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On-chip Grating Coupler Array on the SOI Platform for Fan-in/Fan-out of Multi-core Fibers with Low Insertion Loss and Crosstalk

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Abstract *We design and fabricate a compact multi-core fiber fan-in/fan-out using a fully-etched grating coupler array on the SOI platform. Lowest coupling loss of 6.8 dB with 3 dB bandwidth of 48 nm and crosstalk lower than -32 dB are demonstrated.*

Introduction

The communication capacities of single mode fiber (SMF)-based optical transmission systems have been rapidly pushed towards their 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. Several FI/FOs schemes have been proposed, including free space based coupler[6], three dimensional (3D) waveguides fabricated by ultrafast laser inscription[7], physical-contact type FI/FO[8], etc.

In this paper, we demonstrate a compact on-chip 7-core fiber FI/FO using a fully-etched apodized grating coupler array on the silicon-on-insulator (SOI) platform, as shown in Fig. 1. Coupling loss as low as 6.8 dB with 3 dB bandwidth of 48 nm and less than 3 dB coupling loss variation between spatial channels were achieved. It is a promising technology thanks to its potential for integration of many FI/FO couplers and other functionalities such as switching matrices on the same chip.

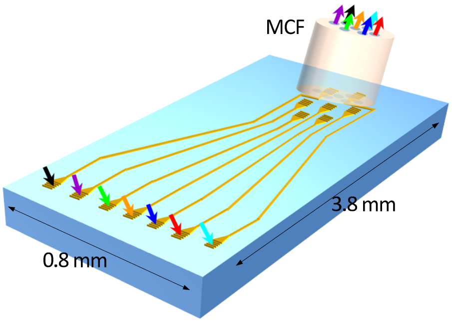

Fig. 1: Schematic of the grating coupler-based FI/FO.

Grating coupler design

An SOI chip enabling coupling from 7 standard SMFs (SSMFs) to one 7-core MCF using grating couplers is proposed, as shown in Fig. 1. The grating couplers, identical at both ends of the circuit, are designed and optimized for coupling to SSMFs. A silica-clad fully-etched silicon photonic crystal (PhC) grating coupler with bonded bottom mirror on a silicon carrier wafer is proposed, as depicted in Fig. 2. There are three advantages for the 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[9]. Secondly, a high coupling efficiency (CE) can be achieved thanks to the bonded 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. 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[9]. SiO_2 is used as upper and lower cladding material with thicknesses of h_u and h_d,

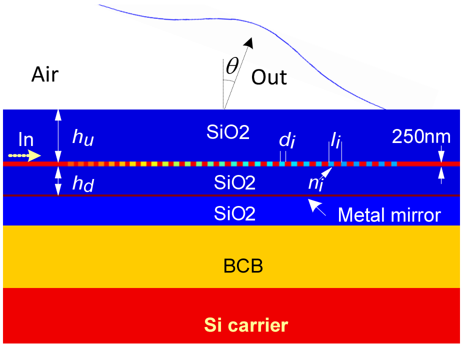

Fig. 2: Structure of the grating coupler.

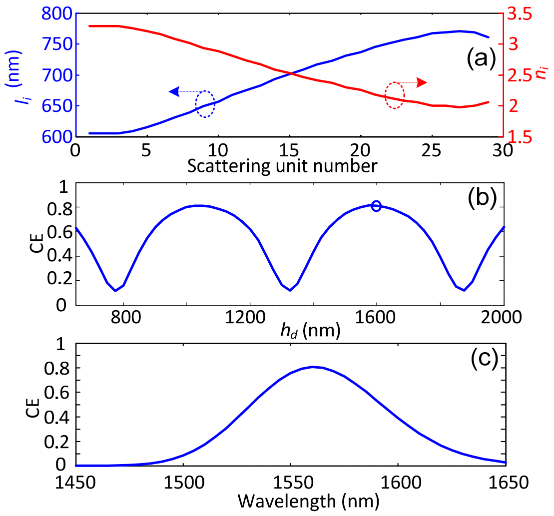

Fig. 3: (a) Designed l_i and n_i distributions of the grating couplers. Simulated coupling efficiency as a function of (b) h_d , with h_u=1000 nm, and (c) wavelength, with h_d=1600 nm, and h_u=1000 nm.

