# Enhancing alignment tolerance of silicon waveguide by using a wide grating coupler

**Jong-Moo Lee,[1] Kap-Joong Kim[1,2] and Gyungock Kim[1]**

[1]*Electronics and Telecommunications Research Institute, 161 Gajong-dong, Yusong-gu, Daejeon, 305-350, Korea*[2]*Department of Physics, KAIST, 373-1 Guseong-dong, Yuseong-gu, Daejeon, 305-701, Korea*
*jongmool@etri.re.kr*

**Abstract:** We fabricate a 20 µm wide grating coupler for a single-mode thermally-expanded-core (TEC) fiber, in order to enhance positional tolerance in alignment. The minimal coupling loss is measured at 5 dB per facet and the optical 3 dB bandwidth is measured at 40 nm. The 3 dB alignment tolerance is measured at ± 7.5 µm in horizontal direction and +290 µm in vertical direction. The 1 dB alignment tolerance is measured at ± 4.2 µm in horizontal direction and +125 µm in vertical direction. The alignment tolerance is enhanced twice in horizontal direction and four times in vertical direction, compared with the coupling of a standard single-mode fiber to a standard 10 µm wide grating coupler which is also fabricated in this experiment.



**OCIS codes:** (230.7390) waveguides, planar; (130.3120) Integrated optics devices; (050.2770) Gratings.

## References and links

1. K. Shiraishi, H. Yoda, A. Ohshima, H. Ikedo, and C. S. Tsai, "A silicon-based spot-size converter between single-mode fibers and Si-wire waveguides using cascaded tapers," Appl. Phys. Lett. **91**, 141120 (2007).
2. V. Nguyen, T. Montalbo, C. Manolatou, A. Agarwal, C. Hong, J. Yasaitis, L. C. Kimerling, and J. Michel, "Silicon-based highly-efficient fiber-to-waveguide coupler for high index contrast systems," Appl. Phys. Lett. **88**, 081112 (2006).
3. R. Orobtchouk, A. Layadi, H. Gualous, D. Pascal, A. Koster, and S. Laval, "High-efficiency light coupling in a submicrometric silicon-on-insulator waveguide," Appl. Opt. **39**, 5773-5777 (2000).
4. D. Taillaert, W. Bogaerts, P. Bienstman, T. F. Krauss, P. Van Daele, I. Moerman, S. Verstuyft, K. De Mesel, and R. Baets, "An Out-of-Plane Grating Coupler for Efficient Butt-Coupling Between Compact Planar Waveguides and Single-Mode Fibers," IEEE Photon. Technol. Lett. **38**, 949-951 (2002).
5. S. Lardenois, D. Pascal, L. Vivien, E. Cassan, and S. Laval, R. Orobtchouk, M. Heitzmann, N. Bouzaida, and L. Mollard, "Low-loss submicrometer silicon-on-insulator rib waveguides and corner mirrors," Opt. Lett. **28**, 1150-1152 (2003).
6. D. Taillaert, H. Chong, P. I. Borel, L. H. Frandsen, R. M. De La Rue, and R. Baets, "A Compact Two-Dimensional Grating Coupler Used as a Polarization Splitter," IEEE Photon. Technol. Lett. **15**, 1249-1251 (2003).
7. D. Taillaert, P. Bienstman, and R. Baets, "Compact efficient broadband grating coupler for silicon-on-insulator waveguides," Opt. Lett. **29**, 2749-2751 (2004).
8. 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 **12**, 1583-1591 (2004).
9. W. Bogaerts, R. Baets, P. Dumon, V. Wiaux, S. Beckx, D. Taillaert, B. Luyssaert, J. Van Campenhout, P. Bienstman, D. Van Thourhout, "Nanophotonic Waveguides in Silicon-on-Insulator Fabricated With CMOS Technology," J. Lightwave Technol. **23**, 401-412 (2005).
10. D. Taillaert, F. Van Laere, M. Ayre, W. Bogaerts, D. Van Thourhout, P. Bienstman, and R. Baets, "Grating Couplers for Coupling between Optical Fibers and Nanophotonic Waveguides," Jpn. J. Appl. Phys. **45**, 6071–6077 (2006).
11. P. Dumon, W. Bogaerts, D. Van Thourhout, D. Taillaert, R. Baets, J.Wouters, S. Beckx, and P. Jaenen, "Compact wavelength router based on a Silicon-on-insulator arrayed waveguide grating pigtailed to a fiber array," Opt. Express **14**, 664-669 (2006).
12. L. Vivien, D. Pascal, S. Lardenois, D. Marris-Morini, E. Cassan, F. Grillot, S. Laval, J. Fédéli, and L. Melhaoui, "Light Injection in SOI Microwaveguides Using High-Efficiency Grating Couplers," J. Lightwave Technol. **24**, 3810-3815 (2006).

