Bridging the Graded-Index Few-Mode Fibre with Photonic Integrated Circuits via Efficient Diffraction Waveguide Gratings

(Student Paper)

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ABSTRACT

Spatial-division multiplexing (SDM) employing few-mode fibres (FMF) has attracted much interest for increasing the capacity of optical fibre communication systems. Graded-index few-mode fibres (GI-FMF) have low modal differential group delay (DGD), allowing extended transmission distance and bandwidth. In this paper, we describe novel efficient waveguide grating couplers fabricated on the silicon photonic platform for selectively launching different modes in the GI-FMF. The waveguide grating couplers may be integrated with transceivers for implementing mode division multiplexing in the fibre communications. The single-polarization diffraction waveguide gratings is measured to have coupling efficiencies into the LP_{01} mode and LP_{11} mode of – 2.8 dB and – 3.88 dB, respectively. The measured 3-dB bandwidth of the two modes are 61.2 nm and 59.0 nm. A two-dimensional grating based on the effective medium theory (EMT) is also demonstrated, supporting totally four optical channels including the two orthogonal polarizations of the LP_{01} mode and LP_{11} mode. The obtained peak coupling efficiency is – 4.89 dB for LP_{01} mode and – 5.71 dB for LP_{11} mode. The 3-dB bandwidth of the two modes are 23.2 nm and 21.6 nm, respectively.

Keywords: Integrated optics, silicon photonics, diffraction gratings, spatial-division multiplexing.

1. INTRODUCTION

The continuing exponential growth of data traffic into and out of the data centres is driving the development of higher transmission capacity optical interconnects. The transmission capacity of standard single-mode fibre (SMF) has already approached the theoretical limit from Shannon's information theory and nonlinear fibre effects [1]. Spatial-division multiplexing (SDM) employing few-mode fibre (FMF) has thus attracted much interest to enable further capacity growth with the potential cost and space savings associated with using a single integrated transmitter for launching mode division multiplexing (MDM) signals in the FMF. Graded-index FMF has the benefit of a low modal differential group delay (DGD), which affects the time delay between the received SDM channels after FMF transmission. Assuming mode mixing in the fibre, any time delay has to be compensated by an equalizing filter with a finite number of taps, a smaller time delay is always preferred for implementable multiple-input multiple-output (MIMO) digital signal processing (DSP) [2].

As an alternative to the fibre photonic lantern and the 3-dimensional (3D) optical waveguides by laser inscription, integrated multimode waveguide grating couplers based on the silicon-on-insulator (SOI) platform offers the advantages of low cost, monolithic integration of multiple channel MDM transmitters and receivers and mass-production scalability [3], [4]. Optical signal processing employing the photonic integrated circuits such as mode unscrambling for high-speed optical communications have been previously explored [5]. In this work, we report efficient mode multiplexers for graded-index FMF (GI-FMF) based on waveguide gratings with record coupling efficiencies. The single-polarization grating coupler has a peak experimental coupling efficiency of – 2.8 dB for LP_{01} mode, and – 3.88 dB for LP_{11} mode. The 3-dB bandwidth are 61.2 nm and 59.0 nm, respectively. A two-dimensional grating based on the effective medium theory (EMT) is also demonstrated to support the two orthogonal polarizations of the LP_{01} mode and LP_{11} mode. The obtained peak coupling efficiency is – 4.89 dB for LP_{01} mode and – 5.87 dB for LP_{11} mode. The 3-dB bandwidth are 23.2 nm and 21.6 nm, respectively.

2. DESIGN AND SIMULATION

The *OFS* two-mode GI-FMF in our experiment has a mode field diameter (MFD) of 11.0 µm. The DGD between the LP_{01} mode and the LP_{11} mode is less than ± 0.2 ps/m, while it is about 2.1 ps/m for the OFS step index FMF. The SOI wafer has a top silicon layer with a thickness of 220 nm. Buried-oxide layer has a thickness of 2 µm. Transverse-electric (TE) modes in the SOI waveguides, TE_0 and TE_1 can selectively excite the LP_{01} mode and LP_{11} mode in the GI-FMF via a single grating structure as illustrated in Figs. 1(a) and 1(b), which is possible as their effective refractive indexes are similar in the wide slab waveguide and grating region. To enhance the grating directionality, a 160-nm poly-silicon layer is deposited on the whole silicon wafer as the grating teeth [6], [7]. 230

