Linearized silicon modulator based on a ring assisted Mach Zehnder interferometer

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Abstract: We demonstrate a Linearized Ring Assisted Mach-Zehnder Interferometer (L-RAMZI) modulator in a miniature silicon device. We measure a record high degree of linearization for a silicon device, with a Spurious Free Dynamic Range (SFDR) of 106dB/Hz²/³ at 1GHz, and 99dB/Hz²/³ at 10GHz.

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OCIS codes: (130.4110) Modulators; (060.5625) Radio frequency photonics.

References and links

A key component for real world RF photonic links and systems is a high speed, low cost, small size, and highly linear electro-optic modulator. Additionally, monolithic integration with RF electronics would be of great advantage. Lithium Niobate (LiNbO₃) Mach-Zehnder Interferometer (MZI) based modulators, the most mature electro-optic modulator platform, have shown a high degree of linearity and a spurious free dynamic range (SFDR) up to 113dB/Hz²/₃ [1]. When operated with a low bias level, which produces high 2nd harmonic distortion, and with very high input power (500mW), an SFDR as high as 121dB/Hz²/₃ was achieved within a sub-octave bandwidth [2]. Approaches to linearize the sinusoidal transfer function of LiNbO₃ modulators with external electronics or with more complex (e.g. nested MZI) structures [3] have shown some improvements in SFDR, but with significantly increased complexity and cost. Additionally, LiNbO₃ does not lend itself to integration with electronics, and, due to the limited refractive index contrast of diffusion waveguides, the devices tend to be large. Electro-absorption modulators are typically fabricated in III-V semiconductor platforms, and have shown SFDRs as high as 128dB/Hz⁴/₅ [4], approaching the performance of LiNbO₃ modulators, but only for narrow instantaneous bandwidth (1MHz) systems. III-V semiconductor materials platforms are not currently compatible with CMOS electronics, involve more costly substrates and epitaxy processes, and, therefore, are more expensive and challenging to integrate with silicon electronic components. High speed and highly linear silicon electro-optic modulators are attractive because of their potential for very low cost and the relative ease of integration with CMOS electronics. They also offer the opportunity for integration with high speed, high power germanium based photodetectors [5–7], and silicon photonics based lasers [8, 9], providing complex RF photonics System on Chip (SoC) devices, through heterogeneous integration on a CMOS compatible platform.

It was theoretically predicted that silicon MZI based modulators could be linearized by simply utilizing the intrinsic nonlinearity of the silicon PN junction phase shifter to compensate for the inherent nonlinearity (sinusoidal modulation transfer function) of the MZI modulator [10]. Recent results [11,12], have shown some improvement in linearity of such devices, with SFDR values reaching as high as 97dB/Hz²/₃ at 1GHz modulation frequency [11], however, these results are well below those obtained from typical non-linearized LiNbO₃ devices, even after allowing for the relative immaturity of silicon photonics based modulators. It appears that using just electrical bias to cancel the MZI nonlinearity does not offer sufficient control of the response to provide reliable and repeatable high SFDR performance. Another approach is to use a device structure that is inherently different to the MZI modulator arrangement, in an attempt to create more linear devices, such as the use of ring modulators [13], where an SFDR of 84dB/Hz²/₃ was reported, however, this is significantly lower than that obtained with MZI based modulators.

