

High Speed Silicon based optical modulators

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Abstract In the last 8 years carrier depletion modulators have become the mainstream high data rate building block for high performance silicon photonics link. In this work we describe carrier depletion MZI and ring modulators, cavity structures for modulation enhancement and QCSE modulators, all of which are under development as part of the UK Silicon Photonics project and the European HELIOS project.

1. Introduction

Submicron silicon photonics has generated a tremendous interest in recent years, mainly for optical telecommunications or for optical interconnects in microelectronic circuits. Silicon photonics is aimed at the reduction of the cost and energy of communications systems through the integration of photonic components and an electronic integrated circuit (IC). One of the core device in integrated silicon photonics is the optical modulators. These devices have experienced dramatic improvements over the last 7 years, and data rates up to 50Gb/s have been demonstrated [1]. However, a significant demand of optical interconnect exists and the research is driven towards devices with a small footprint, broadband characteristics, extinction ratio above 5dB and working for one or both polarisations. Here we describe some of the work undertaken in modulation within the UK silicon photonics and Helios program, which has led to the fabrication and preliminary results of novel slow wave devices as well as self-aligned *pn* junction structures embedded in silicon rib waveguides, with an active length in the tens of microns to millimetre range. High-speed optical phase modulation is produced whilst retaining a high extinction ratio. We also describe recent work on Ge/SiGe quantum-confined Stark effect (QCSE) devices for electroabsorption modulation, in which we have used strain engineering to target the commercially significant 1.3- μm communications 'window'.

2. Carrier depletion modulation

The most successful devices have been based upon the plasma dispersion effect

and use carrier depletion in a reverse biased diode structure to electrically manipulate the free carrier density which is in interaction with the propagating light. Although the plasma dispersion effect can directly cause intensity modulation due to the relationship between free carrier densities and optical absorption, it is more effective to use the accompanying change in the real part of the refractive index to shift the phase of the light and then convert to intensity modulation using a resonant or interference based structure. Two phase modulators based upon this approach have been investigated using *pn* diodes [2, 3]. The two structures were fabricated using silicon-on-insulator (SOI) with silicon thicknesses of 220nm and 400 nm. The 220 nm rib waveguide has a junction self-aligned with the side of the rib, and the 400 nm version has a wraparound junction self-aligned to the 3 sides of the rib waveguide. Both modulators demonstrated 40 Gb/s modulation in a MZI configuration for TE polarisation with a modulation depth up to 10 dB. The 400 nm version also demonstrated 40 Gb/s for TM polarisation whereas the 220 nm demonstrated modulation up to 50 Gb/s [1]. We have analysed the power consumption for the two eye diagrams of figure 1 where for the single drive we obtained 11pj/bit and in dual drive 4.5pj/bit. We have also theoretically analysed the chirp from a silicon modulator in both dual drive and single drive configurations (figure 1), taking into account the experimental DC and high speed characteristics of the

silicon phase modulator. It is predicted that under the operating conditions of our modulator that the peak frequency shift in the dual drive case is less than 0.5GHz resulting in 5.8ps of spreading of the pulse edge over 80km of single mode fibre. In the single drive case the peak frequency shift is in excess of 7.5GHz resulting in a pulse edge spreading above 86ps.

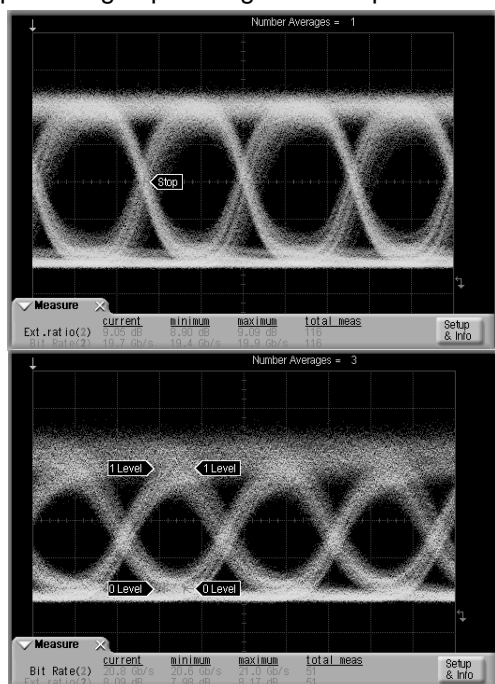


Fig. 1. Optical eye diagrams obtained from the 220 nm SOI device at 20Gbit/s using single-drive operation (top) and dual-drive operation (bottom).

