Robust phase-shift-keying Silicon photonic modulator

Donald Adams,* Abdelsalam Aboketaf, and Stefan Preble

Microsystems Engineering, Rochester Institute of Technology, 77 Lomb Memorial Dr., Rochester, New York 14623, USA
* dbaeen@rit.edu

Abstract: Here we propose a robust silicon modulator that seamlessly generates phase shift keyed data. The modulator has very low insertion loss and is robust against electrical amplitude variations in the modulating signal; specifically a 50%-200% variation in modulating amplitude leads to only a $\pi/9$ variation in output optical phase, corresponding to only $\pm 10\%$ variation in the differentially detected signal. This yields a $\sim 2.5\text{dB}$ enhancement in SNR over OOK (on-off-keying) formats.

©2012 Optical Society of America

OCIS codes: (130.3120) Integrated optics devices; (130.4110) Modulators; (130.5990) Semiconductors.

References and links

1. A. Shacham, K. Bergman, and L. Carloni, “Photonic networks-on-chip for future generations of chip multiprocessors,” IEEE Trans. Comput. 57(9), 1246–1260 (2008).
2. D. Miller, “Device requirements for optical interconnects to Silicon chips,” Proc. IEEE 97(7), 1166–1185 (2009).
3. C. Xu, X. Liu, and X. Wei, “Differential phase-shift keying for high spectral efficiency optical transmissions,” IEEE J. Sel. Top. Quantum Electron. 10(2), 281–293 (2004).
4. L. Xu, W. Zhang, Q. Li, J. Chan, H. L. R. Lira, M. Lipson, and K. Bergman, “40-Gb/s DPSK data transmission through a Silicon microring switch,” IEEE Photon. Technol. Lett. 24(6), 473–475 (2012).
5. Y. Ding, J. Xu, C. Peucheret, M. Pu, L. Liu, J. Seoane, H. Ou, X. Zhang, and D. Huang, “Multi-channel 40 Gbit/s NRZ-DPSK demodulation using a single Silicon microring resonator,” J. Lightwave Technol. 29(5), 677–684 (2011).
6. R. Kou, K. Yamada, H. Nishi, T. Tsuchizawa, T. Watanabe, H. Shinojima, and S. Itabashi, “DPSK demodulation with a single Silicon photonic nanowire waveguide,” in 8th IEEE International Conference on Group IV Photonics (GFP), (2011), pp. 323–325.
7. L. Zhang, J. Y. Yang, M. Song, Y. Li, B. Zhang, R. G. Beausoleil, and A. E. Willner, “Microring-based modulation and demodulation of DPSK signal,” Opt. Express 15(18), 11564–11569 (2007).
8. P. Dong, C. Xie, L. Chen, N. F. Fontaine, and Y. C. Chen, “Experimental demonstration of microring quadrature phase-shift keying modulators,” Opt. Lett. 37(7), 1178–1180 (2012).
9. J. Lloret, R. Kumar, S. Sales, F. Ramos, G. Morthier, P. Mechet, T. Spuesens, D. V. Thourhout, N. Olivier, J. Fédéli, and J. Capmany, “Ultra-compact electro-optic phase modulator based on III-V-on-Silicon microdisk resonator,” Opt. Lett. 37(12), 2379–2381 (2012).
10. K. Padmaraju, N. Ophir, Q. Xu, B. Schmidt, J. Shakya, S. Manipatruni, M. Lipson, and K. Bergman, “Error-free transmission of DPSK at 5 Gb/s using a Silicon microring modulator,” in 37th European Conference and Exhibition on Optical Communications, OSA Technical Digest (CD) (Optical Society of America, 2011), paper Th.12.LeSaleve.2.
11. G. Barbarossa, A. M. Matteo, and M. N. Armenise, “Theoretical analysis of triple-coupler ring-based optical guided-wave resonator,” J. Lightwave Technol. 13(2), 148–157 (1995).
12. R. A. Soref and B. R. Bennett, “Electrooptic effects in Silicon,” IEEE J. Quantum Electron. 23(1), 123–129 (1987).
13. S. Manipatruni, R. K. Dokania, B. Schmidt, N. Sherwood-Droz, C. B. Poitras, A. B. Apsel, and M. Lipson, “Wide temperature range operation of micrometer-scale Silicon electro-optic modulators,” Opt. Lett. 33(19), 2185–2187 (2008).
14. M. R. Watts, W. A. Zortman, D. C. Trotter, G. N. Nielson, D. L. Luck, and R. W. Young, “Adiabatic resonant microrings (ARMs) with directly integrated thermal microphotonicics,” in Conference on Lasers and Electro-Optics (2009), paper CPDR10.
15. Q. Xu, S. Manipatruni, B. Schmidt, J. Shakya, and M. Lipson, “12.5 Gbit/s carrier-injection-based Silicon microring modulators,” Opt. Express 15(2), 430–436 (2007).
16. A. C. Turner, C. Manolatou, B. S. Schmidt, M. Lipson, M. A. Foster, J. E. Sharping, and A. L. Gaeta, “Tailored anomalous group-velocity dispersion in Silicon channel waveguides,” Opt. Express 14(10), 4357–4362 (2006).
1. Introduction

