the multimode behavior of the waveguide has little effect as long as high coupling efficiency into the PhC waveguide is ensured. Obviously, this approach does not resolve the mismatch between the fiber and the PhC waveguide in the vertical direction. One possible approach to overcome this mismatch could be to use grating couplers [13].

Fig. 4 shows the experimental results. Fig. 4(a) shows the power transmission for the unpatterned sample which consists only of a ridge waveguide without the PhC. Fig. 4(b)–(d) shows

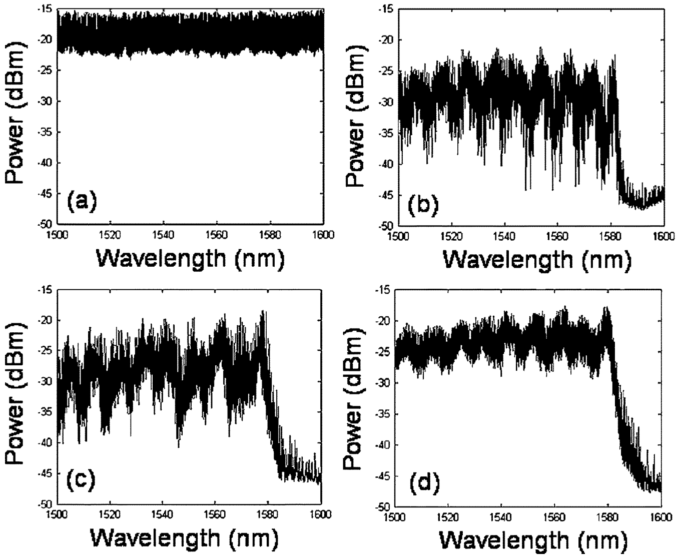

Fig. 4. Experimental transmission spectrum as a function of the wavelength for (a) the unpatterned structure, (b) the butt-coupled structure, and the PhC taper structure (c) without and (d) with the optimized defect.

the power transmission for the butt-coupled and PhC taper structures without and with the optimized defect, respectively. The small length of the PhC waveguide allows us to analyze the coupling efficiency above the light line though it can be seen that the transmitted power decreases at lower wavelengths. Although there are notable Fabry–Pérot resonances in the transmission spectra due to the inefficient coupling into and out the ridge waveguide, experimental results demonstrate a significant power transmission improvement (around 5 dB) when the PhC taper with defect is used compared to the butt-coupled and PhC taper without defect structures. Furthermore, a good correspondence can be seen with the simulations results shown in Fig. 3. For the PhC taper without defect, the power transmission is only improved in small wavelength ranges. However, it can be seen that for the PhC taper with defect, a reduction of the Fabry–Pérot resonances in the transmission spectrum comparable to those obtained for the unpatterned sample is achieved. Furthermore, transmission efficiencies t near 60% for wavelengths around 1.55 μm were obtained by normalizing the transmission spectrum of the PhC taper with defect structure with the transmission spectrum of the unpatterned structure after averaging both spectra. On the other hand, transmission efficiencies lower than 40% and 30% were obtained for the PhC taper without defect and the butt-coupled structures, respectively. It should be noted that this estimation of the transmission efficiency may be underestimated as they implicitly include the PhC propagation losses. However, we measure low propagation losses in the PhC, especially near the band edge (below the light line). Therefore, propagation losses can be neglected due to the small length of the PhC waveguide so that a good estimation of the transmission efficiency will be achieved by normalizing the transmission spectra. Therefore, it can be concluded that the coupling efficiency between the ridge dielectric waveguide and the PhC waveguide $T = \sqrt{t}$ will be around 75% for wavelengths at 1.55 μm for the PhC taper with defect structure. The good agreement between experimental and 2-D simulations results seems to indicate that out-of-plane losses are rather low. Furthermore, good agreement was achieved in the three measured structures: the butt-coupled and the PhC taper structures with and without defect. However, these results must be corroborated by performing 3-D simulations.