In 2004, an arrangement was proposed by Xie and Khurgin [14], which combines a standard
MZI structure with a ring based phase modulator, that could enable high linearity in silicon-based structures. In this arrangement, introduced in [14] as a Ring-Assisted MZI (RAMZI) modulator, the super-linear phase response of a ring resonator is used to cancel the third order component of the MZIs sinusoidal response. The concept of linearization in a RAMZI modulator is briefly illustrated in Fig. 1. One ring is coupled to each arm of the Mach-Zehnder interferometer and the MZI bias can be adjusted to set the operating point of the MZI. The coupling coefficient of the ring resonator is optimized in order to cancel out the MZIs non-linearity. As shown in Fig. 1(b), MZI has a sinusoidal response of power vs. phase difference between its arms, with the negative third order derivative. The dependance of the phase of the output of side-coupled ring resonator on the voltage-controlled round trip optical path length inside the ring, has a positive third order derivative. Thus, with a proper coupling coefficient, the overall dependence of RAMZI output on the voltage has zero third order derivative which eliminates the strongest nonlinearity responsible for the intermodulation distortion. Previous work on RAMZI modulators showed an SFDR of only 72dB/Hz^{1/3}, measured at 1GHz [15], indicating that the device wasn’t optimized for linearization.

Fig. 1. RAMZI linearization concept. a) Schematic of L-RAMZI modulator in push pull configuration. b) Comparison of traditional MZI modulator sinusoidal response, ring resonator phase response, and simulated L-RAMZI response. Note that the vertical axis for the MZI and RAMZI curves is for transmission, while for the Ring it is for phase.

This work demonstrates the Linearized RAMZI (L-RAMZI) modulator, showing that practical RAMZI devices are capable of achieving record high values of SFDR for silicon photonics modulators. The L-RAMZI device used here consists of a balanced Y-junction MZI modulator structure with 70μm radius microring based phase modulators coupled to each arm. The coupling coefficient between the straight waveguide and the ring was optimized for linearization of the device transfer characteristics, with the optimum value being 0.87; the same value used for each ring. The coupling gap between the ring and bus waveguide was 200nm. PN junction diodes were built into the ring resonators to provide high speed phase modulation [16–18], together with NiCr heaters above the rings to thermally tune their resonance frequencies. Note that only the ring resonators were modulated in this device [14], while the MZI structure was held at a fixed bias position, e.g. one of the quadrature points. In order to set the MZI bias point, a heater was placed on one of the MZI arms.

The CMOS compatible L-RAMZI modulator was fabricated on an SOI wafer with a 250nm silicon layer. The 500nm wide waveguides were patterned using e-beam lithography and etched in chlorine chemistry in an inductively coupled reactive ion etcher. Multiple ion implantation steps defined the horizontal PN junction [18]. The p doping (boron) level in the waveguide...
was $5 \times 10^{17}$ cm$^{-3}$, while the n doping (phosphorus) level was $8 \times 10^{17}$ cm$^{-3}$. The device was then clad with $1 \mu m$ of plasma enhanced chemical vapor deposited (PECVD) oxide. NiCr heaters were defined via a lift-off process, and vias were etched to make contacts to the doped regions. Molybdenum silicide and aluminum were deposited using DC sputtering. The aluminum layer was then patterned and etched to define the contact pads and wires, as shown in the photo of the device in Fig. 2. The overall silicon device was 3mm by 5mm, providing its own submount plus contact pads for the heaters and two high speed Ground:Signal contacts for the two ring phase modulators. Angled etched facets, shown on the left and right of the device, provided low reflection coupling to the device, with waveguide tapering used at the ends to expand the beam and reduce coupling losses [19]. Figure 2 shows the MZI waveguide structure, with the two rings coupled to the two MZI waveguides on the right side of the structure. The MZI heater is on the top left branch of the MZI structure. Additionally, contacts were made to the PN junction of the rings (inner and outer connection) and to heaters on top of each ring.