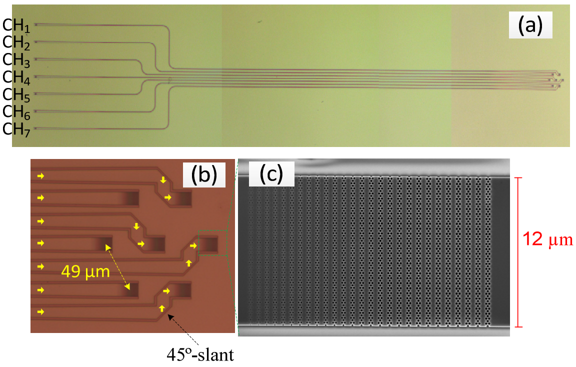

Fig. 4: (a) Fabricated device. (b) Details of the grating coupler array for directly coupling with a MCF. (c) Scanning electron microscopy (SEM) image of the apodized PhC grating coupler.

respectively. A 100 nm titanium (Ti) mirror is introduced below the lower cladding. Another layer of SiO_2 is introduced beneath the Ti mirror and is bonded to the silicon carrier wafer using a benzocyclobutene (BCB) layer. The coupling angle θ is designed to be 15°. The width of the artificial material slots is fixed to be 345 nm, and the scattering strength and coupling angle are tuned by optimizing n_i and l_i. The distributions of n_i and l_i of the grating coupler are designed, as shown in Fig. 3(a), so that a Gaussian output field profile with a beam radius of 5.2 µm is synthesized from the grating with a coupling angle of 15° at 1550 nm. PhCs with triangular lattices can then be used for the artificial material slots, and the hole size for the PhCs can be determined by the effective index approximation[9]. The coupling efficiency of the transverse electric (TE) mode is then calculated by a 2D eigen-mode expansion method (EME) as a function of h_d with h_u set to 1000 nm, as shown in Fig. 3(b). The coupling efficiency depends periodically on h_d, and reaches a local maximum at h_d= 1600 nm. With h_d=1600 nm and h_u=1000 nm, the coupling efficiency is then calculated as a function of wavelength, as shown in Fig. 3(c). A peak coupling efficiency of 81% (corresponding to 0.91 dB coupling loss) is predicted with a 3 dB bandwidth of 74 nm.

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 nm and buried silicon dioxide (BOX) of 3 µm. A single step of standard SOI processing, including e-beam lithography and inductively coupled plasma (ICP) etching was first used to fabricate the grating coupler and silicon waveguides simultaneously. An 800 nm thick layer of SiO_2 was then deposited on top of the chip. Another 800 nm borophosphosilicate (BPSG) glass was deposited and annealed in nitrogen at 950°C for 30 minutes in order to planarize the chip surface. Afterwards, a 100 nm thick Ti layer was deposited on top of the BPSG. Then, about 2 µm 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. Finally the substrate of the chip was removed by ICP fast etching.

Fig. 4 shows details of the fabricated device. The grating coupler is constructed by PhC based scattering slots with waveguide width of 12 µm, as shown in Fig. 4(c). The layout of the output grating couplers correspond to that of the cores of the MCF, with the same pitch of 49 µm, as shown in Fig. 4(a) and 4(b). In addition, 45°-slants with measured low insertion loss of