Efficient optical interconnects are one of the most promising application of Silicon photonics [1,2]. The fundamental element of any optical interconnect is the electro-optic modulator, and there have been many successful demonstrations of amplitude based silicon modulators [1,2]. However, phase encoded modulation has been required for the advancement of all communication technologies. For example, while amplitude modulation was used in optical fiber communications for decades, by the beginning of the last decade there was a rapid transition to phase based encodings due to the exponentially increasing bandwidth requirements of the internet [3]. Silicon photonics is experiencing a similar demand for bandwidth and will also need to move towards using phase encodings [1,2]. There are several reasons that phase modulation is preferred over amplitude modulation: (1) Maximization of signal/noise; (2) Minimization of nonlinear effects; (3) Maximization of channel efficiency (which translates to increased system bandwidth).

As a result phase encoded signals on silicon chip have received increasing attention. There have been several recent studies of the transmission, switching and receiving of phase encoded signals [4–6]. In addition, there have been initial developments in silicon modulators for phase encoding. The first compact microring based phase modulator was proposed in [7], and using this design high speed binary phase-shift keyed (BPSK) and quadrature phase-shift-keyed (QPSK) modulators were demonstrated in [8–10]. However, in all cases the devices required precise voltage inputs, and had high insertion loss.

Here we propose a completely new approach for realizing a compact binary phase modulator. Our design is based on a single ring resonator, with a key output configuration that enables low insertion loss, and robust high speed phase modulation. Using this design it will be possible to realize all of the advantages of phase encoding, particularly the ~3dB enhancement in SNR overOOK [3]. In addition, our design can be extended to the realization of advanced phase encoding formats, such as QPSK and quadrature amplitude modulation (QAM).

2. Binary phase encoding using ring resonators

In order to understand how a ring resonator can be used to modulate phase, consider the spectral response of a ring resonator with a through and drop port:

\[
Y_{\text{through}} = \frac{c_1 - c_2 e^{-(\alpha + j\beta)2\pi R}}{1 - c_1 c_2 e^{-(\alpha + j\beta)2\pi R}}
\]

\[
Y_{\text{drop}} = \frac{-s_1 s_2 e^{-(\alpha + j\beta)\pi R}}{1 - c_1 c_2 e^{-(\alpha + j\beta)2\pi R}}
\]

