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# On-chip grating coupler array on the SOI platform for fan-in/fan-out of MCFs with low insertion loss and crosstalk

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We report the design and fabrication of a compact multi-core fiber fan-in/fan-out using a grating coupler array on the SOI platform. The grating couplers are fully-etched, enabling the whole circuit to be fabricated in a single lithography and etching step. Thanks to the apodized design for the grating couplers and the introduction of an aluminum reflective mirror, a highest coupling efficiency of  $-3.8$  dB with 3 dB coupling bandwidth of 48 nm and 1.5 dB bandwidth covering the whole C band, together with crosstalk lower than  $-32$  dB are demonstrated.

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## 1. Introduction

The communication capacity of single mode fiber (SMF)-based optical transmission systems has been rapidly pushed towards its theoretical limit [1] by the fast growing traffic demand these years. Space-division multiplexing (SDM) based on multi-core fibers (MCFs) has been demonstrated to be a promising technology to further increase the communication capacity over a single fiber. By introducing uncoupled multiple cores in a single fiber, large communication capacities with long transmission distances have been reported [2–6]. One important component for MCF-based SDM technology is a compact and efficient MCF fan-in/fan-out (FI/FO) device with low coupling loss and large bandwidth. Traditional free space-based couplers [6] have been widely used thanks to their high coupling efficiencies with large bandwidths and polarization independence. However, they are very bulky. Recently, more compact physical-contact type FI/FOs [7] have been proposed and demonstrated. On the other hand, from the integration point of view, on-chip MCF couplers are preferred so that many FI/FO couplers and other functionalities such as switching matrices can be integrated on the same chip. In this context, three dimensional (3D) waveguides fabricated by ultrafast laser inscription [8] have been demonstrated.

In this paper, we demonstrate a compact on-chip 7-core fiber FI/FO using a grating coupler array on the silicon-on-insulator (SOI) platform. The grating couplers are fully-etched so that they can be simultaneously fabricated with silicon wires in a single lithography and etching step. In order to maximize the coupling efficiency, grating couplers are designed using an apodized scheme with bottom aluminum (Al) mirrors introduced below. A highest coupling efficiency of –3.8 dB with 3 dB coupling bandwidth of 48 nm and 1.5 dB bandwidth covering the whole C band were achieved. At the same time, low coupling efficiency variation of 1.5 dB between all spatial channels with crosstalk below –32 dB were demonstrated.

## 2. Grating coupler design

An SOI chip enabling coupling from seven standard SMFs (SSMFs) to one seven-core MCF using grating couplers is proposed, as shown in Fig. 1(a). The input and output grating couplers are designed and optimized for coupling to SSMFs and cores of an MCF, simultaneously. An MCF with effective area of around 110  $\mu\text{m}^2$  (corresponding to an estimated mode diameter of 11.8  $\mu\text{m}$ ) [9] for each core with core pitch of 49  $\mu\text{m}$  is used for optimization. A silica-clad fully-etched silicon grating coupler with bonded bottom mirror on a silicon carrier wafer is proposed, as depicted in Fig. 1(b). There are three advantages for the

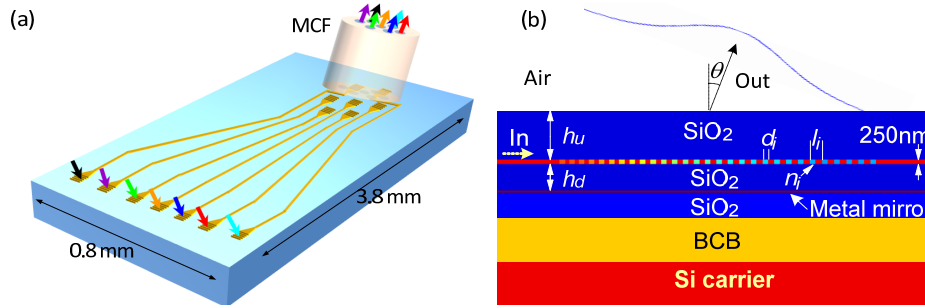


Fig. 1. (a) Schematic of the grating coupler-based FI/FO. (b) Structure of the grating coupler.