#97195 - $15.00 USD Received 9 Jun 2008; revised 7 Aug 2008; accepted 8 Aug 2008; published 11 Aug 2008

13. G. Roelkens, D. Van Thourhout, and R. Baets, "High efficiency Silicon-on-Insulator grating coupler based on a poly-Silicon overlay," Opt. Express **14**, 11622-11630 (2006).
14. W. Bogaerts, D. Taillaert, P. Dumon, D. Van Thourhout, R. Baets, and E. Pluk, "A polarization-diversity wavelength duplexer circuit in silicon-on-insulator photonic wires," Opt. Express **15**, 1567-1578 (2007).
15. G. Maire, L. Vivien, G. Sattler, A. Kaźmierczak, B. Sanchez, K. B. Gylfason, A. Griol, D. Marris-Morini, E. Cassan, D. Giannone, H. Sohlström, and D. Hill, "High efficiency silicon nitride surface grating couplers," Opt. Express **16**, 328-333 (2008).
16. M. Kihara, M. Matsumoto, T. Haibara, and S. Tomita, "Characteristics of Thermally Expanded Core Fiber," J. Lightwave Technol. 14, 2209-2214 (1996).
17. Y. Ohtera, O. Hanaizumi, and S. Kawakami "Numerical Analysis of Eigenmodes and Splice Losses of Thermally Diffused Expanded Core Fibers," J. Lightwave Technol. **17**, 2675-2682 (1999).
18. M.-C. Oh, S.-H. Cho, Y.-O. Noh, H.-J. Lee, J.-J. Joo, and M.-H. Lee, "Variable Optical Attenuator Based on Large-Core Single-Mode Polymer Waveguide," IEEE Photon. Technol. Lett. **17**, 1890-1892 (2005).
19. M.-C. Oh, S.-H. Cho, and H.-J. Lee, "Fabrication of large-core single-mode polymer waveguide connecting to a thermally expanded core fiber for increased alignment tolerance," Opt. Commun. **246**, 337-343 (2005).

## 1. Introduction

Silicon photonic devices, which are based on silicon nano-wire waveguides for a compact design, are very attractive in realizing highly dense photonic integrated circuits fabricated by complementary metal-oxide semiconductor (CMOS) compatible processes [1-15].

The nano-wire silicon waveguide should be coupled to a single-mode fiber (SMF) for an optical characterization and for an optical interconnection with other devices. The silicon waveguide can be coupled with an SMF efficiently by using a lateral spot-size converter [1, 2] or by using a grating coupler [3-15]. Grating coupler is very attractive in many aspects, even though the lateral spot-size converters are superior in coupling efficiency [1-15]. Grating coupler has merits in simple fabrication process, measurement without an edge polishing of a diced chip, optical probing on wafer without a dicing in the middle of the fabrication process, and positional tolerance in alignment better than the lateral spot-size converter.

The positional tolerance in alignment of optical fiber with a silicon-photonic waveguide device is crucial for an industrial application of the device. Cost-effective production of a silicon-photonic waveguide device can be possible based on passive alignment of an SMF to the waveguide, if the positional tolerance in alignment is enough for a mechanical accuracy of connecting components. So, it is necessary to study the enhancement of the positional tolerance in alignment for the silicon-photonic waveguide. One of the important merits of grating coupler is that the size of grating coupler can be easily modified to be properly matched with any modal sizes of interconnecting fibers. We can expect that the positional tolerance in alignment can be enhanced as the size of the grating coupler is increased. A 10 μm wide grating coupler has been popularly used in coupling with a standard SMF [10], and a 30 μm wide grating coupler has been demonstrated in coupling with a free-space beam [12]. But there were no reports on the coupling of a large-core SMF with a wide grating coupler. A large-core SMF can be provided by thermally expanding the core of the standard SMF [16, 17]. A thermally-expanded-core (TEC) single-mode fiber has been used in enhancing the positional tolerance in alignment with a large-core single-mode polymeric waveguide [18, 19].

