Efficient Mode Multiplexer for Few-Mode Fibres Using Integrated Silicon-on-Insulator Grating Coupler

Student Paper

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ABSTRACT

A novel high-efficiency mode multiplexer is proposed to launch four channels including two polarizations of the LP01 mode and LP11 mode into step-index few-mode fibres (FMFs). Simulations predicted the coupling efficiency to be −4.3 dB for LP01 mode and −5.0 dB for the LP11 mode. Back reflections less than −11 dB is obtained within the C band. The design was fabricated in a multi-project wafer (MPW) run for silicon photonics. Experimental coupling efficiency of −4.9 dB and −6.1 dB was obtained for LP01 and LP11, respectively. The proposed mode multiplexer is suitable for future applications with FMFs in space-division-multiplexing networks.

Keywords: Integrated optics, diffraction gratings, few-mode fibres, space-division multiplexing.

1. INTRODUCTION

Driven by the exponential growth of data traffic in recent years, use of the transmission capacity of conventional standard-single mode fibre (SSMF) has already approached the theoretical limit imposed by the Shannon's information theory and nonlinear fibre effects. Dense wavelength-division-multiplexing, polarisation multiplexing, and spectrally efficient advanced modulation formats have all been exploited to increase the optical transmission capacity in SSMFs. Introduction of the new dimension of space-division multiplexing (SDM) using few-mode fibres (FMFs) has attracted much interest to enable further growth in transmission capacity and meet continued exponential growth in data centre traffic [1]. A reliable, efficient and low-cost method to excite the different fibre modes is thus highly desired for future practical applications.

In addition to approaches employing photonic lanterns and free-space optics [1]–[3], integrated diffraction gratings implemented on silicon-on-insulator (SOI) platform is also an interesting alternative. The monolithic integration offers advantages of low cost, mass-production ability and capability of co-integration with other integrated photonic devices such as transceivers [4]. Previous demonstrations include the use of circular gratings for a special ring-core fibre [5], push-pull driven gratings[6]–[8] and a single sub-wavelength gratings [9], [10] for standard FMFs. However, due to severe mode mismatch and limited directionality, it is challenging to obtain an experimental coupling efficiency better than −20 dB with the FMFs. A coupling efficiency of −10.6 dB was demonstrated with the use of an aluminium mirror [11].

Here we report the first experimental demonstration of an efficient mode multiplexer employing a single diffraction grating for excitation of the linear polarized (LP) modes LP01 and LP11 in a standard step-index FMF (four channels including polarization diversity), with an experimental coupling efficiency of −4.9 dB and a mode-dependent loss of 1.2 dB. The proposed device has a good fabrication tolerance and was fabricated in a passive multi-project wafer (MPW) run for silicon photonics at *IMEC*, and thus is suitable for industrial large-volume manufacturing of photonic integrated circuits (PICs).

2. DESIGN AND SIMULATION

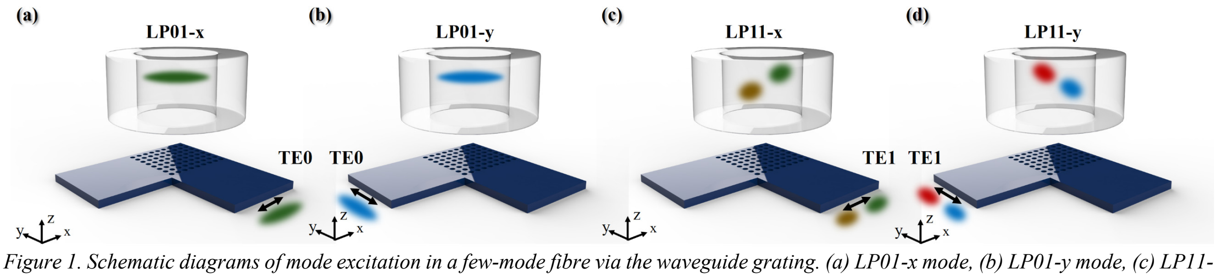

Figure 1. Schematic diagrams of mode excitation in a few-mode fibre via the waveguide grating. (a) LP01-x mode, (b) LP01-y mode, (c) LP11-x mode and (d) LP11-y mode.