The experimental setup used to measure SFDR is shown in Fig. 3. A CW tunable laser and polarizer launched quasi-TE light into the device. Custom probes provided RF connections for the ring phase modulators and the required DC connections to drive the heaters. The PN junction modulators are operated in carrier depletion. The optical output of the device was collected with a lensed fiber, and passed through an EDFA and a 1nm filter (to reduce ASE), to overcome the 10dB total coupling loss of the device, and to increase the power level applied to the high power 12GHz photodetector (Discovery DSC30), which was connected to an RF spectrum analyzer. The SFDR was measured by applying two RF tones to the device, in a push-pull configuration, and measuring the fundamental and $3^{rd}$ order intermodulation products on the RF spectrum analyzer. A frequency separation of 10MHz between the two tones was used, so that for a center frequency of 1GHz the tones were at 995MHz ($F_1$) and 1005MHz ($F_2$), providing $3^{rd}$ order intermodulation distortion products at 985MHz (IM$3_1$) and 1015MHz (IM$3_2$). The device was initially biased with the two ring resonance frequencies aligned and at
Fig. 3. Experimental Setup to measure SFDR. Two signal generator outputs are attenuated (Att), combined (+), and filtered to remove harmonics; this signal is split (+) to provide a push-pull drive to the modulator, with $\pi$ phase shift in one arm. A laser output is polarized (Pol) and coupled to the device via a lensed fiber. The device output is amplified with an EDFA and filtered to remove ASE noise. The harmonic content of the received signal at the detector (Det) is measured on an RF spectrum analyzer.

Fig. 4. Plot of fundamental, $F$, and $F/IM3$ ratio (normalized to $F = -50$ dBm) vs. wavelength for standard biasing.

In order to find the operating wavelength for best SFDR, a set of measurements of $F_{1,2}$ and $IM3_{1,2}$ versus wavelength were taken. An example of the fundamental power ($F$) versus wavelength is shown in Fig. 4 (red trace, scale on right), showing a maximum value of -37 dBm, and a minimum of -52.5 dBm; a range of 15.5 dB. To find the wavelength with the highest SFDR, the value of $F/IM3$ was normalized to a specific value of fundamental output power (-50 dBm was used), using the known slopes of the fundamental (+1) and IM3 (+3) versus input power, so that the calculated ratios were for the same fundamental power values and would have similar noise levels - the other important element in an SFDR calculation. This normalized ratio of $F/IM3$, plotted versus wavelength, is shown in the blue trace in Fig. 4, and varies from a peak of 75 dB to a minimum of 45 dB, following quite well the shape of the fundamental anti-resonance.
power (F) versus wavelength. The peak value in this trace provides the optimum wavelength to measure SFDR; in this case 1556.5nm was chosen. The SFDR was measured by varying the power of the fundamental tones together, measuring $F_1$ and $IM3_{1,2}$ at each power level, as shown in Fig. 5. For this measurement the photodetector current was 10.9mA; providing a noise level at the photodetector (shot noise + thermal noise) of -161dBm in a bandwidth of 1Hz. The SFDR was then calculated from the graph in Fig. 5, being the dynamic range or difference between the IM3 value at the noise floor and the F value at that same input power, which in this case was $90\text{dB/Hz}^{2/3}$.

![Graph showing output power vs input power, noise level, and SFDR for standard bias position; both rings at anti-resonance.](image)

Fig. 5. Measurements of $F_{1,2}$ and $IM3_{1,2}$ versus input power, noise level, and SFDR for standard bias position; both rings at anti-resonance.

The results in Fig. 5 surpass the previous best RAMZI result of $72\text{dB/Hz}^{2/3}$ [15], however they do not reach the values predicted in [14]. The main reason for the lower measured SFDR is the intrinsic nonlinearity of the diode. The simulated variation of effective index with applied voltage is shown in Fig. 6. The optimum coupling ratio for linearization was found while assuming a linear index change versus voltage, however, the nonlinear variation shown in Fig. 6 indicates that at the standard bias position for the L-RAMZI modulator (both rings at anti-resonance, with a round trip phase delay of $(2m+1)\pi$, linearization may not occur.

