Silicon Photonic Modulator based on Coupled Bragg Grating Resonators used as Phase Shifters

Omid Jafari, Hassan Sepehrian, Wei Shi, Sophie LaRochelle*
Centre d'optique, photonique et laser (COPL), Department of Electrical and Computer Engineering, Université Laval, Québec, QC, Canada
*sophie.larochelle@gel.ulaval.ca

Abstract: Bragg gratings with phase-shifts are inserted in a Mach-Zehnder modulator to enhance phase modulation, reduce device length and improve efficiency ($V_\pi \times L$=0.28 Vcm). Simulations show 3 nm optical bandwidth corresponding to 50 K operating temperature range.
OCIS codes: (130.3990) Micro-optical devices; (250.4110) Modulators; (230.5750) Resonators

1. Introduction

Silicon photonic modulators (SPMs) are expected to be one of the key building blocks of future optical interconnects and communications systems. SPMs are generally classified into two broad categories: Mach-Zehnder modulators (MZMs) and resonator-based modulators (RBMs). MZMs present a wide optical bandwidth that confers them temperature insensitive operation and, furthermore, when operated with push-pull driving they also offer small pulse chirp [1]. MZMs are usually combined to travelling waveguide electrodes to achieve high-speed, however, the weak plasma dispersion effect in silicon causes low modulation efficiency, resulting in large device footprint and high power consumption. On the other hand, in RBMs, the resonance phenomenon makes the transmitted phase more sensitive to the applied voltage resulting in a lower radio frequency (RF) driving power and a more compact footprint [2]. Despite the aforementioned advantages, modulating resonating cavities with high quality factor introduces chirp and suffers from a narrow optical bandwidth [3], resulting in high sensitivity to temperature variations. In microring modulators (MRMs), for example, the power consumption for active stabilization can even be significantly higher than the power required by the modulator driver [2]. In this work, we present a novel modulator design that addresses the tradeoff between optical bandwidth and power consumption, reaching a compromise between the large optical bandwidth of conventional MZMs and the high modulation efficiency of MRMs. Below we describe the proposed structure based on coupled resonators with low quality factors and we examine the response as a function of applied voltage. Simulation results show that it should be possible to obtain an optical bandwidth of >3 nm while maintaining high efficiency of $V_\pi \times L < 0.3$ Vcm.

2. Modulator structure

Fig. 1(a) shows the schematic of the proposed Bragg grating resonator assisted Mach-Zehnder modulator (BGR-MZM). Each arm contains an integrated Bragg grating (IBG) with a uniform period of 310 nm and six π-phase shifts located at L/12, 3L/12, 5L/12, 7L/12, 9L/12, 11L/12, where L is the IBG length. The gratings are designed using sidewall corrugations with a duty cycle of 50% in a ridge waveguide having an average width of 575 nm, a 130 nm ridge height and a 90 nm slab height. The maximum waveguide width is 850 nm and the minimum 300 nm

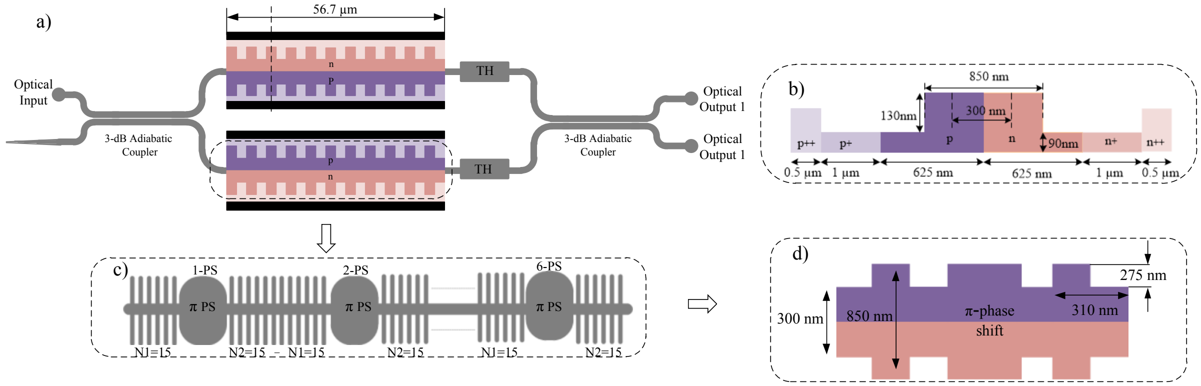

Fig. 1. Schematic of BGR assisted MZM, (a) configuration of the BGR-MZM, (b) cross-section of each arm, (c) phase-shifted integrated Bragg grating of each arm, (d) phase-shifted cavity. TH: Thermal element, PS: Phase-shift.