proposed design. Firstly, the fabrication process can be simplified by using a fully-etched design so that the grating couplers can be simultaneously fabricated with the rest of the circuit [10]. Secondly, a high coupling efficiency (CE) can be achieved thanks to the metal mirror. Finally, both upper and lower cladding thicknesses can be precisely optimized by bonding technology. The thickness of the top silicon device layer is 250 nm. SiO<sub>2</sub> is used as upper and lower cladding material with thicknesses of  $h_u$  and  $h_d$ , respectively. A 100 nm Al mirror is introduced below the lower cladding in order to improve the coupling efficiency thanks to its good reflectivity [11]. Another layer of SiO<sub>2</sub> is introduced beneath the Al mirror and is bonded to the silicon carrier wafer using a benzocyclobutene (BCB) layer. The coupling angle  $\theta$  is designed to be 15°. In order to achieve an apodized grating coupler diffracting a Gaussian field profile, artificial materials are introduced for the scattering units, with refractive indices  $n_i$  and lengths of scattering units  $l_i$  changed along the grating [10]. The width of the artificial material slots is fixed to be 345 nm in our design. The light scatters with a power leakage factor  $2\alpha_i$  when it propagates through each scattering unit. In order to obtain a Gaussian output profile  $G(z)$  for either the SSMF or each core of an MCF, the power leakage factor distribution  $2\alpha(z)$  should satisfy [10]:

$$2\alpha(z) = G^2(z) / \left[ 1 - \int_0^z G^2(z) dz \right] \quad (1)$$

In order to synthesize a Gaussian output profile, firstly one has to calculate the right

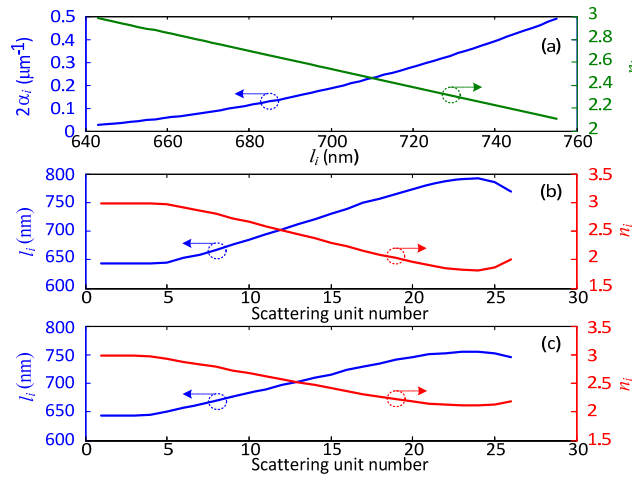


Fig. 2. (a) Calculated required refractive index  $n_i$  of the artificial material of a scattering cell and the corresponding power leakage factor as a function of the cell length  $l_i$ .  $l_i$  and  $n_i$  distributions of the grating couplers designed for coupling to (b) an SSMF and (c) a single core of an MCF.

combination of  $l_i$  and  $n_i$  maintaining the scattering angle of  $15^\circ$  and the corresponding power leakage factor  $2\alpha_i$ , which are shown in Fig. 2(a). With the guidance of Fig. 2(a), one can find the  $n_i$  and  $l_i$  distributions so that Gaussian output field profiles with beam diameters of  $10.4\ \mu\text{m}$  and  $11.8\ \mu\text{m}$  are synthesized for the SSMF and MCF, respectively, both with a coupling angle of  $15^\circ$  at  $1550\ \text{nm}$ , as shown in Figs. 2(b) and 2(c). Photonic crystals (PhCs) with triangular lattices can then be used for the artificial material slots, and their hole sizes can be determined by the effective index approximation [10, 11].