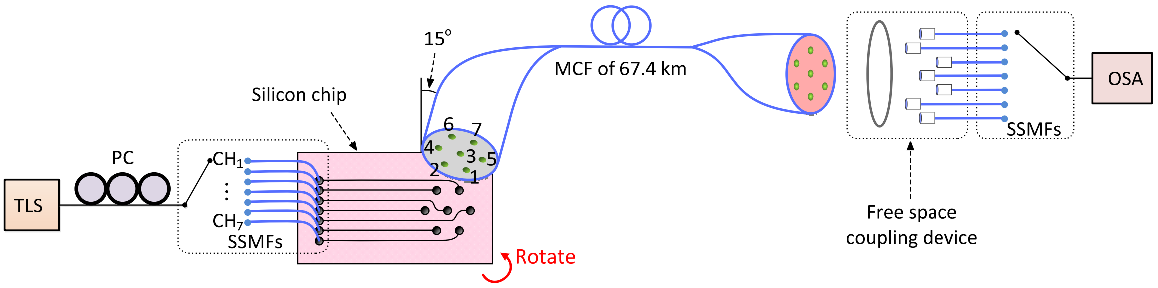

Fig. 5: Measurement setup of the grating coupler array-based on-chip MCF FI/FO.

0.05 dB, are introduced to change the light beam propagation direction so that the 500 μm long taper (from 12 μm for the grating to 450 nm for the silicon single mode waveguide) can be placed outside the grating coupler array, as shown in Fig. 4(b).

The coupling loss from our device to an MCF with core pitch of 49 μm and effective area of 110 μm^2 at 1550 nm was measured for each core. Fig. 5 shows the measurement setup. The device was mounted on a rotatable stage. 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 to a fiber holder with input angle of 15°. The stage was then horizontally rotated until all the grating couplers were well aligned with the corresponding cores of the MCF. The output of the MCF was spatially demultiplexed by a free space coupling device[10], and the output power from each core was measured by an optical spectral analyzer (OSA). The coupling efficiency of the MCF FI/FO is shown in Fig. 6. It was obtained by subtracting the MCF transmission loss and free space coupling loss from the total link loss (from the grating coupler input to the free space coupling output). A lowest coupling loss of 6.8 dB with 3 dB coupling bandwidth of 48 nm and less than 3 dB coupling loss variation for the different spatial channels were measured. 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°-slant, and loss of the output grating coupler to the MCF. It should also be noted that our alignment method by rotating the stage will lead to non-optimum coupling angle for the MCF, resulting in larger coupling loss. Lower coupling loss can be expected by rotating the MCF instead. In addition, aluminum (Al) can be used instead of Ti for the back mirror to further reduce the coupling loss. Moreover, the effective area of 110 μm^2 of each fiber core is larger than that of an SSMF, for which the grating coupler was designed, which also results in higher coupling loss. Optimization of the output grating coupler can further reduce the total coupling loss. The crosstalk was also investigated by launching light into input CH$_1$ and detecting light from the other non-corresponding cores (core 2 to 7) of the MCF. A low crosstalk of -32 dB over a large bandwidth of 100 nm was measured, which is very close to a measured SMF to MCF crosstalk value of -35 dB for the free space coupling device, indicating that the grating coupler array has very low crosstalk.

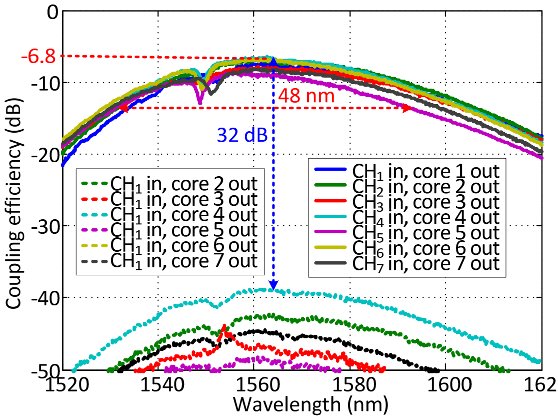

Fig. 6: Measured coupling efficiency and crosstalk for the MCF FI/FO.

Conclusions

We have designed and demonstrated a compact MCF FI/FO using a fully-etched grating coupler array on the SOI platform. A lowest coupling loss of 6.8 dB with 3 dB coupling bandwidth of 48 nm and less than 3 dB coupling loss variation between spatial channels were achieved.

Acknowledgement

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