Performance of 40-Gb/s DPSK Demodulator in SOI-Technology

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***Abstract*—A silicon-on-insulator delay interferometer manufactured in 4-μm rib waveguide technology is presented. The polarization-dependent frequency shift is tuned to a value as low as 0.4 GHz. Continuous-wave device performance and polarization-independent differential phase-shift keying demodulation performance in a 40-Gb/s testbed are demonstrated.**

***Index Terms*—Demodulation, differential phase-shift keying (DPSK), rib waveguide, silicon-on-insulator (SOI) technology.**

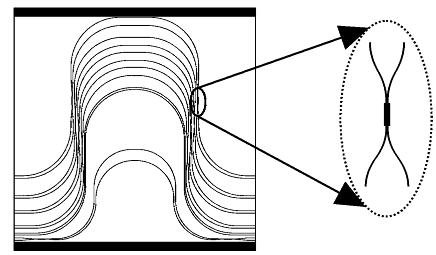

Fig. 1. Layout of the DI chip (five DIs plus test structures). Inset shows a 2 × 2 MMI coupler as part of one DI.

I. Introduction

FOR upgrades of present fiber-optical communication systems to 40-Gb/s differential phase-shift keying (DPSK), component manufacturers seek integrated solutions at the receiver side to reduce footprint, and component costs. The development of integrated receivers has been hampered much by the stringent specifications on polarization-dependent frequency (PDF) shift related to the birefringence of the waveguides. Conventional silica technologies offer control of waveguide birefringence down to $\sim 10^{-3}$, while DPSK receivers require approximately $\sim 10^{-5}$ birefringence control. To achieve such small PDF shifts, these technologies use stress release grooves [1] or half-wave plates [2], and report best PDF shifts of approximately 1 GHz.

DPSK demodulation requires a small relative PDF shift, i.e., a tuning of the shift between adjacent filter curves. In silicon-on-insulator (SOI) rib waveguides, birefringence arises due to the geometry of the waveguide, and due to mechanical stress in the structure. To this extent, integrated optics based on medium-sized SOI rib waveguides offers a technological advantage compared to silica technologies. Since the PDF shift in medium-size rib waveguides results to an approximately equal fraction from modal and stress induced birefringence, very precise birefringence control is achievable in SOI technology.

SOI technology has already been employed commercially [3], and this letter demonstrates the technology's potential for low-polarization-dependence applications. We shall present performance data of a 40-Gb/s Mach–Zehnder (MZ) delay interferometer (DI) device realized in 4-μm SOI waveguide technology.

The letter will demonstrate that SOI waveguide technology can perform up to state-of-the-art in DPSK demodulation, with the lowest ever reported PDF shifts in SOI waveguide technology.

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II. Design and Device Technology

The DI is designed for 40-Gb/s DPSK demodulation (i.e., a delay of 25 ps), which corresponds to a free-spectral range (FSR) of 40 GHz or 320 pm at 1550 nm. The chip area is 25 mm × 25 mm, combining five DI devices and some test structures on a single die (see Fig. 1). The devices are fabricated in rib waveguide technology on 4-μm commercial bonded and etched-back substrates. Waveguides are fabricated using standard contact lithography and reactive-ion etching.

The PDF shift of the transverse electric (TE) and transverse magnetic (TM) filter curves of the device is caused by the birefringence of the waveguides. Our measurements determine the absolute PDF shift of bare waveguides to be about 15 GHz (120 pm), which is in accordance with beam propagation method simulations. To achieve very small relative PDF shifts, we developed a birefringence tuning process, which uses mechanical stress induced by a cladding layer (silicon nitride). The basic mechanism has already been used to minimize the birefringence of silicon waveguides [4]. However, we use the effect in the opposite direction. In our case, the geometrical birefringence and the stress-induced birefringence have the same sign. Combining the two, it is possible to reduce the relative TE/TM shifts down to the required specification of about 1 GHz, and better, while the absolute birefringence of the tuned device corresponds to exactly one FSR. More details concerning chip technology and birefringence control may be found elsewhere ([5], [6]).