where \( R \) is the radius of the ring, \( c_{1,2} = \sqrt{1 - \kappa_{1,2}}, s_{1,2} = \sqrt{\kappa_{1,2}}, \kappa_{1,2} \) represents the power coupling ratio at the through and drop ports respectively, \( \alpha \) is the waveguide amplitude attenuation coefficient of a curved waveguide of radius \( R \), and \( \beta = 2\pi n_g/\lambda \) is the waveguide propagation constant where \( n_g \) is the waveguide group refractive index. First we consider the case of a singly coupled ring response which is obtained by setting \( \kappa_2 = 0 \) (see Figs. 1(a)–1(c)). This configuration is identical to those found in [7–10] and realizes the requisite 0 and \( \pi \) phases for BPSK by operating at two equal amplitude points of an over-coupled resonance. However, this scheme inherently requires precise control of the modulation signal as experimentally observed in [8–10].
In contrast, consider a ring resonator with equal through and drop ports \( (\kappa_2 = \kappa_1) \). As shown in Figs. 1(d)–1(f), when the resonator is off-resonance, the optical power passes to the through port and experiences no phase shift, and when the ring is on resonance, the optical power passes to the drop port and experiences a \( \pi \) phase shift. Therefore, by combining the through and drop port outputs it is possible to realize an optical signal with the required 0 and \( \pi \) phases for BPSK.

To achieve PSK operation the phase shifted signal should be on one output not two, therefore the through and drop ports must be combined. Rather than combining the through and drop ports with a y-splitter or directional coupler (which will induce 3db of loss) we propose to connect the through port output to the drop port input, which we will refer to as a feed-through waveguide (see Fig. 2(a), path l\(_2\)). This will ensure that the device has a minimal insertion loss. A rigorous derivation of the spectral response of this device can be found in [11], and yields:

\[
\frac{Y_2}{X_1} = \frac{c e^{-j(\alpha + \beta)l_1} - s e^{-j(\alpha + \beta)l_2} + e^{-j(\alpha + \beta)(l_1 + l_2 + l_3)}}{e^{-j(\alpha + \beta)l_1} - s c e^{-j(\alpha + \beta)l_3} - 1} 
\]

where \( l_1, l_2 \), and \( l_3 \) represent the lengths of waveguide from coupler to coupler as shown in Fig. 2(a). In [11] it was also shown that optical loss will be minimized first by setting \( \kappa_1 \) equal to \( \kappa_2 \), and second by adjusting the lengths \( l_1, l_2 \) and \( l_3 \) such that:

\[
\beta(l_1 + l_3) = \left( \frac{2\pi n_s}{\lambda} \right)(l_1 + l_3) = M \pi \quad (4)
\]

\[
\beta(l_2 + l_3) = \left( \frac{2\pi n_s}{\lambda} \right)(l_2 + l_3) = M \pi \quad (5)
\]
where $M$ and $N$ are even numbers. For the case where $l_2 = l_1 + l_3$, each resonance will be optimally coupled. This is shown in Figs. 2(b)–2(d) with $l_1 = \pi \cdot 5 \mu m$, $l_3 = \pi \cdot 5 \mu m$, $l_2 = 2\pi \cdot 5 \mu m$, and $n_g = 4.1$. The amplitude response is nearly constant with respect to wavelength, with a very small dip, <5% for 3dB/cm loss in a 5\mu m radius ring as shown in Fig. 2(c). Consequently, the device allows low loss phase modulation operating at two points: on-resonance ($\pi$) and off-resonance (0).

These operating points ensure significantly more robust PSK modulation because the (0), off-resonance condition, can be realized over a wide range of wavelengths, significantly reducing requirements on the electronic control of the device. However, it should be noted that these operating points could in theory be achieved with a single coupled ring resonator. However a close inspection of Eq. (3) reveals a subtle advantage of the dual-coupled design. Assuming $\kappa_2 = \kappa_3 \ll 0.5$ then small index changing effects in waveguide sections $l_1$ and $l_3$ will lead to large changes in the resonant wavelength of the device, whereas small index changing effects in waveguide section $l_2$ will lead to small changes in the resonant wavelength of the device. Effectively this can be thought of as granting a course tuning and fine tuning mechanism for the resonant condition of the device, respectively. Since the exact resonant condition greatly affects the on resonance phase ($\pi$), the symbol distance and ultimately the SNR, a high-sensitivity tuning mechanism will ensure practical deployment of this device.