The coupling efficiencies of the transverse electric (TE) mode for the grating couplers designed for coupling to either an SSMF or a single core of an MCF are then calculated as a function of wavelength by an in-house implementation of the 2D eigenmode expansion method (EME) [12], as shown in Fig. 3, with  $h_d = 1600\ \text{nm}$  and  $h_u = 1000\ \text{nm}$ , which are optimum thicknesses as detailed in [11]. A peak coupling efficiency of  $-0.44\ \text{dB}$  is predicted for both grating coupler designs. Considering that the MCF coupler consists of grating couplers coupling to an SSMF on one side, and the multiple cores of an MCF on the other side, one has to take into account the  $1.5\ \text{dB}$  coupling bandwidth of each grating coupler in order to evaluate the overall  $3\ \text{dB}$  bandwidth of the MCF coupler. One can find that the  $1.5\ \text{dB}$  coupling bandwidth is  $54\ \text{nm}$  and  $49\ \text{nm}$  for the SSMF and MCF grating couplers, respectively, predicting that the whole MCF coupler should have a  $3\ \text{dB}$  coupling bandwidth as large as  $49\ \text{nm}$ .

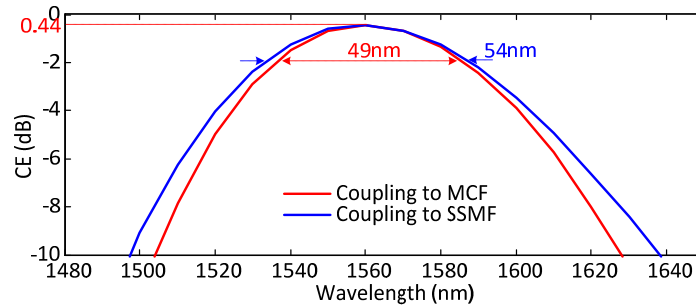


Fig. 3. Simulated coupling efficiency as a function of wavelength for the SSMF and a single core of the MCF, with  $h_d = 1600\ \text{nm}$ , and  $h_u = 1000\ \text{nm}$ .

### 3. Device fabrication and characterization

In order to validate our concept, the device was fabricated on a commercial SOI sample with top silicon thickness of  $250\ \text{nm}$  and buried silicon dioxide (BOX) of  $3\ \mu\text{m}$ . A single step of e-beam lithography and inductively coupled plasma (ICP) etching was first used to fabricate the grating couplers and silicon waveguides simultaneously. An  $800\ \text{nm}$  thick layer of  $\text{SiO}_2$  was then deposited on top of the chip. Another  $800\ \text{nm}$  borophosphosilicate (BPSG) glass was deposited and annealed in nitrogen at  $950^\circ\text{C}$  for 30 minutes in order to planarize the chip surface, giving a planarity across the grating region better than  $100\ \text{nm}$ . Afterwards, a  $100\ \text{nm}$  thick Al layer was deposited on top of the BPSG, followed by another  $1\ \mu\text{m}$   $\text{SiO}_2$  deposition. Then, about  $2\ \mu\text{m}$  thick BCB layer was spun on both the sample and silicon carrier wafer. The sample was then flip-bonded on the silicon carrier wafer and thermally cured in an oven. Following that, the substrate of the chip was removed by ICP fast etching. Finally, the BOX layer was thinned to  $1\ \mu\text{m}$  by buffered hydrofluoric acid (BHF) etching.

Figure 4 shows details of the fabricated device. The grating coupler is constructed by PhC based scattering slots, as shown in Fig. 4(c). The waveguide widths are  $12\ \mu\text{m}$  and  $13\ \mu\text{m}$  for the grating couplers coupling to the SSMF and each core of the MCF, respectively. The layout of the output grating couplers corresponds to that of the cores of the MCF, with the same pitch of  $49\ \mu\text{m}$ , as shown in Fig. 4(a) and 4(b). In addition,  $45^\circ$ -slants are introduced to change the light beam propagation direction so that the  $500\ \mu\text{m}$  long taper (from  $13\ \mu\text{m}$  for

the grating to 450 nm for the silicon single mode waveguide) can be placed outside the grating coupler array,

