A slow light silicon-based Mach-Zehnder Interferometer for frequency mixing applications

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***Abstract*—A silicon photonic-mixer Mach-Zehnder modulator enhanced via slow-light has been demonstrated. An input frequency signal from 1GHz to 10.25GHz is successfully up-converted with low conversion losses ~7dB and excellent quality of the received signal showing an optimum EVM ~8%.**

Keywords-Integrated; Mixing; Up-conversion; Modulator

I. INTRODUCTION

Radio-frequency (RF) analog data processing in Analog Photonic Links (APL) encompasses numerous potentially applications such as Radio-over-Fiber (RoF), antenna remoting, subcarrier transmission or photonic analog-to-digital conversion. The use of silicon photonic devices to generate analog RF signals may lead to chip-size reduction and power-efficiency improvements. In addition, the Silicon-On-Insulator (SOI) platform offers the possibility of mass-manufacturing as well as cost-effective integration with CMOS electronics. In APLs, RF signals are converted into the optical domain by an electro-optic modulator for which the most important achievements have been demonstrated during recent years by means of the plasma dispersion effect, although mostly for digital communications. However, very little attention has been given to analog applications [1,2]. Besides the transport of RF signals over fiber, nowadays, signal mixing is an interesting and necessary technique. In contrast to conventional electrical mixing schemes, photonic mixing techniques for RoF communications feature superior characteristics such as ultra-wide bandwidth and immunity to electromagnetic interference. Several works have reported photonic mixers [3,4] using commercial $LiNbO_3$ modulators due to their highly linear characteristic when operated at quadrature. However, to our knowledge, no work on silicon photonic mixers has been demonstrated so far.

In this work, a silicon-based Mach-Zehnder modulator enhanced via slow-light propagation is used as photonic mixer for frequency up-conversion. Performance of our APL is measured in terms of Spurious Free Dynamic Range (SFDR) and conversion losses. EVM is also measured for the mixed received signal under a QPSK format modulation. Furthermore, comparisons between the slow and fast light regions and optimization of the operating bias point have been carried out.

II. DEVICE STRUCTURE

Silicon-based electro-optic Mach-Zehnder modulator used as photonic mixer is shown in Fig. 1.

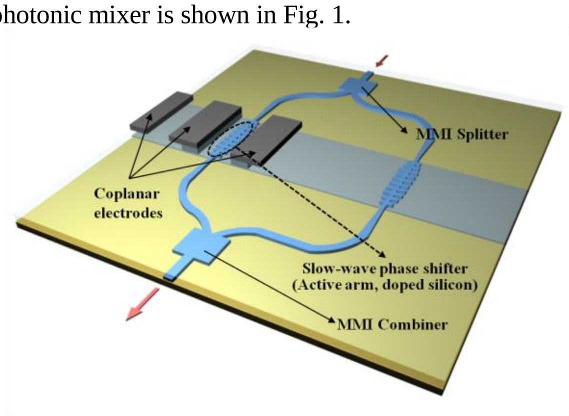

Figure 1. Schematic of the slow-wave modulator used for mixing.

Slow light propagation is achieved through the use of a 1D periodic structure consisting of a laterally corrugated waveguide with a reverse biased *pn* junction embedded. Optical phase modulation in the slow wave waveguide is converted into amplitude modulation via the use of an asymmetric MZI structure. As was demonstrated in [5] from digital measurements, the slow-light effect enhanced the modulation efficiency, allowing modulation data rates up to 40 Gb/s over an interaction length of only 500μm at a group index of only ~11.

III. EXPERIMENTAL RESULTS

For the study of the mixing efficiency, a two-tone test has been carried out. The IF and OL frequencies are set to 1GHz and 9.25GHz respectively. Nonlinearity depends on the operating bias point of the MZI transfer function but also on the nonlinear response intrinsic to the material in the active region. In the case of $LiNbO_3$ modulators, the former is the dominant contribution to the nonlinear performance. Therefore, the quadrature bias (QB) point, is usually exploited to convert the IF frequency to the third-order intermodulation distortion (IMD3) products ($2f_{IF}\pm f_{OL}$). However, in our case, the nonlinear response of the free-carrier dispersion in silicon together with the slow-light propagation also plays a prominent role in the mixing performance. To evaluate the intermodulation distortion performance of our silicon modulator, we have defined and measured the conversion losses, as in [3], as the ratio between the photo-detected electrical power at f_{IF} and the photo-detected electrical power of the considered intermodulation term at $f_{IF}+f_{OL}$=10.25GHz for IMD2 and $2f_{IF}+f_{OL}$=11.25GHz for IMD3. So, when a given intermodulation product power is maximized with the bias point, the conversion losses of the product should be minimized. Initially, we investigated the nonlinear performance and conversion losses at QB. Conversely to $LiNbO_3$ modulators, we obtained large conversion losses (55dB for 15dBm IF input power) for the IMD3. Furthermore, lower conversion losses were measured (35dB for 15dBm IF input power) for the IMD2. Based on these results, the modulator was biased at minimum transmission (MITB), where usually the IMD2 products are maximized and dominate over the third-order and the fundamental terms [6].