As an additional verification of the results, finite-difference-time-domain (FDTD) simulations were performed. As shown in Figs. 3(a)–3(b), when the ring is on resonance the majority of the power passes into the ring (drop port); whereas when the ring is off resonance the majority of the power passes through the feed-through waveguide.
3. Modulation via free-carrier injection/extraction

In principle, the proposed device could be made to function with any index changing effect. Here we will focus on the predominant modulation effect available in Silicon - the free-carrier plasma dispersion effect [12]. It is well known that free-carrier modulation can be performed in a variety of ways, including injection/extraction with a p-i-n diode, depletion region modulation with a reverse biased diode, and others. As will be shown, injection/extraction with a p-i-n diode complements the optical design of the device. Specifically under forward-bias conditions there will be a significant carrier concentration, more than sufficient to shift the resonator to the (0) phase point. And in extraction, very few carriers will be present, ensuring that the (π) phase condition is met, provided thermal effects can be corrected for [13,14]. In contrast depletion region modulation with a reversed biased diode could be used, but is challenging since the effect is relatively weak, in comparison to injection. While it is potentially faster than injection based devices, it requires careful design of the waveguide and diode which is beyond the scope of this work.

Charge injection by a p-i-n diode into a Silicon waveguide was modeled using the charge dynamics model found in [15]. Figure 4(a) shows the average carrier density as a function of forward bias when the carrier response has evolved for 1ns, 200ps, and 100ps after the voltage has been applied (a step function is used). In order to obtain the optical response of the device first we calculate the change in the phase of the device for various index changes, as seen in Fig. 4(c). This was obtained using Eq. (3), with the substitutions: \( n_g = n_{gi} + dn_g \), and \( \alpha = \alpha_i + d\alpha \), where \( n_{gi} = 4.1 \) and \( \alpha_i = 0.69 \) are the group index and amplitude attenuation coefficients of the waveguide without carriers, and \( d\alpha \) and \( dn_g \) are the change in absorption and index as a function of carrier concentration (Fig. 4(b)) [12]. Additionally \( l_i = \pi \cdot 5\mu m \), \( l_g = \pi \cdot 5\mu m \), \( l_2 = 2\pi \cdot 5\mu m \) and \( \kappa_i = \kappa_g = 0.02 \). The model assumes that the device is on resonance when no carriers are present in the ring.

By combining Figs. 4(a)–4(c), we obtain the proposed device output phase as a function of input voltage. As shown in Fig. 4(d), this phase has a sharp response near threshold, and remains relatively constant otherwise. Therefore the device is robust against voltage variation for both the 0 and π phase condition. However as the switching speed increases the response widens, as expected, since the carrier response does not reach a steady state. This can be optimized in any given design by making tradeoffs in the quality factor of the ring and power requirements.

4. Performance

In order to further quantify the robustness of the device we have simulated the effect of drastically varying input voltage on the response. Because Eq. (3) assumes steady-state operation, this simulation uses the following temporal equation model of the device:
where \( r_{i,3} \) are the electric-field in the ring in the corresponding sections \( l_1 \) and \( l_3 \), \( T_{1,2,3} = \frac{l_{1,2,3}}{c} \), \( c \) is the speed of light, and \( d\alpha \) and \( dn \) are determined using the previously described p-i-n diode models, with a 10Gbps modulating input. Figure 5(a) shows the input voltages, ranging from 50% to 200% variation of optimal performance for the device, for both square wave and sine wave inputs in order to characterize variations in rise/fall time. The corresponding carrier concentration change is shown in Fig. 5(b) and its effect on output optical phase is shown in Fig. 5(c). Despite large variation in input voltage and carrier concentration the output optical signal remains relatively constant (phase varies by \(<\pi/9\), which as explained next will only degrade SNR by only 0.5dB). This is for three reasons: (1) the 0 phase symbol can be achieved over a wide range of operating points due to the flat transfer function seen in Fig. 4(d). (2) The \( \pi \) phase symbol is realized when the diode is effectively off, making it insensitive to voltage variations. While the \( \pi \) phase symbol will still be sensitive to thermal fluctuations, this is an issue of all microring based modulators and a variety of techniques have been employed to minimize this [13,14]. (3) The feed-through waveguide enables high sensitivity tuning of the relative phase between the two symbols, ensuring maximum symbol distance.