In order to compensate for the intrinsic nonlinearity of the PN junctions, the ring resonators were tuned away from their standard bias position, changing the effective nonlinearity of each ring. The best results were found when one ring was biased close to resonance, and the other close to anti-resonance. Device measurements of the fundamental power (F) and the normalized F/IM3 at this new bias point are shown in Fig. 7. This plot also includes a scaled trace of the photocurrent in the photodetector (green dashes), which helps explain device operation. Considering the fundamental trace (red), the modulation efficiency is somewhat higher than in the standard bias point case, with a peak F value of -29dBm (1551nm). The normalized ratio of F/IM3 (again, normalized to F = -50dBm) has two peaks, followed by a large dip, then this shape is repeated. The peaks in the ratio reach over 90dB at 1551nm, compared to 75dB for the standard bias. The overall shape is significantly different from the standard bias case, as the fundamental efficiency falls dramatically at the dips; F falls to almost -70dBm (the range of F is 41dB), with the normalized F/IM3 ratio actually falling below zero, indicating that the IM3
components would be larger than the F components (for $F = -50$ dBm).

The large variation in F versus wavelength occurs because the two ring resonances are not aligned with each other, i.e. are unbalanced. Because of this, changing the wavelength changes the effective length (phase) of the two arms differently, effectively shifting the bias point of the MZI modulator versus wavelength. This is clearly seen in Fig. 7, both in the measured RF signals and in the photocurrent trace - similar to changing the bias voltage of a standard MZI modulator, but in this case not over the full $V_{\pi}$ range. The quadrature points of the MZI modulator occur at the maximum negative and positive slopes of the photocurrent versus wave-
length, validated by the maximum fundamental modulation efficiency also occurring at these points (e.g. 1551 and 1551.3nm); this gives rise to the double peaks seen in Fig. 7. When the photocurrent is at a broad maxima, the device is operating at the peak of the MZI modulation function, having very little fundamental output power (F), and in fact larger IM3 power when the result is normalized to F = -50dBm; this is also seen in a standard MZI modulator biased at maximum or minimum output power. The phase difference change between the arms versus wavelength does not cover the full $V_\pi$ range, and so the photocurrent does not reduce to zero; this is why the fundamental efficiency does not fall significantly for the lowest photocurrent values - only reducing slightly between the two close peaks in modulation. The device was measured at 1551nm, and the results for tones around 1GHz are shown in Fig. 8. The SFDR from these results is 106dB/Hz$^{2/3}$, which is almost an order of magnitude higher than previously reported in silicon photonics modulators [11, 13, 15].

![Graph showing measurements of F_1,2 and IM3_1,2 versus input power, noise level, and SFDR for one ring near anti-resonance, the other near resonance at a frequency of 1GHz and 10GHz.](image)

At the same bias conditions an optimum SFDR value of 99dB/Hz$^{2/3}$ was found for modulation around 10GHz (9.995GHz, 10.005GHz). These results are shown in Fig. 8. The SFDR is lower than seen for 1GHz modulation, which can be explained by considering the normalized F/IM3 plot in Fig. 7, in which the optimum ratio is seen as a relatively narrow peak, so that for larger modulation frequencies the ratio is reduced.

Conclusions

This paper describes the design and optimization of a miniature, silicon photonics based L-RAMZI modulator, utilizing ring structures to linearize the modulation performance of an MZI based modulator. By tuning the ring bias positions, therefore controlling the nonlinearity of each ring, an optimum bias condition was found that produced significantly higher SFDR results than found in other silicon photonics modulators, with measured values for SFDR of 106dB/Hz$^{2/3}$ at 1GHz, and 99dB/Hz$^{2/3}$ at 10GHz. Improved SFDR is crucial for a broad range of high performance RF photonics applications. Future design work will increase the SFDR further by incorporating the PN junction nonlinearity in the model for ring optimization, with the goal of
creating the maximum SFDR over the broadest wavelength range.

Acknowledgments
The authors would like to thank Morton Photonics for supporting this work under DARPA STTR contract #W91CRB-10-C-0099, Miniature Silicon WDM Modulators for Analog Fiber-Optics Links. This work was performed in part at the Cornell NanoScale Facility, a member of the National Nanotechnology Infrastructure Network, which is supported by the National Science Foundation (Grant ECS-0335765).