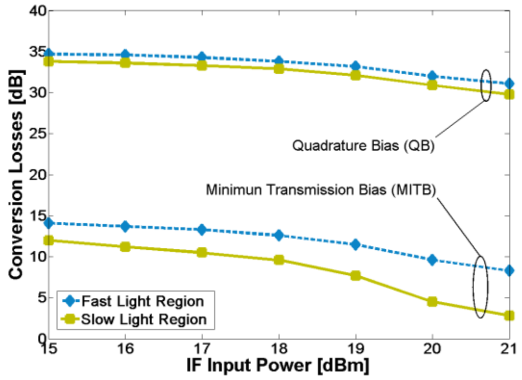

Figure 2. Conversion losses at QB and MITB bias points for both slow and fast-light regions at IMD2 intermodulation frequency. OL input power was set to be 20dBm.

In this case, conversion losses for IMD2, shown in Fig. 2, were reduced by more than half (around 13dB for 15dBm IF input power) and therefore a significant improvement results in conversion losses (~30dB) between biasing the modulator at QB or MITB. On the other hand, lower conversion losses were also obtained in the slow light region when compared to the fast light region (~2-4dB more at MITB and ~1dB at QB). As a result, the IMD2 frequency (10.25GHz) and MITB operation point was chosen to up-convert a vector modulated signal. For our SFDR, defined as the output power difference between the intersection of the IMD3 power signal at 11.25GHz with the noise floor and the IMD2 power signal at 10.25GHz, 62.8dB.Hz$^{2/3}$ and 60.2dB.Hz$^{2/3}$ for the slow and fast light regimes have been measured respectively. These results confirm again the enhanced performance brought by the slow-light regime. In both cases, a third order intercept point around ~25dBm has been measured.

For the EVM measurements, a I/Q modulated signal at the f_{IF}=1GHz under a digital modulation scheme of QPSK with 20Mbps is up-converted to $f_{IF}+f_{OL}$=10.25GHz frequency with the electro-optic modulator biased at MITB point. It is clear from the Fig. 3 that enhanced performance in terms of EVM is obtained in the slow light regime over the entire range of IF input powers. Outstanding results have been obtained with a very low optimum EVM of 8% and 12% for both slow and fast light regimes, respectively, allowing a very clean constellation. This confirms that the received signal is of acceptable quality.

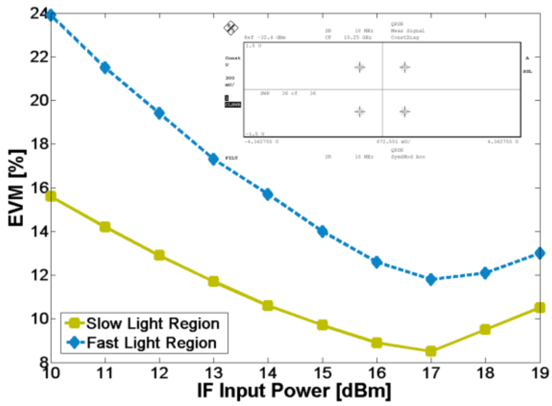

Figure 3. EVM as a function of IF Input Power for both fast and slow light propagation. Inset shows received constellation in the slow light region case at the optimum point of IF input power (17dBm).

IV. CONCLUSIONS

We have shown an efficient method of generating mixing products in a silicon modulator exploiting the nonlinearity produced by both the MZI transfer function and the plasma dispersion effect in silicon. The conversion efficiency has been enhanced via slow-light propagation in the active region of the modulator. Optimum performance has been achieved at MITB with low conversion losses around 7dB and large SFDR of 62.8dB.Hz$^{2/3}$. Finally a 20Mbps QPSK signal at 1GHz has been successfully up-converted to 10.25GHz. A minimum EVM of about 8% has been achieved, meeting well enough the EVM requirements for an acceptable quality of the received constellation.

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