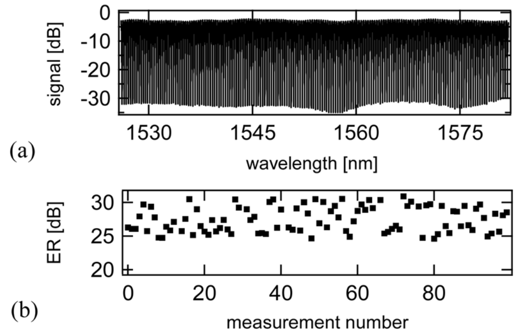

Fig. 2. (a) C-band filter characteristic of a 40-GHz DI on SOI. The curve represents the measurement in TM polarization; (b) extinction ratios (ERs) of 90 consecutive measurements with quasi-depolarized light (at 1550 nm).

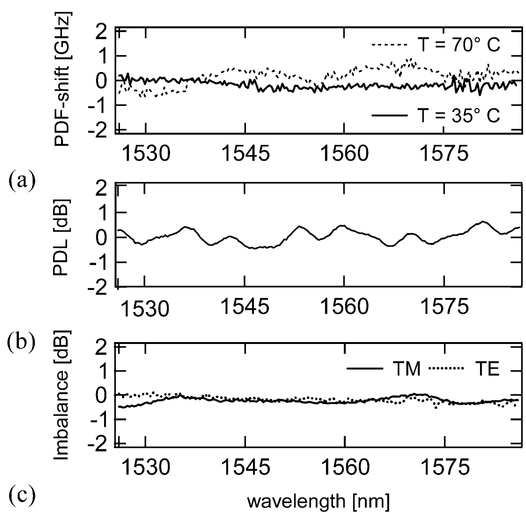

Fig. 3. (a) PDF shift for two temperatures ($T = 35$ °C, 70 °C); (b) PDL of the filter curve maxima for TE and TM mode across C-band; (c) port imbalance of TE/TM light across C-band.

III. Experimental Results

A. Continuous-Wave Filter Characteristic

The C-band transmission characteristics of a 40-GHz DI is depicted in Fig. 2(a) (TM polarization, the filter characteristic of the TE-mode is very similar, and is, therefore, not presented here). The graph reveals a uniform insertion loss (~ -3 dB) as well as uniform high polarized extinction ratio across the entire C-band (minimum 28 dB). The signal was taken with respect to the fiber-to-fiber measurement zero. In Fig. 2(b), we plotted extinction ratios of 90 consecutive measurements of quasi-depolarized light (during the measurement, the Poincaré sphere is scanned with high speed by the polarization controller). The extinction ratios spread over a corridor of 7 dB, with minimum extinction ratio of 24 dB.

Fig. 3 depicts the measured PDF shift over the C-band (a), the measured polarization-dependent loss [(PDL), (b)], and the port imbalance at the two output waveguides (c). The PDF shift never exceeds 3 pm (0.4 GHz). We observed shifts staying below $\sim$1 GHz also for chip-temperatures up to 70 °C [Fig. 3(a)]. These results are comparable to the best values that have been achieved in other technologies ([1], [2], [7], [8]). To our knowledge, such low PDF shift values are shown for the first time in

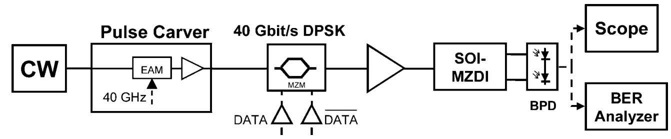

Fig. 4. The 40-Gb/s DPSK setup to test the demodulation performance of the SOI-DI.

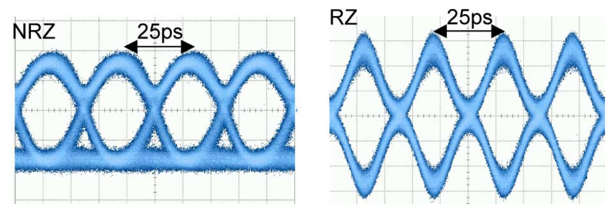

Fig. 5. Eye diagrams after demodulation of 40-Gb/s NRZ/RZ and balanced detection measurements.

SOI waveguide technology. PDL and port imbalance stay below 0.5 dB across the C-band. We attribute PDL to imperfections of the multimode interference (MMI) couplers, a problem already pointed out previously [3]. In general, the SOI rib waveguide technology suffers from the relatively small number of supported modes in MMI couplers, rendering these couplers more prone to excess loss (the major contribution to our insertion loss), port imbalance, and PDL. Use of higher definition lithography and more uniform SOI material could partly remedy that problem, but would also increase fabrication costs.