In these regards, we fabricate a 20 μm wide grating coupler and coupled it with a single-mode TEC fiber with a mode-field diameter (MFD) of 20 μm. The positional tolerance in alignment of the TEC fiber to the 20 μm wide grating coupler is compared with the tolerance in alignment of a standard SMF to a standard 10 μm wide grating coupler which is also fabricated in this experiment. This experiment is the first investigation on coupling a silicon waveguide with a large-core TEC fiber through a grating coupler, to our knowledge.

## 2. Experiments and results

Figures 1(a) and 1(b) show the scanning electron microscope (SEM) images of grating couplers. A standard 10 μm wide grating coupler to be coupled with a conventional SMF is shown in Fig. 1(a) and a 20 μm wide grating coupler to be coupled with a large-core single-mode TEC fiber is shown in Fig. 1(b). The period of the gratings is fixed as 620 nm with a

#97195 - $15.00 USD Received 9 Jun 2008; revised 7 Aug 2008; accepted 8 Aug 2008; published 11 Aug 2008

filling factor of 50% and the gratings are etched by 70 nm in depth, for the both grating couplers. The grating coupler and 2.5 mm long silicon waveguides connecting a pair of grating couplers are fabricated using electron-beam lithography and dry etching on a SOI wafer with a 220 nm thick top silicon layer on a 3000 nm thick buried oxide (BOX) layer. The silicon waveguide is a straight waveguide without a tapered region reducing the width of the waveguide down to a narrow single-mode waveguide. The tapered structure is necessary in real application and the insertion loss and the positional tolerance can be slightly different with and without it, but the overall coupling property of the grating couplers can be studied without the tapered structure. We used a TEC fiber with the 20 μm diameter of an expanded core, supplied by Phoco Co., Ltd. (www.phoco.com), in this experiment. The core of the TEC fiber is thermally expanded partially at one of the ends to be coupled with the grating coupler, while the other region remains as a standard SMF. Phoco supplies TEC fibers with the diameter of 20 μm and 30 μm for the TEC section. The transition loss from the TEC section to the SMF section is specified as less than 0.05 dB.

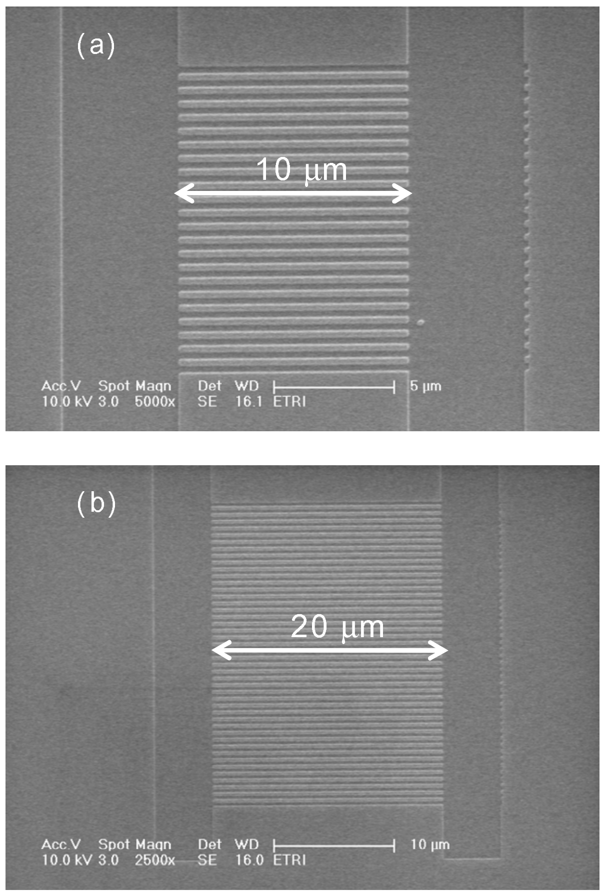


Fig. 1. SEM images for a standard 10 μm wide grating coupler for a standard SMF in (a) and a 20 μm wide grating coupler for a large-core TEC fiber in (b).

