Integrated Dual-Mode Waveguide Interferometer

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***Abstract*—A novel type of interferometer with an ultra-small footprint is presented. The functional principle is based on the excitation of the first and the second order modes in an integrated dual-mode strip waveguide. The light is coupled from a single mode fiber to the dual-mode waveguide by a conventional grating coupler followed by a taper. The difference in the mode propagation velocity leads to a phase difference between the fundamental mode and the second order mode. A proof of concept in the silicon on insulator technology shows promising extinction ratios of around 30 dB.**

I. INTRODUCTION

In the field of integrated silicon photonics the Mach-Zehnder interferometer (MZI) is an important passive component, which is used in many devices, such as high speed modulators [1] or high sensitivity sensors [2]. The input signal of a MZI is divided into two signals, normally with the help of a Y-junction or a multimode interference coupler (MMI). After traveling through MZI arms with different optical path lengths, both signals are combined with a phase shift and interfere. In addition another principle [3] is used. Thereby, one signal excites the quasi transverse electric (TE) mode and the quasi transverse magnetic (TM) mode. After passing the same waveguide section, both signals are combined with the help of a polarizer and interfere with a phase shift based on the different mode velocities. In this paper we present an interferometer that does not need a second arm or additional polarizers. Moreover, the novel approach is beneficial for sensor applications due to the use of a widespread second order mode.

II. FUNCTIONAL PRINCIPLE

The novel interferometer design (Fig. 1) is based on a dual-mode strip waveguide (DMW), in which the first and the second order modes can propagate with different velocities. Both modes are excited, e.g. by a conventional grating coupler followed by a taper as explained later. After excitation, the two modes travel through the DMW. The resulting phase difference between the modes depends, consequently, on the traveled distance L, the wavelength and the propagation velocities. Finally, the modes are combined by a reverse dual-mode excitation process. Hereby, the two modes can excite only one guided output mode and the excitation efficiency depends on

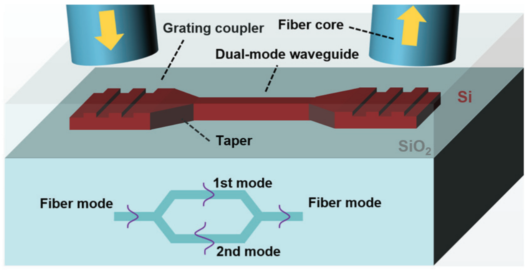

Fig. 1. Schematic design of a dual-mode waveguide interferometer. The signal of a single mode fiber excites different modes in a grating coupler. The excited modes are tapered. Only the two lowest order modes can propagate further in the dual-mode waveguide. Subsequently, the modes travel through the waveguide and are combined by the outcoupling process. Coupling efficiency depends on the phase difference between the modes.

the phase difference between the DMW modes. The excited output mode is in this specific case a fundamental fiber mode. Similar to a MZI, the free spectral range (FSR) can be expressed by the help of the group indices of the first (n_{g1}) and second (n_{g2}) order modes for a wavelength $\lambda >> \text{FSR}$ as

$$FSR \approx \frac{\lambda^2}{L*(n_{g1}-n_{g2})}. \quad (1)$$

The simulated group indices are presented in Fig. 2 for the silicon on insulator (SOI) platform with a pure SiO_2 cladding. An FSR of approximately 9.6 nm results for a Si waveguide

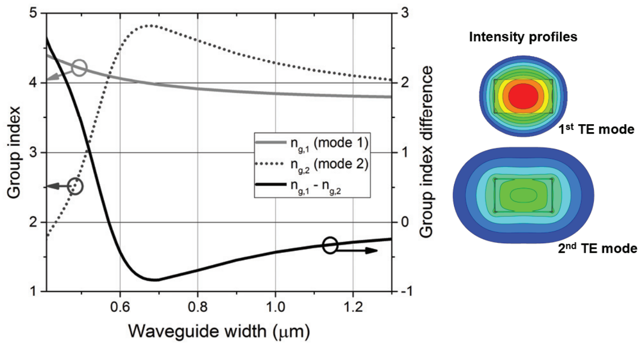

Fig. 2. Group index versus waveguide width of the first and second order TE modes for a DMW and the resulting group index difference are shown at λ = 1550 nm, simulated using the FIMMWAVE film mode matching solver. The silicon layer has a thickness of 250 nm. Exemplary mode intensity profiles are also shown on the right for a waveguide width of 420 nm.

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cross-section of 250 nm x 420 nm and a length L = 100 µm at λ = 1550 nm. The second mode has a fill factor of only 6%, which means that the large part of the mode propagates outside the core (Fig. 2). The enormous difference of the first and second mode fill factors can be controlled by the waveguide width and is profitable for sensor applications.

