Hybrid III-V/Si MZI Modulators for High SFDR Analog Links and Systems

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Abstract: Record high SFDR operation is achieved for heterogeneously integrated silicon photonics modulators, by using hybrid III-V/Si phase modulators within Si MZI modulator structures. 112 dB.Hz$^{2/3}$ SFDR is achieved at 10 GHz with standard MZI modulators, and 117.5 dB.Hz$^{2/3}$ for Ring Assisted MZI (RAMZI) modulators.

Introduction

RF Photonic and Analog fiber optic links and systems for DoD and commercial applications require a high dynamic range, achieved through the use of highly linear components. A key element, and often the limiting component in these systems, is the optical modulator; which transfers an electrical input signal onto an optical carrier signal. The linearity of the system is usually set by the linearity of the modulator. The other part of system dynamic range is the noise; the laser generates relative intensity noise (RIN), other components being the shot noise at the photodetector and the thermal noise of electronic devices in the link. Optical loss within the system also reduces the signal to noise ratio. The overall dynamic range of the system is characterized by its spurious free dynamic range (SFDR).

A typical RF Photonic link is shown in Fig. 1. This includes a high power, low noise (LN) laser with low RIN [1]; a highly linear modulator to convert the electrical RF signal into an optical signal; a low loss optical link that may also include an optical processing component such as true-time-delay (TTD) [2] or optical filtering; and a high speed (HS), high power, linear photodetector to convert the optical signal back to an electrical RF signal.

Fig. 1 Key elements of High SFDR Optical Link with TTD

Silicon Photonics provides a CMOS foundry platform for complex photonic integrated circuits (PICs) for use in a wide variety of applications, including datacom, telecom, RF Photonics and Analog systems. It enables a future generation of PIC devices for DoD systems providing high performance and low cost, through the heterogeneous integration of the optimum materials for each photonic component.

Silicon Photonics Mach Zehnder Interferometer (MZI) modulators based solely on Si waveguide phase modulators have shown good performance for digital systems, where the nonlinearity of the Si waveguide index versus voltage has a limited effect on system performance. However, all-Si MZI modulators have shown significantly worse linearity than the Lithium Niobate MZI modulators used in RF photonics systems; the best published results showing 97 dB.Hz$^{2/3}$ SFDR at a 1 GHz modulation frequency [3]. Khurgin and his research team invented the Ring Assisted MZI (RAMZI) modulator in 2003 [4], which uses the super-linearity of a ring phase modulator (with high coupling to the MZI arms) to balance the sub-linearity (sinusoidal transfer characteristic) of an MZI modulator. All-Si RAMZI modulators showed significant improvement over Si MZI modulators, demonstrating an SFDR of 106 dB.Hz$^{2/3}$ at 1 GHz and 99 dB.Hz$^{2/3}$ at 10 GHz [5], however, still much lower than commercial Lithium Niobate MZI modulators, which show an SFDR of ~112 dB.Hz$^{2/3}$ in similar measurements.

This work utilizes III-V Multiple Quantum Well (MQW) material heterogeneously integrated onto Si to produce hybrid III-V/Si waveguides, using the III-V MQW material to create the phase modulation sections. The III-V material has higher phase modulation efficiency and lower nonlinearity than all-Si phase modulators [7]. The MZI transfer characteristic has a negative third order term, as does the III-V MQW plasma-like effect of free carriers and the state-blocking phase change effect. The Quantum Confined Stark Effect (QCSE) has a positive third order term, and strong wavelength dependence, while the Pockels effect is largely linear. As a result, at some wavelength and modulator bias the positive nonlinearity of the QCSE phase response can become sufficient to cancel the negative nonlinearities of the plasma and state blocking effects, and potentially also the nonlinearity of the MZI itself.

MZI and RAMZI Modulator Designs and Measurements

Schematics for the MZI and RAMZI modulator devices used in this work are shown in Fig. 2, with input(s) on the left and output(s) on the right. A Multi-Mode Interference (MMI) Coupler or a Directional Coupler (DC) is used to split the input 50/50 into the arms of the MZI (MMIs are shown in Fig. 2). Two heaters, one on each arm of the MZI are used to control the bias point of the modulator, e.g. set the modulator to quadrature. A single drive push-pull scheme is used to simplify the drive [6]. Both devices use mostly shallow etched waveguides (magenta), with a deep etch around the heaters (blue), and they align the MQW modulator section direction to maximize the Pockels effect. The RAMZI modulator (bottom) uses deep etched Si waveguides (blue) for small bend radius turns within the rings, which have designed coupling coefficients, κ, in the measured devices of 0.65 and 0.85.