Figure 2 shows the schematic diagram of an experimental setup to measure the coupling property of an optical fiber with a silicon waveguide through a grating coupler. The position of the input fiber is scanned horizontally along X and Z directions, and vertically along a vertically tilted direction Y' to measure the variation of the coupling efficiency depending on the position of alignment. The position of the output fiber is maintained for a maximum

#97195 - $15.00 USD Received 9 Jun 2008; revised 7 Aug 2008; accepted 8 Aug 2008; published 11 Aug 2008

coupling while the input fiber is scanned along the horizontal and the vertical directions. The axis Y' is tilted with vertical axis Y at an angle of 8°.

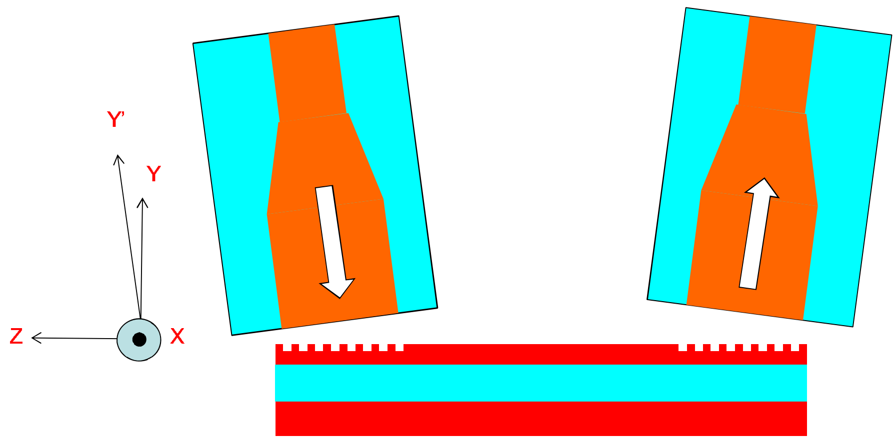


Fig. 2. Schematic diagram of experimental setup to couple a pair of TEC fibers with silicon waveguide through grating couplers. The position of the input fiber is scanned along horizontal X and Z directions, in addition to a vertically tilted Y' direction. The Y' axis is tilted from Y axis at 8°.

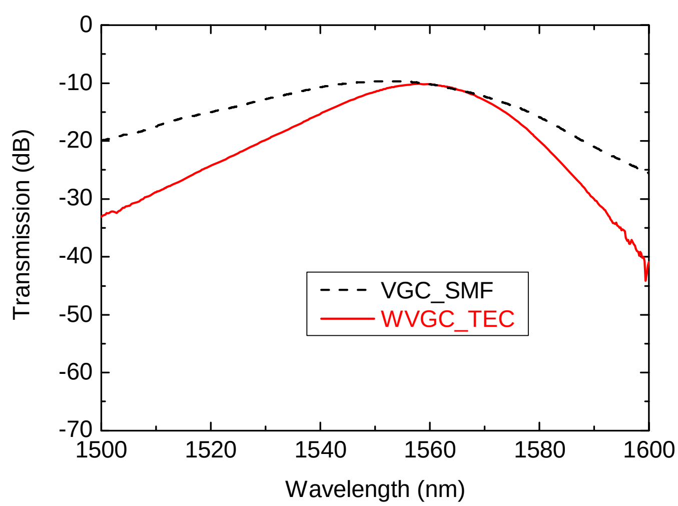


Fig. 3. Measured transmission spectra from a pair of fibers coupled with a silicon waveguide through a pair of grating couplers. VGC_SMF is for the standard SMF coupled through the 10 µm wide grating coupler, and WVGC_TEC is for the TEC fiber coupled through the 20 µm wide grating coupler.

Figure 3 shows the measured transmission spectra from a pair of optical fibers coupled with the 2.5 mm long silicon waveguide through a pair of grating couplers. VGC_SMF is for the standard SMFs coupled through the standard 10 µm wide grating couplers and WVGC_TEC is for the TEC fibers coupled through the 20 µm wide grating couplers in Fig. 3. The minimal insertion loss is measured at about 10 dB, resulting coupling loss of 5 dB per facet, both for the 10 µm wide grating coupler and for the 20 µm wide grating coupler. The

#97195 - $15.00 USD Received 9 Jun 2008; revised 7 Aug 2008; accepted 8 Aug 2008; published 11 Aug 2008

optical 3 dB bandwidth is 65 nm for the standard 10 µm wide grating coupler and 40 nm for the 20 µm wide grating coupler.