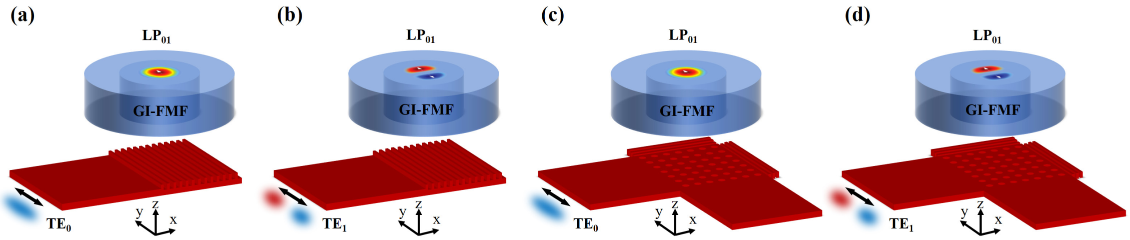

Fig. 1. (a) and (b) Schematics of the single-polarization two-mode grating coupler, which has 380-nm thick grating teeth and 150-nm grating slits. (c) and (d) Schematics of the two-dimensional grating coupler, which has 220-nm thick grating teeth and 70-nm shallow-etched sub-wavelength holes. The grating design is symmetric for the two orthogonal polarizations.

nm etching process is performed reaching 70 nm into the bottom crystalline silicon for the grating slits. For the two-dimensional grating coupler, a symmetric grating design can be employed so that totally four optical channels can be excited in the two-mode GI-FMFs as shown in Figs. 1(c) and 1(d). In the dual polarization two-dimensional grating coupler, the poly-silicon overlay was not used in order to keep grating strength low for efficient coupling across the diameter of the GI-FMF. Instead, the grating teeth have a thickness of 220 nm and the 70-nm shallow etched sub-wavelength holes are employed as the lower index sections. The square-shaped holes used in the 2-D FDTD simulation are converted to the round-shaped holes in fabrication as the latter can be fabricated using the standard deep-ultraviolet (DUV) photolithography with less stringent requirements [8]. Three rectangular slabs with a width of 190 nm and a spacing of 240 nm are utilized as the grating end reflector.

The grating coupler was optimized by genetic optimization algorithm with 2D-FDTD simulations [9]. For the two-dimensional grating, EMT is used and only the performance of the mode TE_0 is considered in the optimization process, as the mode TE_1 has similar effective refractive index and the grating region is symmetric for two orthogonal polarizations [10]. On-chip mode multiplexing of the TE_0 and TE_1 is realized by the asymmetric directional couplers (ADCs) which has a coupling gap of 200 nm [11]. The single-mode input waveguide has a width of 450 nm and the multimode bus waveguide has a width of 962 nm. The multimode waveguide connects with the grating that has a width of about 13.2 µm after a 360-µm linear taper.

Fig. 2(a) shows the structural width of the grating teeth and slits of the optimized single-polarization grating coupler. The minimum feature size is 181 nm for robust fabrication by 193-nm DUV lithography. The corresponding coupling efficiencies including the LP_{01} mode and LP_{11} mode are shown in Fig. 2(b) obtained by 3-D FDTD simulation. The single-polarization grating coupler has a peak experimental coupling efficiency of – 2.30 dB at 1557.14 nm for LP_{01} mode, and – 2.96 dB at 1555.10 nm for LP_{11} mode. The 3-dB bandwidth is 67.4 nm and 65.3 nm, respectively. Grating period of the two-dimensional grating is shown in Fig. 2(c). All the 70-nm shallow etched holes have the same diameter of 328 nm for ease of fabrication. Simulation performance of the grating is shown in Fig. 2(d). The obtained peak coupling efficiency is – 3.20 dB at 1538.78 nm for LP_{01} mode and – 4.01 dB at 1536.73 nm for LP_{11} mode. The 3-dB bandwidth of the two modes are similar of about 28.5 nm.

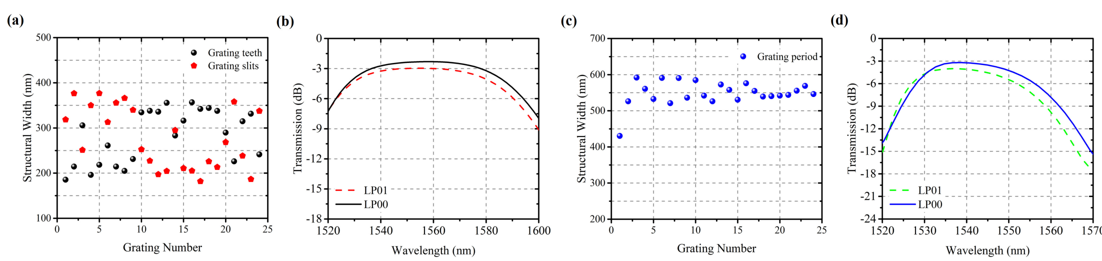

Fig. 2. (a) Structural width of the teeth and slits of the single-polarization grating coupler. (b) Coupling efficiencies of the single-polarization grating coupler with GI-FMF obtained by 3D-FDTD simulation. (c) Width of the grating period of the two-dimensional grating coupler, the shallow-etch holes have the diameter of 328 nm. (d) Coupling efficiencies of the two-dimensional grating coupler with GI-FMF obtained by 3D-FDTD simulation. Performance of the other orthogonal polarization is the same.

