Chirp-free optical modulation using a silicon push–pull coupling microring

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We propose a silicon ring-based optical modulation method to perform chirp-free optical modulations. In this scheme, we locate the light to be modulated at the resonance of the ring and tune the coupling coefficient between the ring and the straight waveguide by using a push–pull coupling structure. The chirp-free phase modulation can be achieved by varying the coupling coefficient in a large range, which can modify the coupling condition of the ring such that the input light experiences an abrupt phase shift of π at the output. If the coupling coefficient is adjusted in a small range such that the coupling condition of the ring is kept unchanged, only the intensity of the light will be modulated. This leads to chirp-free intensity modulation. Our simulations performed at 10 Gbits/s confirm the feasibility of the proposal. © 2009 Optical Society of America

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Optical modulators are key elements in optical communication systems. Recently, silicon microring resonators have been recognized as one of promising electro-optical modulators owing to its potential for high-density integration. Several proposals have been reported on silicon ring-based modulators [1–6]. Typically, the modulation is achieved by shifting the resonance of the ring such that the intensity and the phase of the input light are modulated. However, the category of these schemes has the following drawbacks in nature: (1) the intensity modulation, such as nonreturn-to-zero (NRZ) and return-to-zero (RZ), cannot be chirp-free; (2) continuous phase change between bits 0 and 1 is inevitable in the phase-shift-keying (PSK) modulation; and (3) it is hard to perform the phase-coded intensity modulation, e.g., carrier-suppressed-RZ (CSRZ), by a single ring.

In this Letter, we propose a novel idea for the silicon ring-based chirp-free optical modulator. In our scheme, we employ a single-ring resonator, where the coupling region is replaced by a Mach–Zehnder interferometer (MZI) between two 3 dB couplers [7]. By driving the MZI in a push–pull mode, the coupling coefficient between the ring and the straight waveguide is tuned. In this way, the resonance is kept unshifted while the notch depth and even the coupling condition are modified. If one sets the input light at the resonance and tunes the coupling coefficient such that the coupling condition is changed between the undercoupling and the overcoupling, the light will experience an abrupt phase change of π at the output and the chirp-free phase modulation can be achieved. On the other hand, if the coupling coefficient is adjusted while the coupling condition is not varied, chirp-free intensity modulation can be performed. Simulation results in this Letter verify the feasibility of our scheme.

A ring resonator consists of a microring side-coupled to a straight waveguide as shown in Fig. 1. At the coupling region, the incident fields a_0 and a_1 are related to the output fields b_0 and b_1 by [7]

$$\begin{bmatrix} b_0 \\ b_1 \end{bmatrix} = \begin{bmatrix} t & jk \\ jk & t \end{bmatrix} \begin{bmatrix} a_0 \\ a_1 \end{bmatrix},$$

where t and k are the self- and the cross-coupling coefficients, which are assumed to be independent of frequency and satisfy the relation $t^2+k^2=1$. In the ring with a perimeter of L, b_1 evolves to a_1 after it travels across the ring, which leads to the relation as follows:

$$a_1 = b_1 e^{-\alpha L/2} e^{-\beta L},$$

where α is the loss coefficient of the waveguide and β is the propagation constant. It follows that

$$b_0 = \left(t - \frac{k^2 a e^{-\beta L}}{1 - t a e^{-\beta L}} \right) a_0, \quad (1)$$

where $a=e^{-\alpha L/2}$. At the resonance, $\beta L=2m\pi$ (m is an integer), and Eq. (1) reduces to

$$b_0 = \left(t - \frac{k^2 a}{1 - t a} \right) a_0. \quad (2)$$

In Eq. (2), the first term is the field directly coupled from the input to the output, and the second term is the field transmitted through the ring. These two

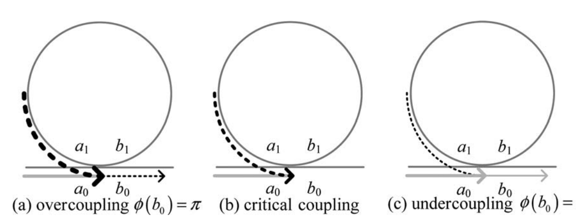

Fig. 1. Different coupling conditions: (a) Overcoupling, (b) critical coupling, and (c) undercoupling.