To evaluate the performance of this device in a PSK interconnect system we have modeled a standard differential detection scheme (e.g. where a one-bit time delayed
interferometer is used to interfere adjacent symbols) [3]. The results are seen in Fig. 5(d), where the 10Gbit/s optical output (Fig. 5(c)) is differentially detected. It is seen that the differentially detected signal amplitude spans ± 0.9 ± 0.05, which in part is achieved by tuning the phase in the feed-through waveguide to $\pi/9$ to counteract the minor phase offset in high speed operation. Therefore, the proposed device directly gains a 2.5 dB enhancement in SNR over OOK, which is comparable to measured results in commercial grade PSK based telecommunication systems [3].

The amplitude variations in the output signal are also of importance in evaluating the performance of the modulator, and are shown in Fig. 6(a). It is seen that there are peaks and dips, which inherently are caused by the build-up and release of energy in the ring resonator. Firstly, these amplitude fluctuations correspond to the bit transitions and minimally impact the differentially detected signal in Fig. 5(d). They can also potentially be used for clock-recovery, as is the case in Mach-Zehnder based PSK modulators [3]. Secondly, the amplitude variations correspond to points where the phase makes transitions as seen in Fig. 6(b), which leads to chirp in the optical signal. This can also be represented by the complex plane diagram (Fig. 6(c)), which demonstrates that the chirp of the $\pi$-to-0 transition is considerably larger than the 0-to-$\pi$ transition. However, while chirp is of a concern in telecommunication systems with long lengths fiber, it is much less significant for chip-scale optical interconnect applications. Specifically by taking the temporal derivative of the phase output the maximum chirp of the modulator when operating at 10 Gbit/s was determined to be ~40GHz. The largest dispersion in Silicon waveguides is considerably less than 10000ps/nmkm [16], and with propagation lengths on the order of only centimeters this would only yield a signal shift <100fs, which is negligible at 10 Gbit/s. Lastly, the amplitude variations could induce nonlinear effects. However, we expect these will be minimal since similar amplitude spikes in microring based OOK modulators have been shown to have a minor impact [12,17]. Regardless we expect the nonlinearities will be even less than with OOK since the amplitude is considerably more constant in PSK.

Fig. 6. (a) Optical output amplitude of the PSK modulator. (b) Phase output with the two transitions highlighted (0 to pi; pi to 0) (c) Complex plane transition diagram.

5. Conclusions

Here we have presented a novel microring phase-shift-keyed modulator. It realizes low insertion loss while being relatively insensitive to modulation variations. This will allow for high speed performance over a wide range of operating conditions. Additionally even though the proposed device produces a BPSK signal, it can be easily be extended to more complicated QPSK and QAM designs [8].

#165779 - $15.00 USD

Received 29 Mar 2012; revised 4 Jun 2012; accepted 10 Jul 2012; published 17 Jul 2012

(C) 2012 OSA

30 July 2012 / Vol. 20, No. 16 / OPTICS EXPRESS 17446
Acknowledgments

The authors would like to thank Dr. Gernot Pomrenke, of the Air Force Office of Scientific Research for his support under FA9550-10-1-0217.