The proposed grating coupler is designed for an *OFS* standard two-mode step-index FMF with a core diameter of 19.4 µm, which can support LP01 mode and LP11 mode with a mode field diameter (MFD) of 15.6 µm and 13.6 µm, respectively. The principle of mode excitation via a single diffraction grating is schematically depicted in Figs. 1(a)-(d). Transverse-electric (TE) modes, TE0 and TE1 are employed to selectively excite the LP01 mode and LP11 mode in FMF. Efficient coupling of the two TE modes is possible because the difference between their effective refractive index is very small in the wide slab waveguide and grating structure. Excitation up to four channels in FMFs is achieved by exploiting the orthogonal polarization. The silicon-on-insulator (SOI) wafer has a 220-nm-thick top silicon layer and a 2-µm-thick buried-oxide layer.

MFD of LP01 mode and LP11 mode in the step-index FMF is larger than the typical MFD of the SSMF. Reduced grating strength is thus necessary by employing the 70-nm shallow-etched subwavelength holes in the standard fabrication process provided by the fabrication foundry.

Due to the diffraction symmetry of the proposed structure, perfectly vertical coupling is required to reduce the channel-dependent coupling loss. Typical grating couplers are designed to couple the light at a small angle relative to the chip-surface normal to suppress the second-order Bragg reflection into the waveguides. We recently achieved an efficient perfect vertical coupling by using the genetic optimization with finite-difference time-domain (FDTD) simulations [12].

Schematic diagram of the proposed PICs is presented in Fig. 2 (a). Four input optical signals are coupled via the 10° off-vertical standard single-mode grating couplers to 450-nm single-mode waveguides. Asymmetric directional couplers (ADCs) with a 200-nm coupling gap are utilized for the mode multiplexer of the TE0 mode and TE1 mode [13], [14]. The 1.006-µm-wide multimode waveguide are connected to the 22-µm-wide grating by a 600-µm-long linear adiabatic taper with negligible loss for both TE0 mode and TE1 mode. 40 rows and columns of the round-shaped holes with the same diameter are utilized to cover an area of 22×22 µm^2 for the grating coupler.

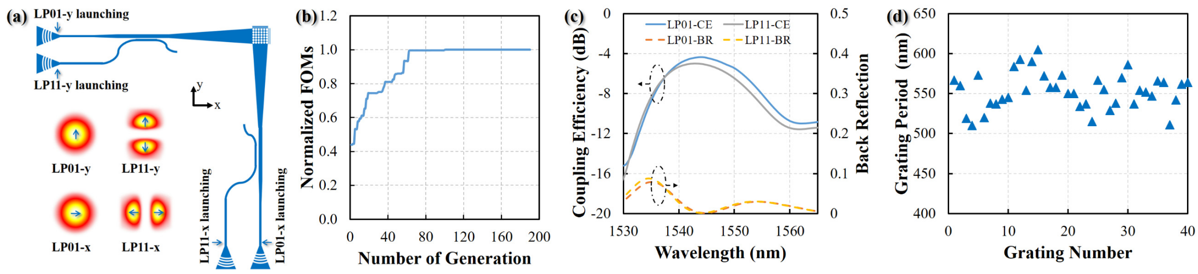

Figure 2. (a) Schematic diagram of the proposed PICs. (b) Evolutionary diagram of the normalized fitness against the number of iterations. (c) Coupling efficiency (CE) and back reflection (BR) of the final-optimized grating coupler. (d) Optimized grating periods.

Structural parameters including the grating periods, the hole diameter and the end-reflectors are optimized by the genetic optimization algorithm to suppress the back reflection and improve the coupling efficiency. The fitness *F* is denoted by Eq. (1), where CE is the coupling efficiency and BR corresponds to the back reflection.

$$F = \sum_{i=1}^{N} CE\left(\lambda_i\right) - BR\left(\lambda_i\right) \tag{1}$$

To save the simulation time for numerical iterations of the multiple parameters space, 2-dimentional (2-D) FDTD combined with the effective medium theory is used [15], [16] for optimization of the TE0 mode. Coupling performance of the TE1 mode is thus not considered in the optimization process, under the premise that it has a similar effective refractive index with the TE0 mode in the grating region. Coupling performance of both the TE modes was finally verified by the 3-D FDTD simulations. Due to the design symmetry of the grating structure, an equivalent performance is expected for the two orthogonal polarizations.

