Silicon-on-Insulator (SOI) Delay-Line Interferometer with Low Polarization-Dependent Wavelength Shift

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Abstract: *A 40 Gbit/s delay-line interferometer realized in SOI rib waveguide technology is presented. Across the C-band we demonstrate high uniformity, low loss, low PDL, and PDF as low as 1 GHz for the SOI interferometer.*

1. Introduction

Silicon photonics has become a vast and quickly growing area of photonics R&D within less than a decade. Most of the attractiveness of the technology stems from the vision of a convergence of electronics and photonics on one substrate, using only Silicon manufacturing tools. The high index contrast of the Silicon-on-Insulator (SOI) material system allows for very compact devices [1], while the integration with CMOS electronics permits the fabrication of photonic integrated circuits [2]. Silicon-on-Insulator (SOI) waveguide technology for optical communications motherboards, on the other hand, has recently attracted attention for different reasons. Devices fabricated in this technology have larger footprints than ultra-compact SOI waveguide devices. However, they feature distinct advantages compared to the latter, such as low-cost fabrication technology, much reduced birefringence, and the possibility to match silicon waveguide mode size to that of III-V active devices.

In course of another work we have previously demonstrated a 4-wavelength CWDM transmitter chip for LX4 applications. The chip comprised a SOI motherboard with an arrayed waveguide grating multiplexer combined with four flip-chip-soldered DFB laser-diodes [3]. Here we present a Mach-Zehnder-Delay Interferometer (MZI) device realized in SOI waveguide technology, which exhibits very low Polarization-Dependent Wavelength / Frequency (PDWL / F) shift. The device is to be integrated with a balanced photodiode pair to implement a DPSK receiver chip for direct demodulation of 40 Gbit/s DPSK signals. Since PDF shift is a major performance issue for all balanced DPSK detection schemes this paper shall demonstrate the potential of SOI waveguide technology, respectively.

2. Device technology and design

The devices were fabricated in rib-waveguide technology on 4 µm commercial BESOI (Bonded and Etched-back SOI) substrates. Waveguides were fabricated using standard contact lithography and reactive-ion etching (RIE), which in our case was based on Fluorine chemistry. The devices received an antireflective coating before measurements.

The MZI layout followed a straight-forward left-in / right-out design that is adapted to the geometry of our measurement setup. We chose 2x2 paired Multi-Mode Interference (MMI) couplers as splitting and combining elements [4], because of their comparatively low sensitivity to process variations. The chip-area was 25 x 25 mm^2, combining 3 MZI devices and some test-structures on a single die. The size of the chip could be further reduced if test-structures and other MZI-devices are omitted. The layout of the actual chip is shown in Fig. 1. The MZI was designed for 40 Gbit/s DPSK demodulation, which corresponds to a free spectral range of 0.32 nm at 1550 nm.

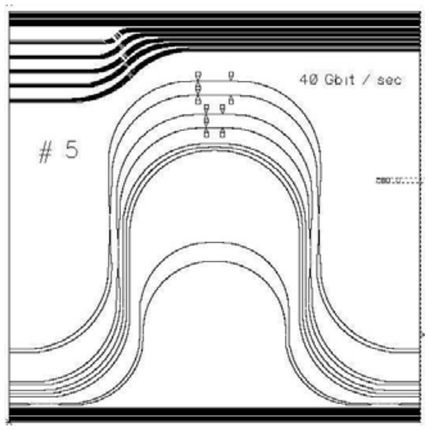

Fig. 1. Layout of the delay interferometer chip (three delay interferometers plus test structures).

3. Experimental results

PDF-specifications for balanced DPSK receivers are in the range of 1 GHz (~ 8 pm at 1550 nm) [5]. To measure such small shifts, polarization and temperature need to be carefully controlled. Our measurement setup is sketched in Fig. 2. A tunable laser source (Agilent 81940A) feeds a programmable polarization controller (8169A), which provides a well defined state of polarization. Light is coupled-in and out of the samples using lensed single-mode fibers with a spot-diameter of ~ 3 µm, corresponding to typical coupling-loss values of 1 dB per facet. A fiber optical power sensor (81634B) provides the dynamic range and measurement speed required for stable measurements of the MZI transmission characteristics.