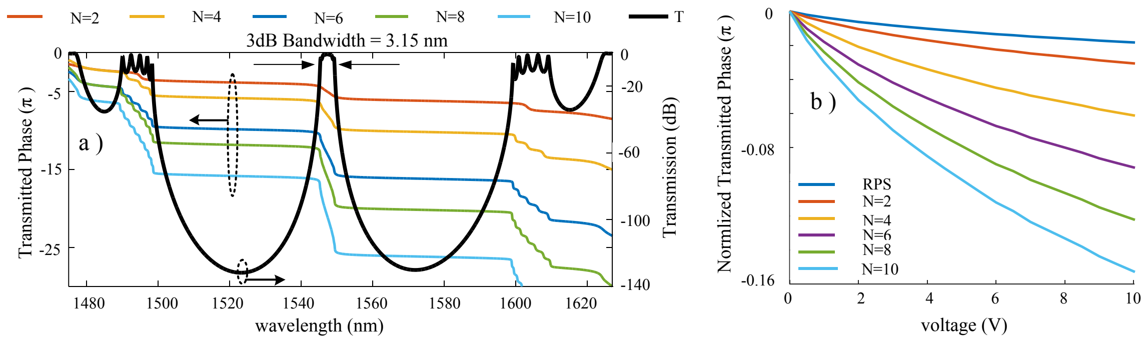

Fig. 2. (a) Transmission and transmitted phase of each arm of the BGR-MZM (b) Normalized transmitted phase as a function of applied reverse voltage. N is the number of resonators and RPS is a reference phase-shifter (waveguide with pn junction and length of 56.7 μm).

(total corrugation amplitude 550 nm). Fig. 1(b) shows the p-n junctions formed over the entire IBG length. Free-carrier plasma dispersion is used to achieve modulation by applying a reverse-bias voltage across the p-n junction.

In RBM, high modulation efficiency is usually achieved by designing high quality resonators that enhance phase modulation but at the expense of reduced optical bandwidth. In the present case, we use cavities with low quality factors to improve optical bandwidth. The phase modulation enhancement is then achieved by placing several of these resonators along the waveguide (Fig. 1(c)), each resonator providing a fraction of the total required phase shift. The proposed modulator thus reduces power consumption and footprint compared to conventional MZMs and provides larger operating temperature range than MRMs. Furthermore, these results are achieved by designing strong IBGs, with high photonic bandgaps, that are obtained by using large grating corrugations (see Fig. 1(d)). With these gratings, a large number of resonators can be placed in series, while keeping the overall length of the Mach-Zehnder (MZ) arms quite small (<57 μm). In [4], cascaded MRMs were similarly inserted in MZ to increase modulation efficiency. In our proposed modulator structure, the use of phase-shifted IBGs overcomes the usual free spectral range limitation of MRMs and a single peak is observed over the whole C-band. Also, the BGR-MZM design is based on coupled resonators rather that cascaded ones, which leads to further performance improvement. Finally, when implemented with strong corrugations, the BGR-MZM structure has a very small footprint area, which directly contributes to making the design more robust to fabrication variations.

3. Results

To simulate the device, we first use FDTD-Lumerical to determine the grating coupling coefficient. Thereafter, the transfer matrix method with MatLab is used to calculate the IBG transmission amplitude and phase [5] as shown in Fig. 2(a). The transmission amplitude (black line) shows a 3dB bandwidth of 3.15 nm confirming that the use of cavities with low quality factor (Q=332) increases the operating temperature range. For comparison, in [2], MRM with quality factor around 18000 were used. In Fig. 2(a), the colored lines show the transmitted phase for different number of resonators. The phase modulation efficiency at the bias wavelength (λ_0=1547.3 nm) depends on the derivative of the phase with respect to wavelength. If the slope is small, a larger Vpp is needed to achieve the required phase modulation. As seen in Fig. 2 (a), this slope can be increased by increasing the number of resonators. To quantify the phase enhancement, we consider the derivative of the phase with respect to applied voltage; an enhancement factor, γ, is then defined as the ratio between the value of this derivative evaluated for a IBG with multiple phase-shifts to that of a simple phase-shifter (waveguide with p-n junction) with the same length. In the present case, with six resonators, the enhancement factor is 5. The amplitude response show that some small ripples appear when the number of resonators is increased but changes in the 3-dB optical bandwidth is negligible. Fig. 2(b) compares the transmitted phase as a function of voltage for various numbers of cavities, with the top blue curve corresponding to the reference phase-shifter. Results show a strong enhancement of the phase modulation, proportional to the number of resonators. In order to have a compact design and thus low modulation power, we designed IBGs with a large photonic band gap of 82 nm, for which 15 periods are placed on each side of the resonators to provide a 3.15 nm 3dB bandwidth resulting in a remarkably small IBG length of only 56.7 μm, in comparison to conventional MZM (typically several millimeters).