Figure 4 shows the measured relative transmission depending on the horizontal deviation of the input fiber. VGC_SMF_X and VGC_SMF_Z are for the standard SMF coupled with the 10 µm wide grating coupler, and WVGC_TEC_X and WVGC_TEC_Z are for the TEC fiber coupled with the 20 µm wide grating coupler, respectively in Fig. 4. The horizontal 3 dB alignment tolerance is measured at ±7.5 µm for the 20 µm wide grating coupler and it is twice larger than the tolerance of the standard 10 µm wide grating coupler, whose horizontal 3 dB alignment tolerance is measured at ±3.7 µm. The horizontal 1 dB alignment tolerance is measured at ±4.2 µm for the 20 µm wide grating coupler, which is also twice tolerable compared with ±2.0 µm for the standard 10 µm wide grating coupler.

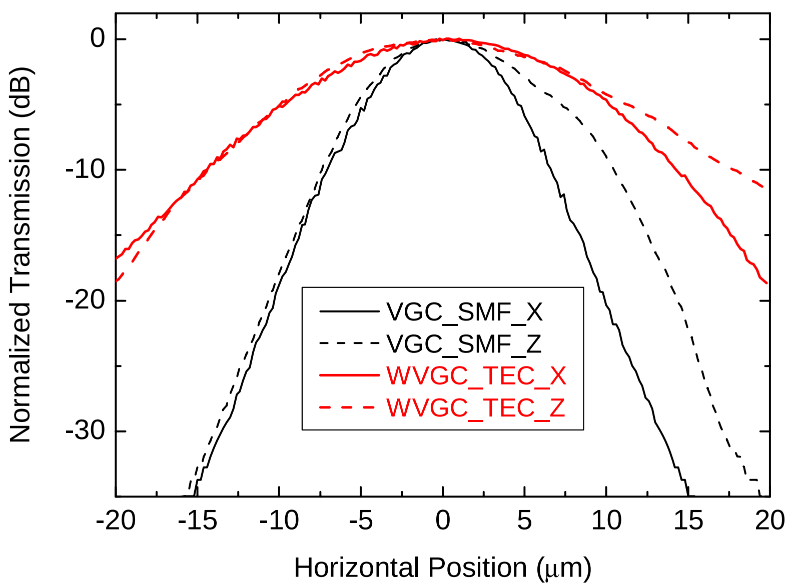


Fig. 4. Measured relative transmission depending on the horizontal deviation of an input fiber. VGC_SMF_X and VGC_SMF_Z are for the standard SMF coupled with the 10 µm wide grating coupler, and WVGC_TEC_X and WVGC_TEC_Z are for the TEC fiber coupled with the 20 µm wide grating coupler.

Figure 5 shows the measured relative transmission depending on the vertical positional deviation of the input fiber along Y'-axis. VGC_SMF_Y is for the standard SMF coupled with the standard 10 µm wide grating coupler and WVGC_TEC_Y is for the TEC fiber coupled with the 20 µm wide grating coupler, in Fig. 5. The vertical 3 dB alignment tolerance is measured at +290 µm for the 20 µm wide grating coupler and it is four times larger than the tolerance of the standard 10 µm wide grating coupler, whose vertical 3 dB alignment tolerance is measured at +70 µm. The vertical 1 dB alignment tolerance is measured at +125 µm for the 20 µm wide grating coupler, which is five times tolerable compared with +25 µm for the standard 10 µm wide grating coupler. These results show that the horizontal and vertical alignment tolerance can be dramatically improved using a combination of a wide grating coupler with a large-core TEC fiber.