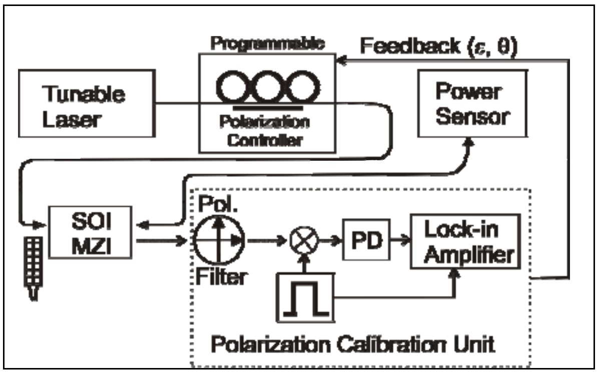

Fig. 2. Setup for PDWL shift measurements. Solid lines correspond to fiber or cable connections, dotted lines represent free space transmission paths. The photodiode (PD) of the polarization calibration unit provides a feedback signal depending on the (ε, θ)-settings of the polarization controller.

During the measurements the samples were temperature-stabilized. To compensate the birefringence properties of the fiber at the coupling-in side, a feedback signal from the polarization calibration unit was used. Only linearly polarized light was employed during the experiments. The stability of the state of polarization delivered by the setup was confirmed by identical polarization calibration curves taken before and after the experiment. In the following, all measurements are presented with respect to the fiber-to-fiber transmission signal.

Wavelength scans were conducted with 1 pm increment for small wavelength ranges (< 10 nm), and with 4 pm resolution for larger ranges. To determine the PDWL shift-value, transmission curves were measured for both polarizations (TE/TM). We observed that within the scanned wavelength window (e.g. 2nm around 1550nm in Fig. 3), PDWL shift-values varied randomly between positive and negative (see the lower part of Fig. 3). It is therefore not sufficient to state a PDWL shift-value measured at a single minimum. To determine an upper limit for the PDWL shift-values we always calculated an rms-shift-value over 10 minima, as shown in the upper part of Fig. 3. In this paper, unless stated otherwise, we shall, thus, always list the rms-value.

The C-band transmission characteristics of a 40 GHz SOI-MZI is depicted in Fig. 4 (TM-polarization, the filter characteristic of the TE-mode is very similar, and is therefore not presented here). Fig. 4 reveals a uniform insertion loss (~ -3 dB) as well as high extinction ratios across the entire C-band (minimum 24 dB).

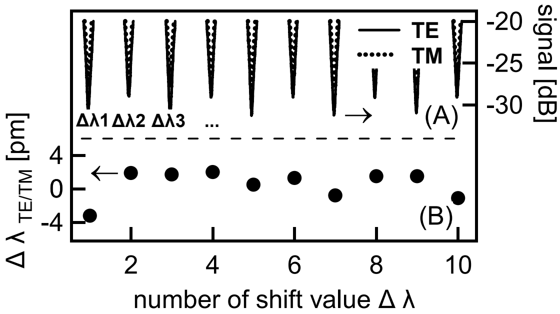

Fig. 3. TE/TM-transmission curve minima (A), and PDWL shift-values (B). The minima in (A) were measured in the range 1550 ± 2 nm . In (B), each Δλ-value was determined from the corresponding pair of TE/TM-minima in (A).

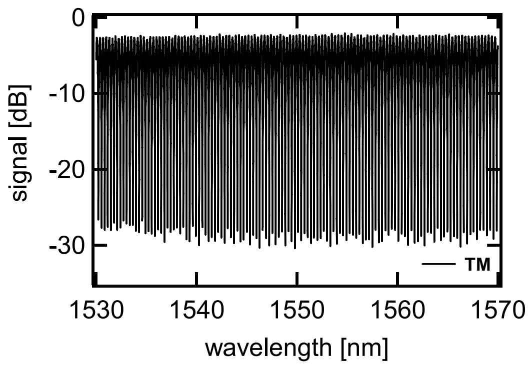

Fig. 4. C-band filter characteristic of a 40 GHz MZI on SOI. The curve represents the measurement in TM-polarization (T= 35 ºC). The signal values were determined with respect to the fiber-to-fiber signal.

We noticed (Fig. 5) a slightly higher insertion loss (~ -4 dB) for the TM-mode, which we attribute to a higher excess loss of the MMI-couplers in the TM-case. Polarization-dependent excess loss of MMI-couplers in this technology has also been reported by others [6]. Slightly higher extinction ratios were observed in case of TM-polarization (minimum 26 dB). Fig. 5 shows that our MMI-couplers exhibit correct splitting ratios and phase relation between the ||-port and the X-port.