3. EXPERIMENTAL RESULTS

The silicon photonic chip was fabricated in a multi-project wafer (MPW) run at *IMEC*. Fig. 3(a) shows the microscopic image of the photonic integrated circuits including the input single-mode grating coupler, ADCs, linear waveguide taper and the diffraction gratings for GI-FMF. The input single-mode grating coupler is based on 10° off-vertical coupling. On-chip mode multiplexing of the TE_0 and TE_1 is realized by ADCs which has an experimental crosstalk lower than – 15 dB from 1520 nm to 1620 nm. A peak coupling efficiency of – 2.8 dB for LP_{01} mode is measured at 1552.0 nm for the single-polarization waveguide grating as depicted by Fig. 3(b). The LP_{11} mode has a peak efficiency of – 3.88 dB at 1539.4 nm. The 3-dB bandwidth of the two modes are 61.2 nm and 59.0 nm, respectively. Fig. 3(c) shows the measured coupling efficiencies of the two-dimensional grating for

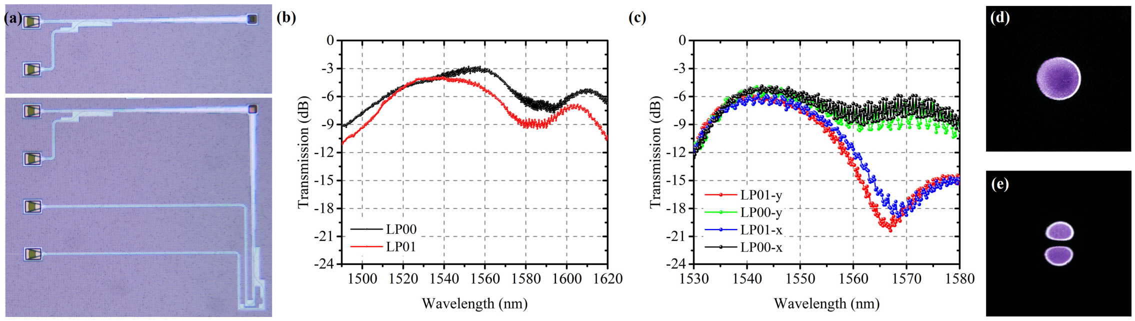

Fig. 3. (a) Microscopic image of the photonic integrated circuits consisting of the input single-mode grating coupler, ADCs, linear waveguide taper and the single-polarization or two-dimensional few-mode grating coupler. (b) Experimental coupling efficiencies of the single-polarization grating coupler for GI-FMF. (c) Experimental coupling efficiencies of the two-dimensional grating coupler for GI-FMF including two orthogonal polarizations. (d) and (e) Mode field profiles of the GI-FMF captured by an infrared camera with a 40× lens when LP_{01} mode and LP_{11} mode are excited by the waveguide gratings.

launching the two polarizations of the LP_{01} mode and LP_{11} modes. The obtained peak coupling efficiencies are – 4.89 dB and – 4.96 dB for LP_{01} mode. LP_{11} mode has peak coupling efficiencies of – 5.87 dB and – 5.71 dB. The 3-dB bandwidth are 23.2 nm and 21.6 nm, respectively. Mode field profiles of the GI-FMF captured by an infrared camera with a 40× lens, are presented in Figs. 3(d) and 3(e), demonstrating the selective launch of LP_{01} mode and LP_{11} modes via the diffraction waveguide gratings.

4. CONCLUSIONS

We propose novel diffraction waveguide gratings on SOI for a two-mode GI-FMF, which has a low DGD of less than ± 0.2 ps/m for future high-speed data transmission. The experimental coupling efficiency of the single-polarization waveguide grating is – 2.8 dB for the LP_{01} mode, and – 3.88 dB for the LP_{11} mode. The 3-dB bandwidth of the two modes are 61.2 nm and 59.0 nm, respectively. A two-dimensional waveguide grating which supports two orthogonal polarizations of the LP_{01} mode and LP_{11} mode is also demonstrated with peak coupling efficiency of – 4.89 dB for LP_{01} mode and – 5.71 dB for LP_{11} mode. The 3-dB bandwidth are 23.2 nm and 21.6 nm respectively. The multimode waveguide gratings couplers for GI-FMF can enable the integration of transceivers with four data channels per wavelength in the future SDM networks.

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