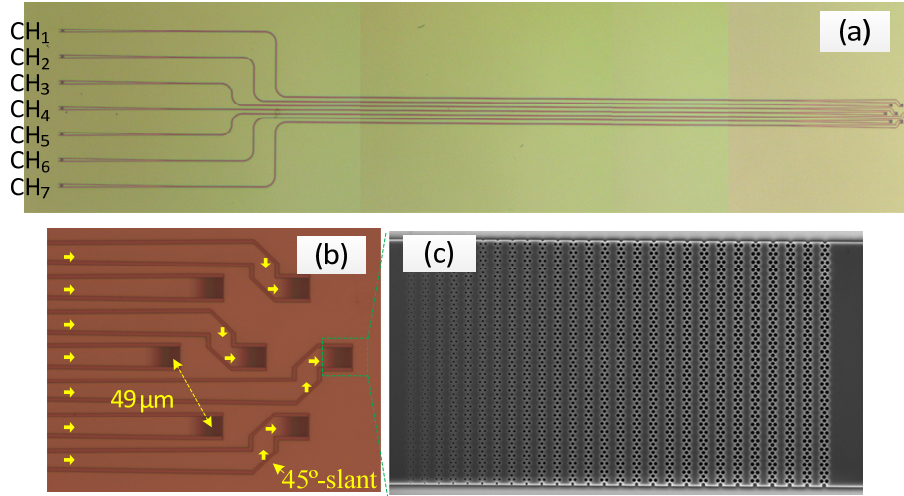


Fig. 4. (a) Fabricated device. (b) Details of the grating coupler array for directly coupling with an MCF. (c) Scanning electron microscopy (SEM) image of the apodized PhC grating coupler.

as shown in Fig. 4(b). In reality, one can also use a focused grating coupler scheme that has ultra-short tapering sections [13].

The insertion loss of the 45°-slants was firstly investigated by cut-back method, in which different insertion loss for cascading different numbers  $N$  of the 45°-slants was measured. A low insertion loss of only 0.05 dB can be achieved over a large bandwidth, as shown in Fig. 5.

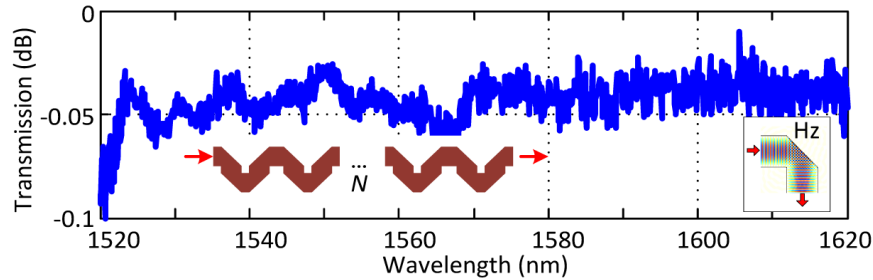


Fig. 5. Measured transmission of a single 45°-slant. The inset shows the 3D finite-difference time-domain (FDTD) simulated field distribution when light gets reflected by the 45°-slant.

The coupling loss from our device to an MCF was measured for each core. Figure 6 shows the measurement setup. Continuous wave (CW) laser light from a tunable laser source (TLS) was polarization-tuned by a polarization controller (PC), so that the light was launched to the input grating coupler on the TE mode. The MCF was mounted on a rotatable fiber holder with input angle of 15°. The MCF was rotated until all the cores of the MCF were well aligned with the corresponding grating couplers. The output of the MCF was spatially demultiplexed by a free space coupling device [14], and the output power from each core was measured using an optical spectral analyzer.



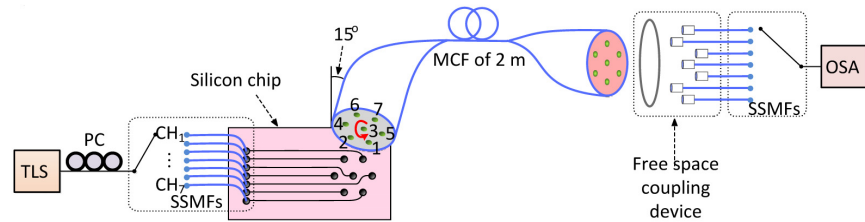


Fig. 6. Measurement setup of the grating coupler array-based on-chip MCF FI/FO.