#97195 - $15.00 USD Received 9 Jun 2008; revised 7 Aug 2008; accepted 8 Aug 2008; published 11 Aug 2008

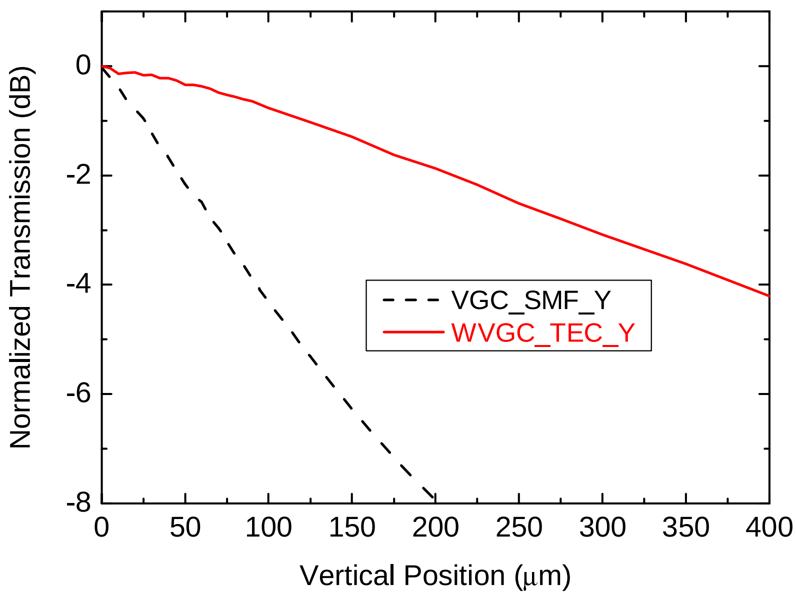


Fig. 5. Measured relative transmission depending on the vertical positional deviation of the input fiber along Y' axis. VGC_SMF_Y is for the standard SMF coupled with the 10 μm wide grating coupler and WVGC _TEC_Y is for the TEC fiber coupled with the 20 μm wide grating coupler.

## 3. Simulations

The experimental data show that the alignment tolerance can be improved using a 20 μm wide grating coupler without a big penalty in insertion loss, even though the design parameters of the grating was not specially optimized for the 20 μm wide grating. The coupling efficiency and spectral property of the grating can be varied with several parameters such as the period of grating, the filling factor, the etching depth, and the angle of incidence.

We simulate transmission spectra for a TEC fiber coupled with a silicon waveguide through a 20 μm wide grating coupler, using a commercial simulation tool, FullWave, which is based on finite-difference time-domain (FDTD) method. The simulation is performed in two-dimensional (2-D) vertical (y-z) plane. There should be a slight difference in 2-D FDTD simulation from three-dimensional FDTD simulation, but the 2-D simulation can be used in finding the optimal parameters of the grating. The main parameter varied in this simulation is the etching depth, since it is the most crucial parameter influencing the coupling efficiency. The common parameters in the simulation are 220 nm for the thickness of the top silicon, 2000 nm for the thickness of BOX, 620 nm for the period of the grating, 50% of filling factor, and 8$^{o}$ for the angle of incidence.

#97195 - $15.00 USD Received 9 Jun 2008; revised 7 Aug 2008; accepted 8 Aug 2008; published 11 Aug 2008