The small temperature dependence of the PDF shift is slightly counterintuitive. We would expect a larger shift. The temperature difference of 35 K between the two PDF shift measurements in Fig. 3(a) would imply a significant change in cladding-induced stress (deposition temperature 200 °C–300 °C). The reason for the observed relatively small additional PDF shift is presently not understood.

B. Balanced Detection Measurements

To test the system performance of the SOI interferometer, a DI device was used to demodulate a 40-Gb/s DPSK signal (see Fig. 4). The signals to drive the modulator were pseudorandom bit sequences (word length $2^7 - 1$), amplified in high-bandwidth broadband driver amplifiers. The return-to-zero (RZ) modulation format was generated with an electroabsorption modulator (EAM)-based pulse carver (duty cycle 40%–50%).

The modulated 40-Gb/s signal was amplified, fiber coupled in and out of the MZ demodulator, and detected by an integrated balanced photodetector (BPD). Fig. 5 shows the eye diagrams after demodulation and balanced detection, measured with a digital scope including a 70-GHz sampling head (nonreturn-to-zero (NRZ) measurement was done without EAM).

For RZ-DPSK, the bit-error rate (BER) was measured as function of received power. The resulting characteristics have been plotted in Figs. 6 and 7. To demonstrate the dependence of BER performance on PDF shift, we compared two DI devices: DI-1 (PDF shift: 0.4 GHz), and a device slightly off the optimum birefringence, DI-2 (PDF shift: 2.5 GHz). The input polarization was varied by means of a looped-fiber polarization controller. The state of polarization in the graphs was labeled

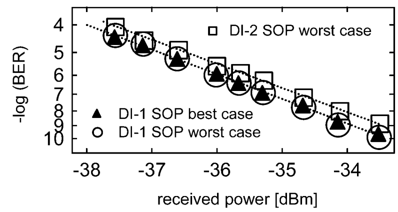

Fig. 6. Comparison of two SOI DIs. BER performance for best- and worst-case input polarization for DI-1 (PDF: 0.4 GHz), and for DI-2 (PDF: 2.5 GHz). The polarization-dependent penalty was only significant (∼1 dB) in the case of DI-2.

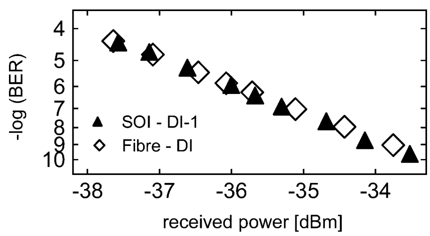

Fig. 7. BER performance of two types of devices: DI-1 in SOI technology, and a fiber DI (40 Gb/s). The performance of the two technologies is comparable.

best case for optimum BER performance, and *worst case* for lowest BER performance.

The measurement in Fig. 6 shows a polarization-dependent penalty of 0.1 dB in BER performance in the case of device DI-1 (small PDF shift). The BER performance of DI-2 is slightly worse due to the residual PDF shift of the device. The penalty in BER performance for DI-2 is ∼1 dB.

Fig. 7 compares the BER performance of a 40-Gb/s DI in SOI technology and a device in fiber technology for an arbitrary input polarization. The two BER curves are virtually indistinguishable, demonstrating equivalent performance of the two technologies.

IV. Summary and Conclusions

The presented SOI DI device exhibits across the entire C-band: PDF shifts 0.4 GHz, extinction ratios substantially exceeding 20 dB, uniform insertion loss, and low PDL. The 40-Gb/s DPSK measurements show state-of-the-art performance. This demonstrates the high potential of SOI rib waveguide technology for low-PDF shift applications. When comparing SOI technology with state-of-the-art fiber-based [7] and free-space devices [8], the following differentiators can be noted: SOI offers potentially smaller footprints (single device footprints, including sufficient area for hybrid integration of a balanced photodiode, are smaller than 25 mm $\times$ 10 mm), potentially lower sensitivity to vibrations than free space devices (due to monolithic planar structure), wafer-level fabrication technology, intrinsically high tuning efficiency (∼10 GHz/K). Due to the latter, stability problems might be anticipated for rapid temperature changes. Commercial temperature control systems stabilize better than $\pm$0.01 K. Although we did not implement advanced temperature control, real applications might require the use of such systems.

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