Ring resonator structures for active applications in Silicon

Estructuras basadas en anillos resonantes para aplicaciones activas en silicio

M. Aamer(*), A. M. Gutiérrez, A. Brimont, P. Sanchis

Nanophotonics Technology Center, Universidad Politécnica Valencia, Camino de Vera s/n, 46022 Valencia, Spain.

(*) Email: maaa@ntc.upv.es


ABSTRACT:

In this paper we make a review of ring resonators structures for active applications in silicon. Specifically, we analyze and demonstrate microring tunable resonators for thermo-optic tuning and electro-optic modulation. A Thermo-optically tunable Silicon-On-Insulator (SOI) microring demultiplexer with high extinction ratio and low insertion losses is presented and experimentally demonstrated. Concerning Electro-Optic modulation, single ring resonator structures and ring enhanced Mach-Zehnder interferometer (REMZI) structures have been theoretically analyzed. The goal is to take advantage of such structures in terms of extinction ratio, required power consumption and device size to achieve high speed modulation..

Key words: Silicon-on-insulator, Tunability, Thermo-Optic Effect, Electro-Optic Effect.

RESUMEN:

En este artículo, realizamos una revisión de estructuras basadas en anillos resonantes para aplicaciones activas en silicio. En concreto, analizamos y demostramos resonadores en anillo para sintonización termodóptica y modulación electro-dóptica. Un demultiplexor en tecnología SOI (Silicon-On-Insulator) sintonizable termodópticamente es presentado y experimentalmente demostrado, con bajas pérdidas de inserción y una alta relación de extinción. En lo referente a la modulación electro-dóptica, se han analizado tanto estructuras basadas en un único anillo resonante, así como estructuras basadas en interferómetros Mach-Zehnder con un anillo acoplado. El objetivo es aprovechar estas estructuras en términos de relación de extinción, potencia consumida, y tamaño del dispositivo para mejorar la modulación a alta velocidad..

Palabras clave: Silicon-On-Insulator, Sintonizabilidad, Efecto Termo-Óptico, Efecto de Dispersión de Plasma.

REFERENCE Y ENLACES / REFERENCES AND LINKS


1. Introduction

Silicon-On-Insulator (SOI) microphotonics is an attractive technology to reduce photonic systems down to micrometer-scale size. Microring resonators (MRR) are one of the most suitable structures to achieve very compact devices and very low power consumption. Unfortunately, SOI MRRs are extremely sensitive to fabrication variations and imperfections. As a result, very small size variations may cause appreciable deviations in device performance. Fortunately, silicon has a relatively large thermo-optic coefficient, which enables efficient thermal tuning, an essential feature required to provide flexibility in data transmission, routing or switching.

In this paper, we report two of the key building blocks in photonics systems: an optical tunable filter, to implement (de)multiplexers for channel transmission in wavelength division multiplexing systems (WDM), and an electro-optically tunable modulator based on MRRs for future architectures capable of transmitting data at Tb/s. Reducing component size and lowering power consumption are the goals of both studies.

The paper is structured as follows: First, key parameters of a microring resonator are presented, and its tunability is experimentally shown. Subsequently, two different applications using tunability in MRR are studied and presented. Finally conclusions are provided.

2. Theory of tunability in a MRR

A single ring resonator structure is shown in Fig. 1. The key parameters, which are depicted in the figure below, are the gap (d) or separation between the bus waveguide and the ring in the coupling region, the ring radius (R), the coupling length (Lc) and the ring losses (α (dB/cm)). In principle, the ring parameters must be designed to operate at the critical coupling point when the applied voltage is zero, at a wavelength around 1550nm.

The refractive index in the ring can be modified by using the Thermo-Optic effect (TO) or by Electro-Optical effect (EO). Therefore, by tuning the refractive index of the silicon and hence the effective index of the mode, a single wavelength can be switched between the output ports. A shift of the effective index, Δn_{eff}, causes a shift of the resonance wavelength [1] as depicted in Fig. 2 as illustrated by the equation below:

\[ \Delta \lambda = \lambda_0 \frac{\Delta n_{eff}}{n_g}. \]  

Fig. 2. Shift of the resonant wavelength due to a shift of the effective index.
The TO effect presents a strong refractive index tuning in silicon and it has been shown to provide a large wavelength shift on the order of $\Delta \lambda \sim 20$ nm [2] while operating on a time scale of a few µs using direct heating [3], suitable for circuit-switched networks. TO tuning is realized by heating the component, for example, via metal heaters deposited on top of precisely determined regions of the ring resonator.

The EO effect in silicon is possible by making use of the plasma dispersion effect. This physical effect is basically based on free carrier concentration variations in a semiconductor, which alters both the real and imaginary part of the refractive index, respectively known as electro-refraction and electro-absorption. These parameters were derived experimentally by R. A. Soref from the Drude-Lorenz equations at the specific telecommunication wavelengths (1.3 µm and 1.5 µm) [4]. As for electronic devices, silicon needs to be doped with elements from the third and fifth columns of the periodic classification of elements to form a semiconductor junction capable of injecting, depleting or accumulating charge carriers (electrons and holes). This enables to control accurately the electrical response of silicon-based devices. Such a control is required to make diodes, transistors, detectors, and others devices. Using conveniently this existing technology, it becomes possible to combine an optical structure guiding the propagating mode with an electrical structure in charge of injecting, depleting or accumulating a plasma of free carriers overlapping the mode in question. In the field of light modulation in silicon, the last experimental evidences shown that the most effective mechanism to achieve multi-GHz modulation in all-silicon devices is proven to be such plasma dispersion effect [5].