IV. CONCLUSION

The experimental demonstration of a high efficiency coupling technique based on setting a single defect within a PhC taper has been reported. The coupling efficiency of $\sim$75% could be improved if a more optimum defects configuration is obtained by using better optimization tools (e.g., genetic algorithms [14]). Finally, the obtained results confirm the usefulness of the coupling technique for PhC structures formed by air holes in a high-index dielectric background.

REFERENCES

[1] J. D. Joannopoulos, R. D. Meade, and J. N. Winn, *Photonic Crystals*. Princeton, NJ: Princeton Univ. Press, 1995.

[2] T. D. Happ, M. Kamp, and A. Forchel, "Photonic crystal tapers for ultracompact mode conversion," *Opt. Lett.*, vol. 26, pp. 1102–1104, 2001.

[3] A. Talneau, Ph. Lalanne, M. Agio, and C. M. Soukoulis, "Low-reflection photonic-crystal taper for efficient coupling between guide sections of arbitrary widths," *Opt. Lett.*, vol. 27, pp. 1522–1524, 2002.

[4] A. Talneau, M. Mulot, S. Anand, and Ph. Lalanne, "Compound cavity measurements of transmission and reflection of a tapered single-line photonic crystal waveguide," *Appl. Phys. Lett.*, vol. 82, pp. 2577–2579, 2003.

[5] P. Pottier, I. Ntakis, and R. M. De La Rue, "Photonic crystal continuous taper for low-loss direct coupling into 2D photonic crystal channel waveguides and further device functionality," *Opt. Commun.*, vol. 223, pp. 339–347, 2003.

[6] M. Dinu, R. L. Willett, K. Baldwin, L. N. Pfeiffer, and K. W. West, "Waveguide tapers and waveguide bends in AlGaAs-based two-dimensional photonic crystals," *Appl. Phys. Lett.*, vol. 83, pp. 4471–4473, 2003.

[7] P. Sanchis, J. Martí, J. Blasco, A. Martínez, and A. García, "Mode matching technique for highly efficienct coupling between dielectric waveguides and planar photonic crystal circuits," *Opt. Express*, vol. 10, pp. 1391–1397, 2002.

[8] S. J. McNab, N. Moll, and Y. A. Vlasov, "Ultra-low loss photonic integrated circuit with membrane-type photonic crystal waveguides," *Opt. Express*, vol. 11, pp. 2927–2939, 2003.

[9] W. Bogaerts, P. Bienstman, D. Taillaert, R. Baets, and D. De Zutter, "Out-of-plane scattering in photonic crystal slabs," *IEEE Photon. Technol. Lett.*, vol. 13, pp. 565–567, June 2001.

[10] M. Notomi, A. Shinya, K. Yamada, J. Takahashi, C. Takahashi, and I. Yokohama, "Singlemode transmission within photonic bandgap of width-varied single-line-defect photonic crystal waveguides on SOI substrates," *Electron. Lett.*, vol. 37, pp. 293–295, 2001.

[11] A. Taflove, *Computational Electrodynamics: The Finite-Difference Time-Domain Method*. Norwood, MA: Artech House, 1995.

[12] W. Bogaerts, V. Wiaux, D. Taillaert, S. Beckx, B. Luyssaert, P. Bienstman, and R. Baets, "Fabrication of photonic crystals in silicon-on-insulator using 248-nm deep UV lithography," *IEEE J. Select. Topics Quantum Electron.*, vol. 8, pp. 928–934, July/Aug. 2002.

[13] W. Bogaerts, D. Taillaert, B. Luyssaert, P. Dumon, J. Van Campenhout, P. Bienstman, D. Van Thourhout, R. Baets, V. Wiaux, and S. Beckx, "Basic structures for photonic integrated circuits in silicon-on-insulator," *Opt. Express*, vol. 12, pp. 1583–1591, 2004.

[14] J. Jiang, J. Cai, G. P. Nordin, and L. Li, "Parallel microgenetic algorithm design for photonic crystal and waveguide structures," *Opt. Lett.*, vol. 28, pp. 2381–2383, 2003.