Recent Progress on High Contrast 40Gb/s and Low Drive Voltage 10 Gb/s Slow Light-Based Silicon Photonic Modulators

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The increasing need of more sophisticated means of communication is driving the demand for products and devices with high-speed and large bandwidth in data transfer along with low cost and high energy efficiency. Photonics technologies currently allow colossal amounts of data to be transmitted throughout the world via countless optical fiber links forming the global optical communication network. To address the ever increasing demand for bandwidth over shorter and shorter distances, silicon photonics seems to be the ideal candidate, solving in the near term the foreseeable electric interconnect bottleneck. As a result, integrated silicon photonics, which smartly benefits from the mature industrial complementary metal-oxide-semiconductor (CMOS) microelectronics technology, is expected to provide a very powerful, inexpensive and energy efficient platform to increase the interconnection bandwidth of processors (intra-chip), multi-core processors (intra-chip and chip-to-chip), boards and racks (off-chip).

In this context, silicon electro-optical modulators, which write electrical data onto an optical carrier at very high speeds, have attracted an increasing interest. Nevertheless, despite continuous efforts in realizing high performance devices, carrier depletion modulators remain subject to parametricadjustment trade-offs. In fact, fabricating a modulator that simultaneously features, high speed (40 Gb/s), small footprint (a few hundred microns), low insertion loss (<6dB) and low drive voltage (~1V) appears to be extremely challenging [1-6]. Fortunately, the well know slow light phenomenon is a good candidate to help mitigate these issues by significantly enhancing conventional "fast light" devices via enlarged light-matter interactions [4, 7].

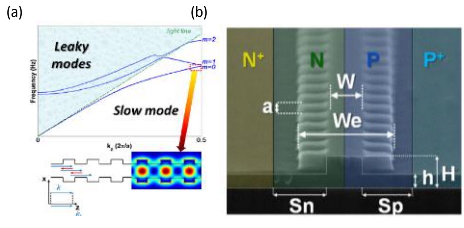

Figure 1: (a) Typical dispersion curve of a 1 dimensional corrugated waveguide. The slow forward movement is produced by the superposition (interference) of electromagnetic waves propagating back and forth in the direction indicated by the wave vector (slightly off-z-axis). (b) SEM picture of the corrugated waveguide.

In this paper, we showcase two attractive features of silicon slow wave modulators. Namely, we show their capacity to dramatically shrink the footprint of conventional rib waveguide based carrier depletion modulators while sustaining similar drive voltages and operating speed. Furthermore, we demonstrate that the use of slow light provides an attractive solution to reduce the drive voltage of carrier depletionbased Mach-Zehnder modulators fulfilling hence the consumption requirements of future CMOS electrophotonic transceivers.

Slow light propagation (Fig. 1 (b)) is achieved through the use of a corrugated waveguide whose parameters are indicated in Fig. 1 (b) (W=300nm; W_e=650nm; a=310nm). The slow wave modulator has been patterned in a standard CMOS fabrication line on a 220nm thick epilayer (designated H in Fig. 2 (b)) 8-inch wafer, using 193nm deep-UV lithography. The waveguide was shallow-etched, leaving a remaining slab thickness of height h=100nm. Electro-optical modulation is achieved via a carrier depletion mechanism, that is, when the majority carriers are depleted from a reverse biased p-n junction, which in this case is positioned in the middle of the waveguide. The two *p*-type and *n*-type regions are connected to highly doped p^+ and n^+ regions, which are respectively situated at a distance of S_n=550nm and S_p=500nm from the edge of the narrow waveguide section. Low resistive and low microwave loss compound AlCu electrodes were finally deposited on top of the highly doped regions to ensure good ohmic contacts. Net doping concentrations in the *p*-type and *n*-type regions are respectively 4.10^{17} cm^{-3} and 5.10^{17} cm^{-3}.Highly p^+ and n^+ regions were implanted at a concentration of 1.10^{20} cm^{-3}.Two modulators of lengths 1000 µm and 500µm were used to demonstrate low drive voltage operation at 10Gb/s and high contrast performance at 40Gb/s, respectively.

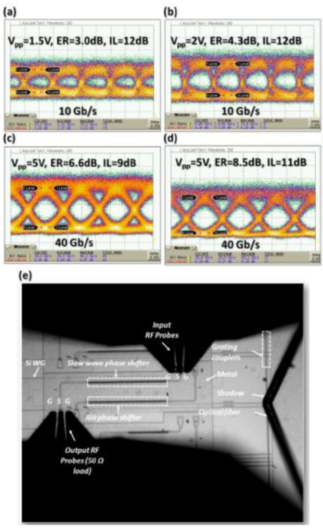

Figure 2: (a) 10 Gb/s eye diagrams for 1.5V and (b) 2V peak-to-peak drive voltages (1000-µm long modulator) (c) 40 Gb/s eye diagrams for a 5V peak-to-peak drive voltage at quadrature and (d) 2dB below quadrature (500-µm long modulator) (e) Optical microscope image of the slow-light modulator under test. V_{pp}= Voltage peak-to-peak; ER=Extinction ratio; IL=insertion loss.

To evaluate the high speed performance of the 1000µm slow wave modulator under low drive voltages, 10Gb/s eye diagrams were acquired at quadrature, as shown in Fig. 2 (b). The modulation efficiencies are 0.62V.cm and 0.70V.cm for 1.5V_{pp} and 2V_{pp} voltage swings, respectively. Extinction ratios of 3 dB and 4.3dB at 10 Gb/s were achieved. These results have been obtained for a group index of ~9.5. The insertion loss of the modulator is ~12dB [8]. Additionally, 40 Gb/s operation has been shown using the shorter version of the slow wave modulator (500µm), which exhibits a modulation efficiency of 0.85 V.cm for a 5V voltage swing and for a group index of ~8 [9]. Besides the lower optical losses, the choice of using such a group index value is motivated by the possibility of achieving a better electro-optical velocity matching and thus a higher modulation bandwidth. The device features an onchip insertion loss of only 6dB, including the 1dB loss of the two MMI structures. The extinction ratios at 40 Gb/s are 6.6 dB (respectively, 8.5 dB) achieved at quadrature (respectively, 2dB below quadrature) and with 9 dB (respectively, 11dB) optical loss.

In conclusion, low drive voltage 10 Gb/s and high contrast 40 Gb/s operation of compact slow light modulators have been demonstrated. The perspective of using engineered corrugated waveguide featuring a broad optical bandwidth [10] offer exciting prospects for slow light-based modulators.

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