The coupling efficiency of the MCF FI/FO is shown in Fig. 7. It was obtained by subtracting the free space coupling loss (1.5 dB [14]) from the total link loss (from the grating coupler input to the free space coupling output). Note that no index matching gel was used between the device and the fibers. A highest coupling efficiency of  $-3.8$  dB with 3 dB coupling bandwidth of 48 nm and 1.5 dB coupling bandwidth covering the whole C band were measured. In addition, less than 1.5 dB coupling loss variation for the different spatial channels was demonstrated. It should be noted that the coupling loss includes the loss of the input grating coupler, propagation loss along the silicon waveguides, insertion loss of the  $45^\circ$ -slant, and loss of the output grating coupler to the MCF. It is believed that the use in the simulations of an estimated mode diameter of  $11.8 \mu\text{m}$ , which might not precisely correspond to the actual mode size, is the main reason for the lower measured coupling efficiency compared with the theoretical predictions. Careful optimization of the output grating coupler used for coupling to the MCF taking the actual mode size into account could further reduce the total coupling loss. The crosstalk was also investigated by launching light into different input channels and detecting light from the other non-corresponding cores of the MCF. A low crosstalk of  $-32$  dB over a large bandwidth of 60 nm was measured, which is very close to a measured SMF to MCF crosstalk value of  $-37$  dB for the free space coupling device, indicating that the grating coupler array has very low crosstalk. The ripples in the crosstalk curves are due to noise since the power level is too low. The back reflection of the designed grating couplers should be below 1.4%, as reported for identical devices in Ref [11].

In the present work, the use of BCB is not compatible with conventional CMOS processes. However, CMOS-compatible thermocompression bonding using aluminum [15] can be used to solve the problem as well as to simplify the fabrication process. In addition, since the grating couplers in the present work are designed to work only on the TE mode, polarization diversity coupling with 2D grating coupler designs [16] can be used in order to realize polarization independent coupling.

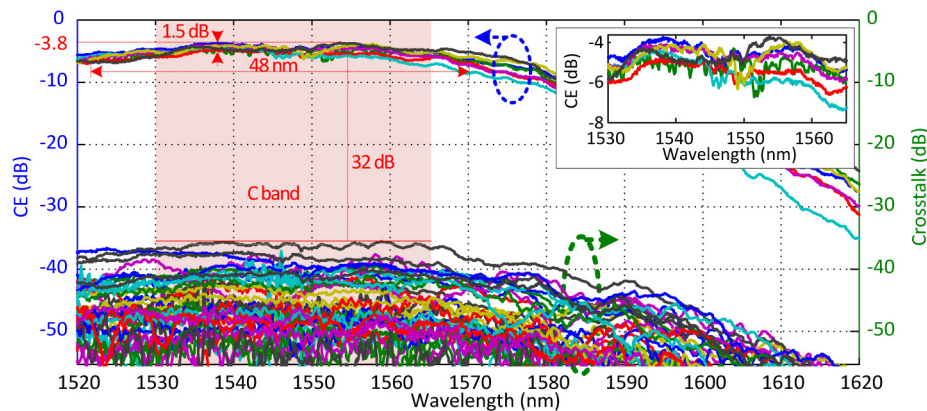


Fig. 7. Measured coupling efficiency and crosstalk for the MCF FI/FO. The inset shows details of the coupling efficiency over the C-band.

## Conclusions

We have designed and demonstrated a compact MCF FI/FO using a fully-etched grating coupler array on the SOI platform. A highest coupling efficiency of  $-3.8$  dB with 3 dB coupling bandwidth of 48 nm and 1.5 dB coupling bandwidth covering the whole C band, together with a low coupling efficiency variation of 1.5 dB and low crosstalk lower than  $-32$  dB between all spatial channels were achieved.

## Acknowledgments

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