fields have a phase difference of π, and their destructive interference yields b_0. Depending on the intensities of these two fields, the ring is overcoupled, critical coupled, or undercoupled. This is illustrated in Figs. 1(a)–1(c), where the arrowed gray line denotes the first term in Eq. (2) and the arrowed black line stands for the second term. Correspondingly, the phase of b_0 is π or 0, assuming that the phase of a_0 is 0. In other words, if one changes the coupling condition of the ring, e.g., from the overcoupling to the undercoupling while keeping the resonance unshifted by adjusting t or k, the light at the resonance will experience an abrupt phase shift of π at the output. This feature potentially enables the chirp-free optical phase encoding, such as PSK and CSRZ modulations. Also, the phase of the light at the resonance will remain unchanged if the coupling condition of the ring is fixed, which allows chirp-free intensity modulation.

Based on the above observation and analysis, we propose the silicon-based optical modulator in Fig. 2, where a microring is side coupled to two straight waveguides. The coupling region between the ring and the waveguide at the bottom is replaced by an MZI between two 3 dB couplers [7]. Each arm of the MZI consists of a metal-oxide-semiconductor (MOS) waveguide configuration [1,2] so that a differential phase shift $\Delta\phi$ can be introduced between the two arms by applying a pair of opposite-sign driving voltages on them. In this way, the coupling between the ring and the bottom waveguide is tunable [7]. It is easy to calculate the relationship between the input and the output of the MZI as follows:

$$\begin{bmatrix} b_0 \\ b_1 \end{bmatrix} = \begin{bmatrix} -j\sin\dfrac{\Delta\phi}{2} & j\cos\dfrac{\Delta\phi}{2} \\ j\cos\dfrac{\Delta\phi}{2} & j\sin\dfrac{\Delta\phi}{2} \end{bmatrix} \begin{bmatrix} a_0 \\ a_1 \end{bmatrix}, \tag{3}$$

and the output b_0 is given by

$$b_0 = e^{-j\beta L_x}\left(\frac{-j\sin\dfrac{\Delta\phi}{2} - t' a e^{-j\beta L}}{1 - jt' a \sin\dfrac{\Delta\phi}{2} e^{-j\beta L}} \right) a_0, \tag{4}$$

where L_x is the length of the MZI arm and t' is the self-coupling coefficient of the coupling region on the top. At the resonance, $L = 2m\pi + \pi/2$ and Eq. (4) reduces to

$$b_0 = je^{-j\beta L_x}\left(\frac{t'a - \sin\dfrac{\Delta\phi}{2}}{1 - jt'a\sin\dfrac{\Delta\phi}{2}} \right) a_0. \tag{5}$$

Hence, the coupling condition of the ring containing a push–pull structure is determined by the difference between $t'a$ and $\sin\Delta\phi/2$. Figure 3 plots the output intensity and the phase of the resonant wavelength

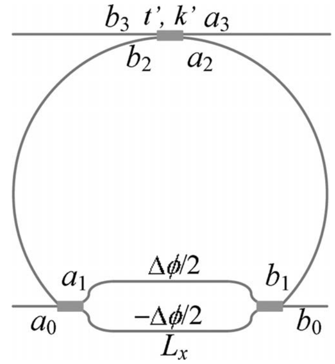

Fig. 2. Push–pull coupling ring, where the coupling region consists of two 3 dB couplers with an MZI in between.

changing with the value of $\Delta\phi/\pi$, where the perimeter of the ring is $L = 2\pi \times 30\ \mu\text{m}$, the length of the MZI arm is $L_x = 3L/4$, and the optical loss coefficient $\alpha = 9\ \text{dB/cm}$. With an increase of $\Delta\phi/\pi$, the cross-coupling coefficient $j\cos\Delta\phi/2$ in Eq. (3) decreases and the ring resonator changes from the overcoupling to the undercoupling. Accordingly, the intensity of the resonant wavelength at the output first decreases and then increases, and the phase experiences an abrupt phase shift of π around the critical coupling.