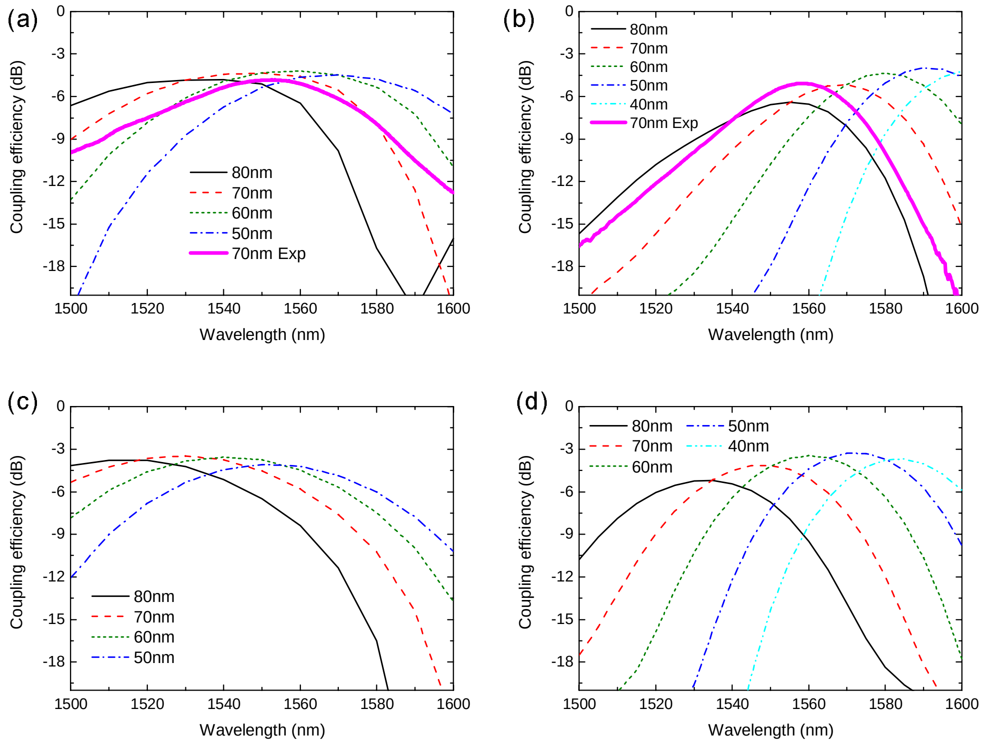


Fig. 6. Simulated coupling efficiency to the conventional SMF from the 10 μm wide standard grating coupler in (a) and to the TEC fiber from the 20 μm wide grating coupler in (b), for various etching depths from 40 to 80 nm. (c) and (d) are simulated for the same conditions but the background refractive index with (a) and (b) respectively. The background index is the index of air in (a) and (b), when it is the index of BOX in (c) and (d). 70nm Exp in (a) and (b) is for experimental data in comparison with the simulated data.

Figure 6 shows the simulated transmission spectra in comparison with the experimental data. Figure 6(a) shows the simulated coupling efficiency to the conventional SMF from the 10 μm wide standard grating coupler with the various etching depths from 50 to 80 nm and Fig. 6(b) shows the coupling efficiency to the TEC fiber from the 20 μm wide grating coupler with the various etching depths from 40 to 80 nm. Figures 6(c) and 6(d) are simulated for the same conditions but the background refractive index with (a) and (b) respectively. The background index is the index of air in Figs. 6(a) and 6(b), when it is the index of BOX in (c) and (d). 70nm Exp in Figs. 6(a) and 6(b) is for experimental data in comparison with the simulated data.

The maximal coupling efficiency for the 20 μm wide grating coupler is about 5.2 dB for the etching depth of 70 nm, which is comparable to the coupling efficiency of 5 dB in experiment, and it can be enhanced, with the etching depth of 50 nm, as 4.0 dB with the background index of air in Fig. 6(b) and as 3.3 dB with the background index of BOX in Fig. 6(d). The optimized coupling efficiency for the 20 μm wide grating coupler in Fig. 6(d) is as good as the coupling efficiency of 3.5 dB at the etching depth of 70 nm for the 10 μm wide grating coupler in Fig. 6(c). The peak wavelength is varied with the etching depth but it can be optimized either by adjusting the period of the grating or the angle of incidence. The slight difference in experimental data from the simulation is regarded coming from a little deviation in etching depth, filling factor, and the angle of incidence from designed parameters. The

#97195 - $15.00 USD Received 9 Jun 2008; revised 7 Aug 2008; accepted 8 Aug 2008; published 11 Aug 2008

coupling efficiency for the 20 μm wide grating coupler is expected to be increased even further up to 1 dB by using a high-index overlay as the grating coupler in reference [13].

## 4. Conclusion

We experimentally investigated on the positional tolerance in alignment for a single-mode thermally-expanded-core (TEC) fiber with a silicon waveguide, by fabricating a 20 μm wide grating coupler for the TEC fiber. The minimal coupling loss of the TEC fiber to the 20 μm wide grating coupler is 5 dB per facet and the optical 3 dB bandwidth is 40 nm. The 3 dB alignment tolerance of the TEC fiber to the 20 μm wide grating coupler is ± 7.5 μm in horizontal direction and +290 μm in vertical direction. The 1 dB alignment tolerance of the TEC fiber to the wide grating coupler is ± 4.2 μm in horizontal direction and +125 μm in vertical direction. The alignment tolerance is enhanced twice in horizontal direction and four times in vertical direction, compared with the coupling of a standard single-mode fiber to the standard 10 μm wide grating coupler which was also fabricated in this experiment. These experimental results show that the positional tolerance in alignment can be dramatically enhanced by using a grating coupler properly designed for a large-core fiber.

#97195 - $15.00 USD Received 9 Jun 2008; revised 7 Aug 2008; accepted 8 Aug 2008; published 11 Aug 2008