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Silicon photonics frequency shifter based on I&Q dual Mach-Zehnder modulator

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***Abstract*—We present a fully CMOS compatible frequency shifter device, in a I&Q dual Mach-Zehnder architecture. Frequency shift up to 410 MHz are obtained, with carrier and image sideband extinction from 27 to 51 dB.**

I. Introduction

Optical frequency shifting has a broad range of scientific applications either in the optical telecommunication domain, where frequency shift keying (FSK) protocols can be implemented using single-sideband (SSB) frequency shifters, or in the sensing area for heterodyne detection systems, optical gyroscopes, spectroscopy or laser cooling. Depending on the application, the required agile frequency shifts can typically vary from the MHz to GHz range.

Accousto-optic modulators (AOM) are a commercial solution for 10's to few 100's of MHz with good efficiency, but suffer from a relatively narrow frequency tuning range. Conversely, the serrodyne approach, in which a sawtooth-like waveform is applied to a phase modulator, offers an efficient and wideband frequency shifting technique. This method was successfully demonstrated based on $LiNbO_3$ modulators [1]. Fueled by microelectronics, Silicon photonics is now a key platform for many optical devices and systems, which motivates the development of the frequency shifter building block in a CMOS compatible technology. A serrodyne frequency shifter was demonstrated based on thermo-optic effect in silicon, but limited to 1 kHz frequency shift by the slow thermal effect [2]. Through plasma dispersion effect, carrier depletion or injection modulators can be much faster, but an amplitude modulation is inevitably associated with the phase modulation, which impairs the serrodyne technique and limits the achievable extinction ratio. An alternative solution is the dual Mach-Zehnder I and Q architecture, as demonstrated in [3] on a $LiNb0_3$ platform, or more recently on a hybrid organic and silicon platform [4]. Although excellent performances were reported here, the process used is not directly CMOS compatible. Nevertheless, the interferometric principle of this I/Q modulator approach makes it more immune to spurious amplitude modulation, and therefore compatible with depletion-mode PN junction phase modulators.

Within the PLAT4M (*Photonic Libraries And Technology for Manufacturing*) project, we developed a carrier depletion-based dual Mach-Zehnder frequency shifter, monolithically integrated with balanced photodetectors for heterodyne detection applications. This device is one of the test-vehicles that drive the project with the purpose of bringing the existing silicon photonics research platform to a level that enables transition to industry. The device conception, fabrication and packaging will be detailed, and the frequency shifting performances will then evaluated and discussed.

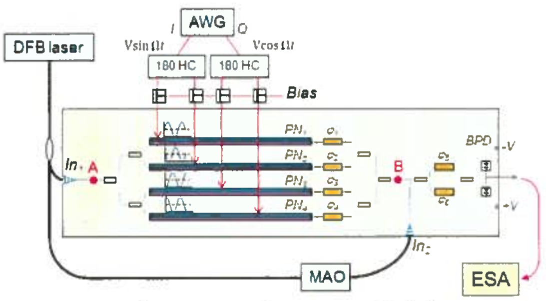

Fig. 1. Schematic of the photonic integrated chip (inside yellow box) and experimental setup. PN_k are the carrier depletion phase modulation sections, φ_k are thermal phase shifters. BPD: balanced photodetectors. AWG: arbitrary waveform generator; 180 HC: 180° hybrid couplers; MAO: acousto-optic modulator; ESA: electrical spectrum analyzer.

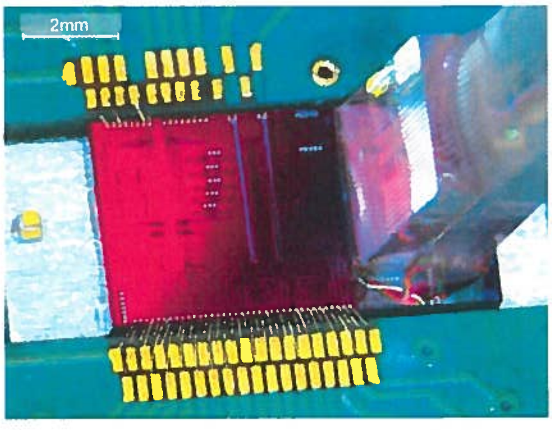

Fig. 2. Photograph of the packaged photonic circuit. The Si-PIC is housed onto a custom PCB and a fibre array is aligned and attached on top of the photonic IC using UV cure epoxy