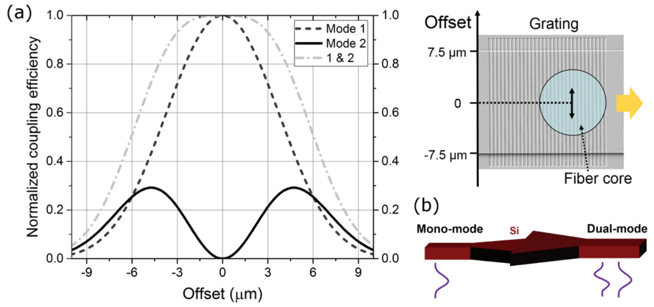

Fig. 3. (a) Approximated coupling efficiency to the first and second order TE modes for a 15 µm broad SOI grating coupler versus lateral offset of the fiber core with respect to the grating coupler center. The Gaussian fiber mode profile has a mode field diameter of 10.4 µm. (b) Suggestion for dual-mode excitation with mono-mode waveguide input enabled by two laterally displaced tapers.

In this experiment the DMW mode excitation is done by a grating coupler with a single mode fiber input and depends on the lateral position of the fiber core above the grating. Coupling efficiency (Fig. 3a) to the modes can be approximated by an overlap integral of the fiber mode with the mode profiles in the broad silicon grating strip [4]. The position of equal excitation (PEEX) of the first and second mode is achieved for a lateral offset of about 6 µm. At this point the overall coupling efficiency decreases to half of the maximum single mode coupling efficiency for a 15 µm broad periodic grating coupler. The PEEX itself and the overall coupling efficiency at the PEEX depend especially on the grating width. In this experiment the fiber-to-fiber insertion loss (IL) is determined by the two offset-specific grating coupling efficiencies, the taper losses and the DMW loss. For some applications the development of novel devices with an integrated single-mode input and dual-mode output (Fig. 3b) or the use of multimode fibers [5] for dual-mode excitation are useful options.

III. Validation

DMWs with a width of 420 nm and 15 µm broad grating couplers are structured lithographically by a reactive-ion etching (RIE) process at the Institute for Microelectronics

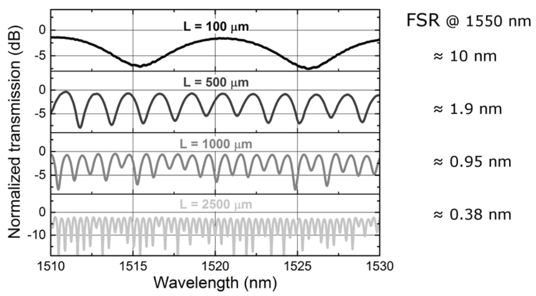

Fig. 4. Optical transmission of different DMWs with grating coupler input and output versus wavelength normalized to the zero-offset transmission. The presented FSR values are calculated for different spectral maxima and minima in the vicinity of 1550 nm. The used TE grating couplers have a 400 µm long taper.

Stuttgart on a SOITEC SOI wafer with a nominal Si thickness of 250 nm on top of a 3 µm thick buried SiO_2 layer. The wafer is passivated by an approximately 1 µm thick SiO_2 cladding. Fig. 4 shows the measured optical transmission spectra and the resulting FSR values for four different DMW lengths. The 400 µm long taper has only a small influence on the FSR, caused by the marginal difference between the two TE propagation velocities in a widened silicon strip (Fig. 2). Therefore the resulted values fit well with (1). A high extinction ratio (ER) above 30 dB can be achieved as depicted in Fig. 5.

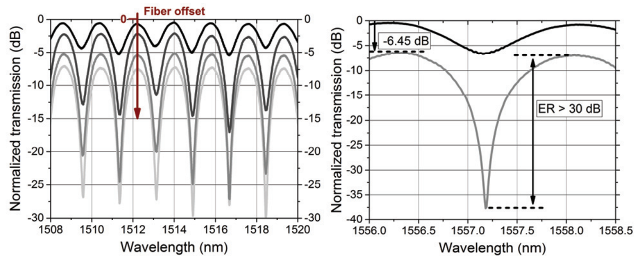

Fig. 5. Normalized transmission for a DMW interferometer with L = 500 µm for different lateral offsets of the input and output fiber cores. Both fibers are adjusted by piezoelectric actuators to maximize the first order mode excitation, defining the zero-offset position. At this point the minimum total IL is 8.3 dB at λ = 1552.8 nm, mostly due to the grating coupling efficiencies. Afterwards the chip is moved in lateral direction and the fiber positions remain unchanged. The achieved ER depends on the offset.

The dependency of the ER on the DMW mode excitation is presented for different fiber offsets. The spectral positions of the minima and maxima are unchanged, whereas the ER shows a symmetric dependency on the offset of the two grating couplers as expected. In this setup the ER can be maximized by the positions of the fiber cores for applications to achieve a high ER. Hereby, inequal propagation losses of the modes can be compensated.

IV. Conclusion

The novel interferometer design based on a dual-mode waveguide offers a compact and useful functionality. With the use of the fundamental mode in combination with a second order mode a new approach of integrated interferometer is demonstrated, which utilizes the differences of mode velocities and mode-field profiles. Such novel interferometers offer the possibility of ultra-compact sensor applications, spectrometer applications and high speed modulation, not only in the silicon on insulator platform.

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