Note that some applications, such as CSRZ modulation, require a symmetrical modulation curve. Let $\Delta\phi_1$ be the point where the ring is critical coupled and $\Delta\phi_2$ be the value at which the intensity of the resonant wavelength is equal to that at $\Delta\phi = 0$. The ratio $\Delta\phi_1/\Delta\phi_2$ can be used to indicate the symmetry of the modulation curve. From Eq. (5), at the resonance, $|b_0/a_0|^2 = t'^2 a^2$ at $\Delta\phi = 0$ and $|b_0/a_0|^2 = 0$ at $\Delta\phi = \Delta\phi_1$, which implies that $\Delta\phi_1/2 = \arcsin(at')$. According to our definition, $\Delta\phi_2$ is the value such that $|b_0/a_0|^2 = t'^2 a^2$. Hence, $\Delta\phi_2/2 = \arcsin[2at'/(1 + a^2 t'^2)]$. To get a sufficiently symmetrical curve, we should have $|\Delta\phi_2 - 2\Delta\phi_1| < \varepsilon$, where ε is an arbitrary small positive number. Since $0 \leqslant \Delta\phi_1/2 \leqslant \Delta\phi_2/2 \leqslant \pi$, the above inequality is equivalent to

$$\left| \cos\frac{\Delta\phi_2}{2} - \cos 2\frac{\Delta\phi_1}{2} \right| < \varepsilon.$$

Using the trigonometric identities as well as the values of $\Delta\phi_1/2$ and $\Delta\phi_2/2$, the inequality changes to

$$\left| \frac{2a^2 t'^2}{1 + a^2 t'^2} \right| < \varepsilon.$$

It is easy to show that the inequality will hold if $a^2 t'^2$ is sufficiently small. For example, in Fig. 3, $\Delta\phi_1/\Delta\phi_2$

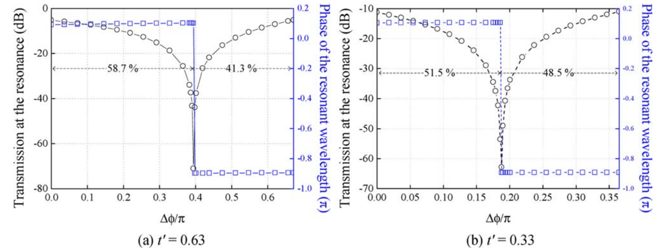

Fig. 3. (Color online) Modulation curves of the push–pull coupling ring; (a) $t' = 0.63$ and (b) $t' = 0.33$.

is 58.7% at $t'=0.63$, while it is 51.5% at $t'=0.33$, given $\alpha=9$ dB/cm. Also, a small t' will bring two more advantages. First, as displayed in Fig. 3, for the modulation, the required phase shift and thus the driving voltage decrease with the value of t'. Second, a smaller t' implies that more optical energy will escape from the top waveguide, which results in a shorter photon lifetime and thus increases the modulation data rate. However, a smaller t' will increase the optical loss at the output b_0, which can also be observed in Fig. 3.

To simulate the optical modulations, we drive the ring resonator by a 10 Gbits/s pseudorandom binary sequence (PRBS) with a length of 2^7-1, which is sent to a low-pass Butterworth filter such that the driving voltage possesses a rising/falling edge of 15 ps. The push–pull coupling ring employed in the simulation has the same parameters as that used in Fig. 3(b). In the MZI region, we employ the waveguide structure introduced in [2], where the light is confined to the metal-oxide layer such that the driving voltage applied to the modulator can be small. We use the charging process of a capacitance to emulate the variation of carrier concentration in the waveguide following the driving voltage [2,5,6]. The carrier transit time, defined as the duration required for the carrier density to increase from 10% to 90%, is assumed to be 10 ps.