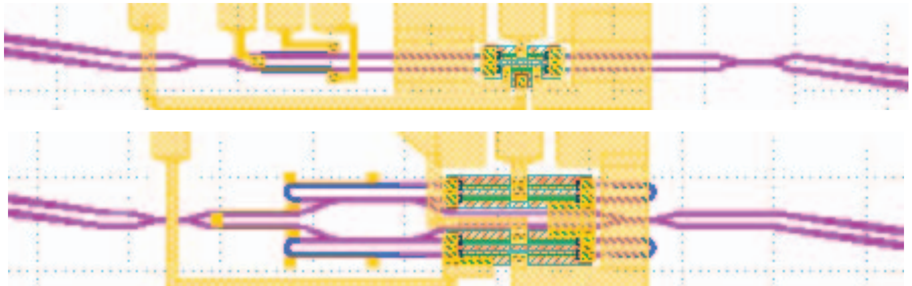

Fig. 2 (top) MZI and (bottom) RAMZI modulator schematic designs (wiring for RAMZI heaters not shown)

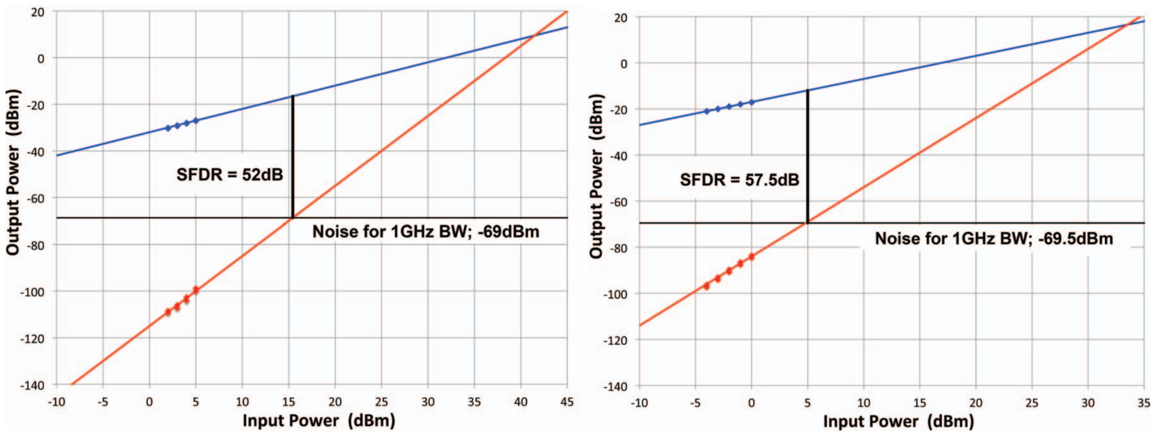

Fig. 3 SFDR Measurements for (a) MZI and (b) RAMZI modulators

SFDR measurements [7] taken at 10 GHz modulation frequency for (a) MZI and (b) RAMZI modulator devices are shown in Fig. 3. When operated at quadrature the MZI device produced a maximum SFDR of 52 dB for 1 GHz bandwidth, or 112 dB.Hz$^{2/3}$; equivalent to Lithium Niobate modulators. The RAMZI devices produced even higher SFDR measurements over a wide range of operating parameters, with the maximum for the lower κ device (operated at low bias) of 57.5 dB (1 GHz), or 117.5 dB.Hz$^{2/3}$. The higher κ RAMZI device also showed significant improvement over the standard MZI device, providing a maximum SFDR of 57 dB (117 dB.Hz$^{2/3}$). These results demonstrate that Silicon Photonics can provide integrated MZI modulators with similar linearity to the large and expensive commercial Lithium Niobate modulators, and improved performance using RAMZI modulator devices.

Acknowledgements

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