

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

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Received January 6, 2009; accepted January 22, 2009;  
 posted February 12, 2009 (Doc. ID 105817); published March 10, 2009

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  $\pi$  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

OCIS codes: 060.0060, 060.4080, 130.0130.

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  $\pi$  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  $\alpha$  is the loss coefficient of the waveguide and  $\beta$  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

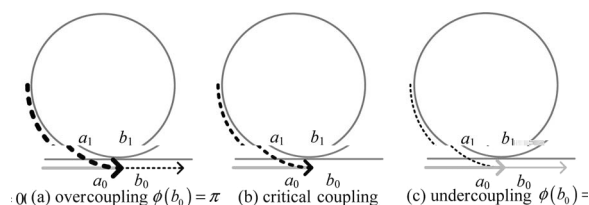


Fig. 1. Different coupling conditions: (a) Overcoupling, (b) critical coupling, and (c) undercoupling.

fields have a phase difference of  $\pi$ , and their destructive interference yields  $b_0$ . Depending on the intensities of these two fields, the ring is overcoupled, critically 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  $\pi$  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  $\pi$  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:

$$\begin{bmatrix} b_0 \\ b_1 \end{bmatrix} = \begin{bmatrix} -j \sin \frac{\Delta\phi}{2} & j \cos \frac{\Delta\phi}{2} \\ j \cos \frac{\Delta\phi}{2} & j \sin \frac{\Delta\phi}{2} \end{bmatrix} \begin{bmatrix} a_0 \\ a_1 \end{bmatrix}, \quad (3)$$

and the output  $b_0$  is given by

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

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

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

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

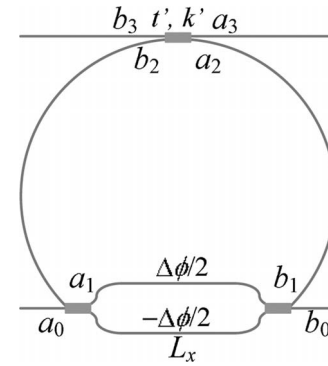


Fig. 2. Push-pull coupling ring, where the coupling region consists of two 3 dB couplers with an MZI in between.

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  $\pi$  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,  $\Delta\phi_2/2 = \arcsin[2at'/(1+a^2t'^2)]$ . To get a sufficiently symmetrical curve, we should have  $|\Delta\phi_2 - 2\Delta\phi_1| < \varepsilon$ , where  $\varepsilon$  is an arbitrary small positive number. Since  $0 \leq \Delta\phi_1/2 \leq \Delta\phi_2/2 \leq \pi$ , 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,  $\Delta\phi_1/\Delta\phi_2$

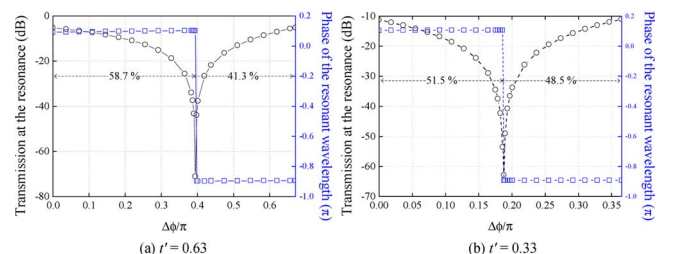


Fig. 3. (Color online) Modulation curves of the push-pull coupling ring; (a)  $t' = 0.63$  and (b)  $t' = 0.33$ .

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