First, we assume that the wavelength of the input light is exactly located at the resonance. We apply a 10 Gbits/s NRZ signal with a peak-to-peak voltage of $V_{pp}=7$ V to the MZI. Accordingly, $\Delta\phi/\pi$ changes from 0 to 0.365, as displayed in Fig. 3, which yields a 10 Gbits/s optical PSK signal in Figs. 4(a) and 4(b). As seen from the results, the obtained PSK signal has an intensity dip and an abrupt phase change of π at each bit transition, which indicates that the phase modulation is chirp-free.

We show that the push–pull coupling ring can act as a CSRZ pulse carver owing to its chirp-free property. Sending a 10 GHz sinusoidal voltage with $V_{pp}=7$ V to the MZI arms, we obtain a CSRZ pulse train in Figs. 4(c) and 4(d), where its intensity changes, such as an RZ pulse train with a repetition ratio of 20 GHz and its phase inverses at every pulse. Therefore, one can achieve CSRZ-PSK modulation using two cascaded push–pull coupling rings.

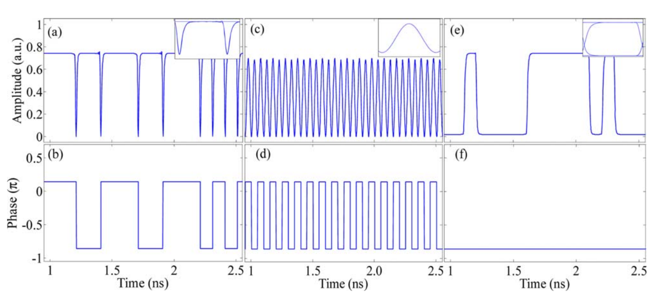

Fig. 4. (Color online) Chirp-free modulations with the assumption that the input light is precisely at the resonance. (a) Amplitude and (b) phase of the PSK signal, (c) and (d) for the CSRZ signal and (e) and (f) for the NRZ signal.

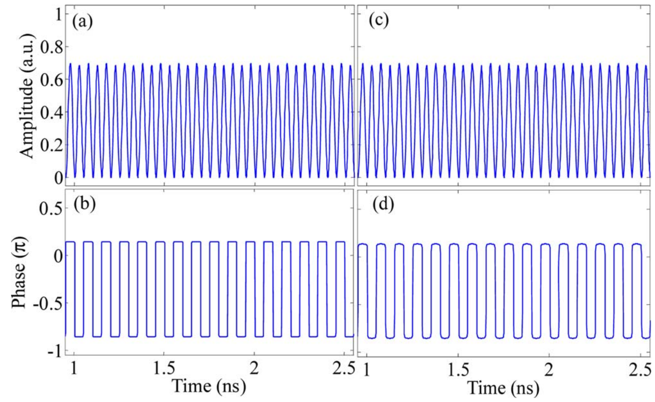

Fig. 5. (Color online) CSRZ modulation with the wavelength misalignment between the input light and the resonance. (a) Amplitude and (b) phase for the misalignment of 0.001 nm and (c) and (d) for the misalignment of 0.01 nm.

According to the modulation curve, we can perform a chirp-free NRZ modulation if the amplitude of the driving NRZ voltage is less than 3.5 V. From the simulation results in Figs. 4(e) and 4(f), one can find that there is almost no phase fluctuation in all the bits, which confirms the chirp-free intensity modulation.

In practice, the wavelength misalignment between the input light and the resonance is inevitable. Therefore, we investigate the impact of such a misalignment on the modulation performance in Fig. 5, where the CSRZ modulation is performed. Figures 5(a) and 5(b) are the results for the wavelength misalignment equal to 0.001 nm and have no visible degradation compared to that in Figs. 4(c) and 4(d). When the misalignment increases to 0.01 nm, one can see an ~6 ps phase transit time between two pulses, which is still tolerable for a 10 GHz CSRZ signal. It can be expected that the chirp-free property will be lost if the misalignment is large. Fortunately, in practical applications, it is easy to make the wavelength misalignment smaller than 0.01 nm.

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