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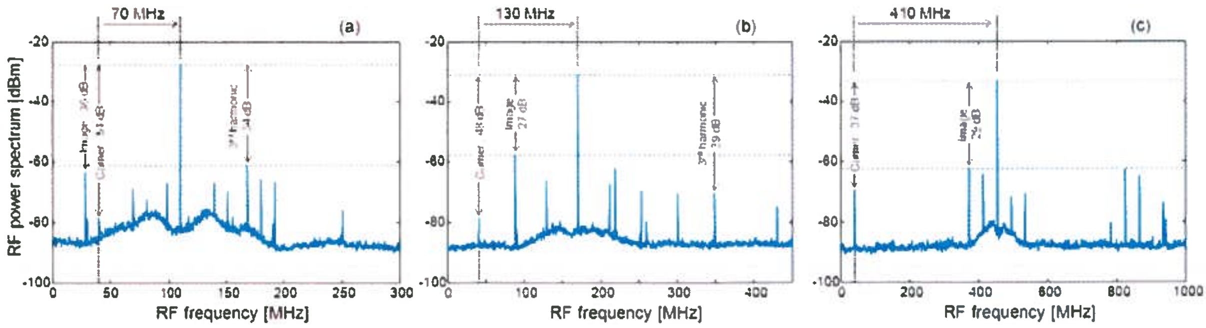

Fig. 3. Electrical power spectrum measured at the output of the balanced detectors for a frequency shift of 70 MHz (a), 130 MHz (b) and 410 MHz (c). Suppression ratii for the image, carrier and third harmonic are indicated, and range from 27 to 51 dB.

II. DEVICE DESIGN, FABRICATION AND PACKAGING

The device architecture is depicted in Fig. 1. High efficiency grating couplers [5] are used to couple light in and out of the chip. 50/50 multimode interference couplers (MMI) are used to construct the 4 branch interferometer structure. On each branch, a 1.5 mm-long carrier depletion phase modulator is used to impinge the RF modulation. Low doped PN junctions were used to optimize the modulator figure of merit, defined as the product $V_\pi L_\pi$ times the insertion loss [6]. Thermal phase shifters [7] are inserted to control the DC phase bias between the branches. The output of the 4 branch structure is combined with a second optical input of the chip (In_2) using a tunable coupler made of a Mach-Zehnder interferometer with thermal phase shifters. A precise 50/50 coupling ratio can then be adjusted to feed 2 photodetectors in balanced configuration. The silicon chips were fabricated in IMEC's 200 mm CMOS pilot line, and are finally housed on a custom test board (see Fig. 2), were the heaters, PN modulator and photodiode contacts are connected. A polarization maintaining fiber array is aligned and attached on top of the circuit using UV cure epoxy. The final fiber-to-chip insertion loss is 3.5dB.

III. FREQUENCY SHIFTER PERFORMANCES

A -3 V bias voltage is superimposed on the modulation signals. An external acoustooptic modulator (AOM) generates a 41 MHz shifted optical beam that is mixed with our frequency shifted signal on the balanced photodetector. This allows the separation of positive and negative frequency shifted compounds on the output RF power spectrum. Fig. 3(a), (b) and (c), show recorded RF spectra when modulation of respectively 70, 130 and 410 MHz are applied to the carrier depletion modulators. A carrier suppression of 37 up to 51dB is achieved, with an image sideband suppression of 27 to 36 dB. The frequency shifter conversion efficiency is plotted on Fig. 4 as a function of the voltage amplitude applied to the PN junctions. It represents the ratio between the optical power in the shifted sideband at the output of the structure (point B in Fig. 1) versus the optical power at the input of the 4 branch device (point A in Fig. 1). Fitting these measurements with the theoretical Bessel of first kind expression [3] leads to estimated $V_\pi L_\pi$ of 2 V.cm at -3V bias, and 7.3 dB/cm loss in the junction.

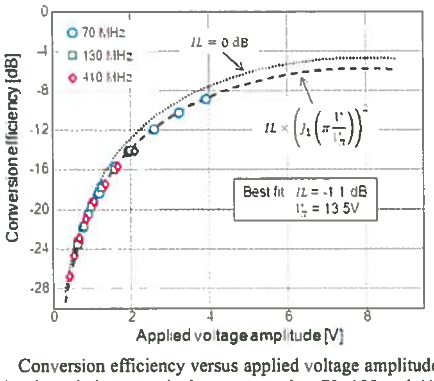

Fig. 4. Conversion efficiency versus applied voltage amplitude. Blue, green and red symbols respectively correspond to 70, 130 and 410 MHz frequency shift. The dashed solid line shows the best fit with the Bessel of first kind expression. The fitting parameters are an insertion loss of -1.1 dB and $V\pi$ of 13.5 volts.

IV. DISCUSSION

We demonstrated a fully CMOS compatible frequency shifter device, based on a dual Mach-Zehnder architecture with carrier depletion PN junction modulators. High spurious extinction ratio was obtained at frequencies up to 410 MHz. In the current device, the phase shifters were adjusted manually, but a next version with integrated photodiodes is being manufactured, for automatic phase bias adjustment. The maximum frequency shift of ~400 MHz is currently limited by electrodes design and test board, but GHz or multi-GHz can be reached with this technology, to address more demanding applications as in the telecommunications. Finally, with this work, we validated the full silicon photonics supply chain, from design to packaging, thanks to the design tools and mature technologies developed in the PLAT4M project.

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