Polarization-dependent frequency of the demodulator MZI is considered a severe threat to DPSK receiver performance. Specifications for the PDF were discussed previously [5], typical limits are ~1 GHz. Fig. 6. depicts the transmission minima for TE/TM-polarization at the outer limits as well as in the middle of the C-band. The measured polarization-dependent shift never exceeds 1 GHz. We observed shifts staying below 1 GHz also for chip-temperatures up to 70°C. These results are comparable to the best values that have been achieved in other technologies [7]. To the best of our knowledge, such low PDWL / F shift values are shown for the first time in SOI waveguide technology. The polarization-dependent envelope of the transmission characteristic at maximum leads to a Polarization Dependent Loss (PDL) of ~1 dB.

Due to drift and offset, the demodulator will need to be tuned to the laser frequency by temperature control. Linearity of the tuning characteristic is a desirable feature of the demodulator chip. In our setup, we have varied the temperature of the chip (using a Peltier element), to study the tuning characteristic of our SOI MZI. The position of the minimum of the TM-curve at 1550nm relative to an arbitrary zero at 35 ºC is shown in Fig. 7. together with a linear fit of the data.

The shift of the minimum position as a function of chip temperature follows a linear characteristic, with a tuning increment of ~ 80 pm/K, for both, TE and TM polarization.

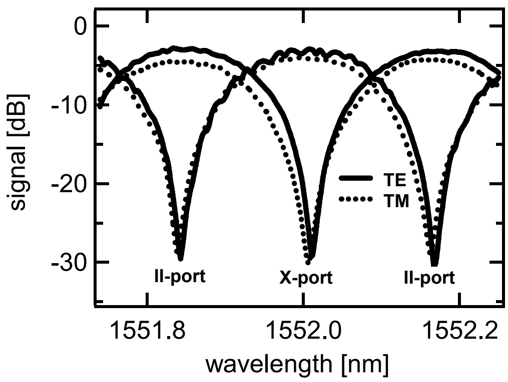

Fig. 5. Signals at the II- and the X-port for both polarizations.

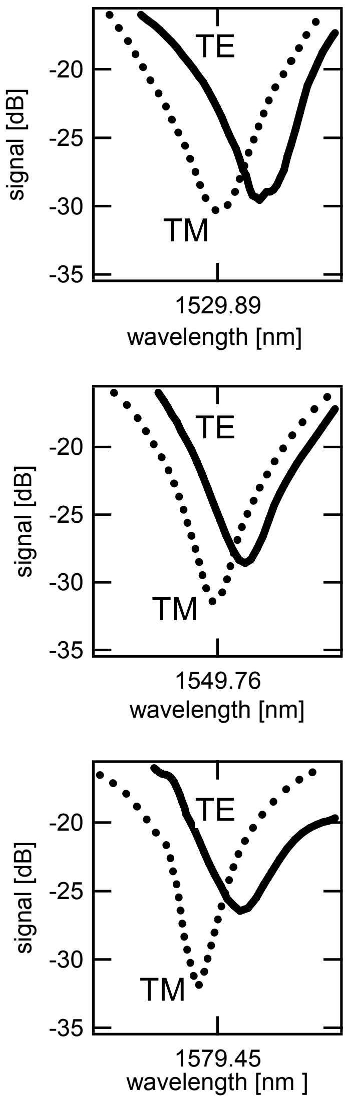

Fig. 6. Polarization dependent frequency shift of the minimum transmission (TE/TM) across the C-band, at 1530 nm, at 1550 nm, and at 1570 nm (each graph depicts a wavelength range of 50 pm). The measured shift in all three cases is ~ 8pm (1 GHz). T = 35 ºC.

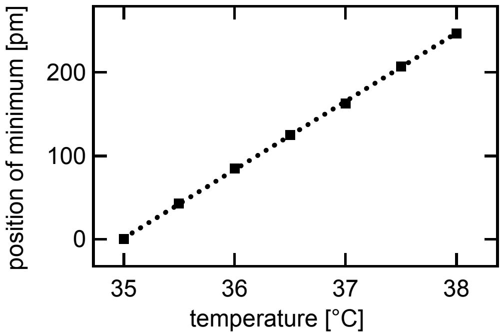

Fig. 7. Position of the minimum of the TM curve as a function of chip temperature. The position is relative to an arbitrary 0 at 35 ºC. Also shown is the linear fit of the data, the increment is ~ 80pm / K.

4. Summary and conclusions

Our MZI devices based on SOI rib waveguide technology exhibit across the entire C-band PDF as low as 1 GHz, extinction ratios substantially exceeding 20 dB, uniform insertion loss, and low PDL. The here presented results demonstrate for the first time the high potential of SOI rib waveguide technology for low-PDF applications, in particular for balanced DPSK reception. A system validation experiment of fiber-optical 40 Gbit/s DPSK transmission using the here presented SOI delay-line interferometer is planned for the near future.

5. References

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