Evolutionary diagrams of the normalized fitness against number of iterations is shown in Fig. 2 (b). Obvious convergence progress is observed. Performances of final-optimized grating coupler are obtained by 3-D FDTD simulation as presented in Fig. 2(c). TE0 mode has a coupling efficiency of −4.3 dB (36.8%) at 1544 nm. TE1 mode has a coupling efficiency of −5.0 dB (31.8%) at 1542 nm. 3-dB bandwidth is about 20 nm for both modes. Reflection into the SOI waveguide is suppressed below −11 dB within C band. The optimized grating periods are shown in Fig. 2(d). The side length of the square-shaped holes is 286 nm, which corresponds to round-shaped holes with a diameter of 322 nm. Three rectangular slabs with a width of 190 nm and a spacing of 240 nm are used as an end reflector at the end of the grating. The minimum feature size of the proposed structure is ≥190 nm for robust fabrication using 193 nm deep-ultraviolet lithography.

3. EXPERIMENTAL RESULTS

The coupling efficiency is characterized by measuring the fibre-waveguide-fibre insertion loss with a SSMF as the input and a FMF as the output. The coupling spectrums of the LP01-x, LP01-y, LP11-x and LP11-y using a single diffraction grating are shown in Fig. 3(a), after normalizing out the loss from the ADC, the linear taper and the single-mode grating coupler fabricated on the same chip. A coupling efficiency of −4.9 dB is obtained at 1551.0 nm for LP01-x mode and LP01-y mode. LP11-x mode and LP11-y mode have a coupling efficiency of −6.1 dB at 1549.6 nm. 3-dB bandwidth for all the four channels is about 15 nm. Output field profiles of the FMF are captured by an infrared camera with a 40× lens as shown in Figs. 3(b) and 3(c), demonstrating that the grating coupler can selectively launch LP01 and LP11 modes in the FMF. Scanning electron microscope (SEM) images of the PICs are obtained by removing the top protective resist of the same chip without oxide deposition. The fabricated ADCs, single-mode grating couplers and grating coupler for mode-selective launching are shown in Fig. 3(d) and 3(e).

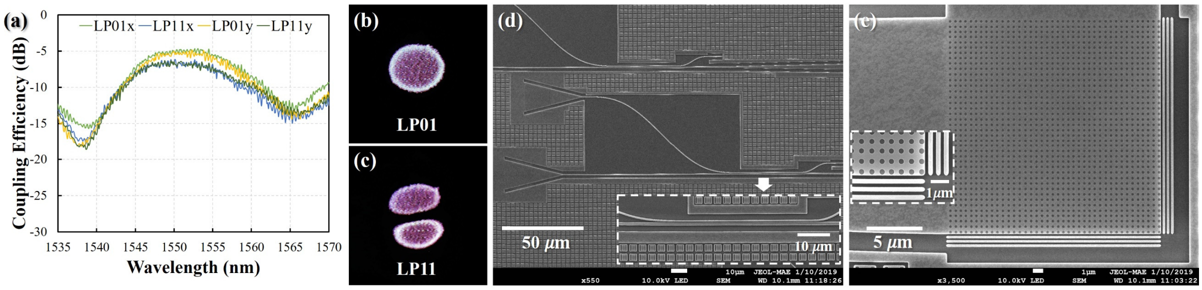

Figure 3. (a) Coupling efficiencies of the grating coupler for LP01-x, LP01-y, LP11-x and LP11-y, respectively. (b), (c) Output field profiles of the FMF when LP01 mode and LP11 mode are selectively coupled. (d) SEM image of the single-mode gratings and ADCs with a zoom-in view shown in the inset. (e) SEM image of the fabricated grating coupler with a zoom-in view shown in the inset.

4. CONCLUSIONS

We propose a novel design of the mode multiplexer employing a single diffraction grating on SOI capable of excitations of the LP01-x, LP01-y, LP11-x and LP11-y modes in a step index FMF. Coupling efficiency up to −4.3 dB is obtained in simulation with a mode-dependent loss of 0.7 dB. Experimental coupling efficiency of −4.9 dB and −6.1 dB is demonstrated respectively for two polarizations of the LP01 mode and the LP11 mode. To the best of our knowledge, this is the first experimental demonstration of such high-efficiency four-channel mode multiplexer for FMFs using integrated grating coupler on SOI. The demonstrated mode multiplexer is suitable for future applications with FMFs in space-division-multiplexing networks.

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