The pn junction was also implemented in a ring resonator structure with a radius of 6 microns and the modulation speed was measured up to 40 Gb/s with a power consumption of 32 fJ/bit. The associated eye diagrams are shown in figure 3

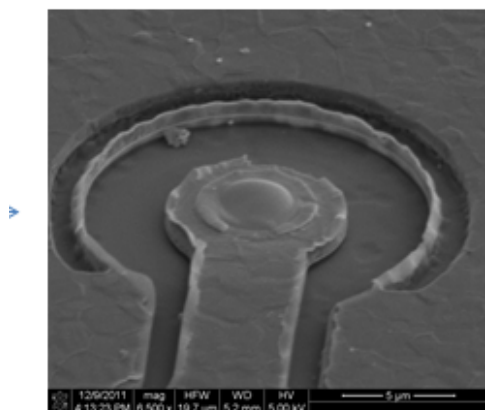


Figure 2—Ring resonator modulator in 220nm SOI

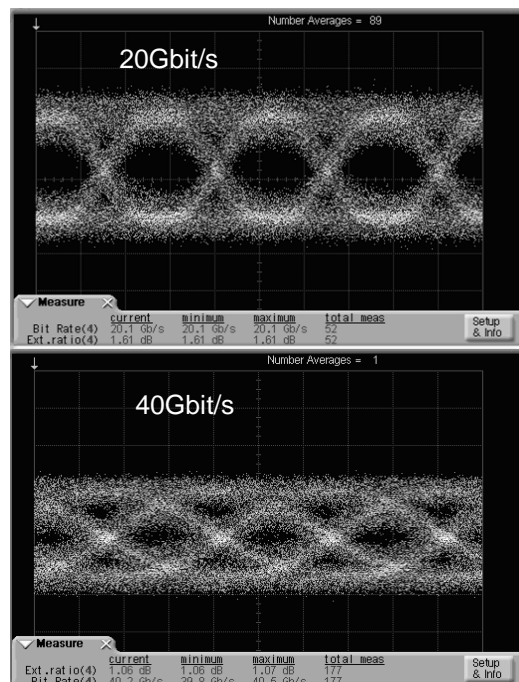


Figure 3—Optical eye diagram from the ring resonator @ 20Gb/s (top) and 40Gb/s (bottom)

We also report a simple but effective design for an optical interconnects shown in figure 4. This design is based on a low refractive index contrast access waveguide coupled to multiple high Q photonic crystal cavities, each of which can modulate or detect individual channels.

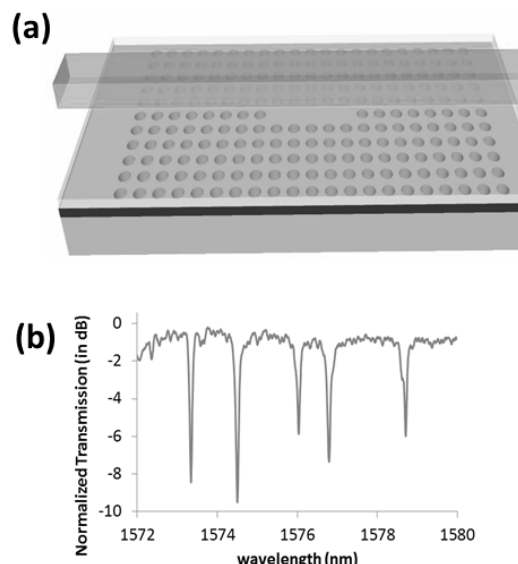


Figure 4: (a) Schematic of the PhC resonator and bus waveguide, (b) Transmission spectra for an access waveguide coupled to 5 cavities, where each dip in transmission corresponds to a different cavity. Disorder causes minor fluctuations in the resonance wavelength.

Due to the wavelength selective nature of the cavities, individual channels can be modulated or detected while in the access waveguide, thus avoiding the use of complex multiplexers or demultiplexers. The technique of vertical coupling is the key breakthrough that eliminates the need for complex, fault intolerant components, such as arrayed waveguide gratings, while simultaneously providing highly efficient coupling to an optical fiber. We report a 1-Gb/s modulation in the cavity.

3. QCSE modulation

The QCSE was first demonstrated in a silicon-based system in 2005 using Ge/SiGe multiple quantum well (MQW) layers, which were epitaxially grown using reduced pressure chemical vapour deposition (RP-CVD) [4]. In III-V ternary or quaternary systems, the MQW structure can be designed to target specific operating wavelengths by choosing the composition of the well material. Such flexibility of materials is not available in Si-based MQW systems; however, control over the operating wavelength can be achieved by exploiting the strain in the Ge quantum well layers through choice of the virtual substrate composition. We have recently reported modulation of the absorption coefficient at 1.3 μm using such a strain engineering approach [5]. We grew 9-nm-thick Ge quantum wells with 7-nm-thick $\text{Si}_{0.4}\text{Ge}_{0.6}$ barriers grown on a $\text{Si}_{0.22}\text{Ge}_{0.78}$ buffer layer, and fabricated $p-i-n$ diodes in order to apply an electric field across the MQW layers. A change in the absorption coefficient of a factor of 3.6

was observed at 1300nm, and was larger than 3.2 in the range 1290–1315 nm.

4. Acknowledgements

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