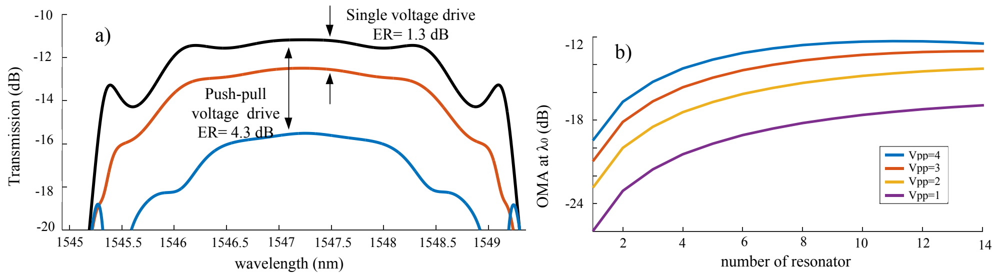

Fig. 3. (a) DC optical modulation for reverse bias voltage for single voltage drive (blue line) and push pull voltage drive (red line). V_{bias_DC} = -4 V, Vpp=-4 V on each arm, (b) Optical modulation amplitude for different Vpp on each arm based on number of resonator in V_{bias_DC}= -4V.

Considering a MZ interferometer with ideal 3 dB splitters, the output power of the BGR-MZM is

$$P_{out} = P_{in}\, e^{-\alpha L} \cos^2\left(\frac{\Delta\varphi_v + \Delta\varphi_0}{2}\right) \quad \text{where} \quad \Delta\varphi_v = \frac{2\pi}{\lambda}\Delta n_{eff}\left(V\right)\gamma L \qquad (1)$$

In (1), P_{in} is input power, α represents propagation loss, $\Delta\varphi_v$ is the voltage dependent phase shift that includes the enhancement effect, and $\Delta\varphi_0$ is the initial phase bias. Also, Δn_{eff} is the change of refractive index with applied reversed voltage V. The calculated modulation efficiency ($V_\pi \times L$) is 0.28 Vcm at λ_0, confirming that this modulator is significantly more efficient than conventional MZM [4]. Fig. 3(a) shows the output of the BGR-MZM when driving only one arm (single-drive) or both arms in a push-pull configuration, using a -4 V bias, V_{pp}=4 V on each arm, and $\Delta\varphi_0$=0.8π. The ON/OFF extinction ratio for single drive is 1.3 dB and is increased to 4.3 dB by using push-pull. The optical modulation amplitude (OMA), i.e. the difference between maximum ("1") and minimum ("0") output power normalized to input power P_{in}, is shown in Fig. 3 (b). We conclude that the OMA scales with the number of resonators for a given V_{pp}. The OMA spectral dependence is illustrated in Fig. 4 that shows a 3dB bandwidth of 3.9 nm. Considering a typical resonance shift of 80 pm/K, the BGR-MZM operating temperature range is near 50 K. It is worth to note that this value is just a few kelvins for MRM [2].

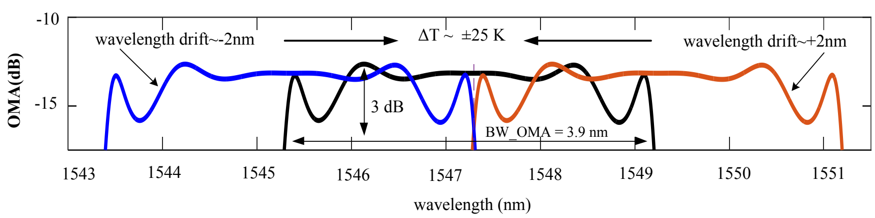

Fig. 4. OMA spectrum of the modulator with push-pull driving as a function of wavelength (black line). OMA spectra for the modulator with operating temperature shifted by ΔT = -25 ^{0}C (blue line) and ΔT = 25 ^{0}C (red line)

5. Conclusion

We proposed a novel silicon photonic modulator design in which the straight phase shifters in conventional MZMs are replaced by IBGs with multiple phase shifts to enhance phase modulation. Through numerical simulations of the static device response, we estimate that the BGR-MZM should lead to a drastically improved efficiency ($V_\pi \times L$) of 0.28 V.cm. Despite the use of multiple cavities, the length of each arm remains remarkably short (L = 56µm) due to the use of IBGs with high photonic band gap. The low quality factor cavities allow a carrier wavelength offset of ~±2 nm from the resonance, corresponding to an operating temperature range of 50 K, drastically reducing the requirements on thermal control of such resonant based modulators.

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