3. Thermo-optically tunable microring demultiplexer filter

To overcome fabrication mismatches and imperfections, tunability is required. The demultiplexer filter design based on a MRR is depicted in Fig. 3. The radius has been fixed to 20µm. Two input optical carriers are filtered by centering one of them at a ring resonance, so each one of the inputs can be processed independently from the other one. The quality of the device is highly dependent on the insertion losses and the extinction ratio at the output ports. By using the TO effect, the extinction ratio and the insertion losses are tuned by using the through electrodes (see Fig.3), so that depending on the application and the required separation between carriers, the demultiplexer filter will be tuned in order to satisfy the specifications. The spectral response of the whole structure has been modeled by using transfer matrix formalism [6].

Figure 4 shows a SEM image of the fabricated device before metal deposition. The separation between the ring and the waveguide was chosen to be 200 nm and 320 nm for the Through and Drop ports respectively.

The structure was fabricated on SOI wafer with silicon core thickness of 220 nm and buried oxide (BOX) of 2 µm. The ring and bus waveguide width is 450 nm which were covered by a 2 µm-thick silica overcladding. The fabrication process was carried out by using electron beam lithography (EBL) and dry etching by using an inductively coupled plasma (ICP)
Plasma enhanced chemical vapor deposition (PECVD) was also used, to grow the overladdling silica layer. Finally, microheaters and electrical contact pads are sequentially patterned with lithography (PMMA resist), evaporation, and lift-off processes. The microheaters and contact pads consist of 115 nm thick Ti. The heater width is 500 nm.

For optical characterization, light from a tunable laser source is initially coupled into the sample by using a lensed fiber, while an objective is used to collect the output light.

Figure 5 shows that the extinction ratio varies significantly by varying the voltage applied to the electrodes. It is also noted that there is almost no shift in the resonance when the voltage varies. Thus, with only 1.3V voltage variation, the extinction ratio can be varied from 0 to nearly 20 dB.

Figure 6 shows the variation of the extinction ratio as a function of the applied voltage. As it can be seen, and considering that the coupling factor varies sinusoidally with the applied voltage, we have that the extinction ratio has the same sinusoidal behavior. Moreover, the maximum consumed power by the device when the voltage is 8V is around 15.5 mW while the consumed power is only 6.5 mW for 5.5V.

Regarding the insertion losses, the goal is to decrease them as much as possible, while the extinction ratio increases during tuning. Figure 7 shows the simulated variation of the insertion losses for different applied voltages. It can be seen that as the applied voltage is closer to the voltage that provides the greater extinction ratio, the insertion losses decreases, as expected.

Although the results are quite satisfactory, the next step is to study the possibility of tuning the extinction ratio of both output ports, using the structure shown in Fig. 8.

According to some theoretical studies based on [6], one might be able to get an extinction ratio of -50 dB and insertion losses of less than -0.5 dB, as depicted in the Figs. 9.
4. Electro-optical modulators based on MRRs

The second device which is analyzed in this work is the ring resonator electro-optic modulator.

Different configurations of ring resonator structures have been investigated to enhance modulator performance in terms of extinction ratio and required effective index variation. Modulation based on the intensity and phase response of a ring resonator was analyzed and their performances compared. Furthermore, a sensitivity analysis was carried out to evaluate the impact of fabrication deviations on the modulators performance. It was concluded that phase modulators are preferred with respect to intensity modulators due to the higher robustness against fabrication deviations mainly because the ring does not need to be operated at the critical coupling point to achieve a high extinction ratio.

Basic performance of an intensity modulator based on a ring resonator is already shown in Fig. 10. A continuous wave (CW) of a certain wavelength is injected into the ring resonator. Minimum transmission is achieved when the wavelength is located at a ring resonance. Furthermore, this transmission is ideally zero when the ring operates at critical coupling, i.e. when the coupled power is equal to the lost power in the ring. Thus, the output power increases up to a maximum value when the frequency shift is enough to move the resonance out of the working wavelength.

On the other hand, the phase response of the ring resonator can also be used to achieve phase modulation. This phase modulation is converted to an intensity modulation by using a Mach-Zehnder interferometer (MZI), as it is shown in Fig. 11. In this case, it is also supposed that the input signal is a continuous wave (CW) located at the ring resonance. The ring induces a \( \pi \) phase shift to the signal that travels through the upper arm of the MZI which will interfere destructively with the signal that travels through the lower arm of the MZI, thus giving rise to minimum transmission at the MZI output. If the frequency shift is enough so that the operation wavelength is now out of the resonance, the ring will not introduce an additional phase shift and the signal at the upper arm will interfere constructively with the signal that travels through the lower arm giving rise to maximum transmission at the MZI output.

The extinction ratio of this modulator is ideally infinite if the attenuation at both arms of the MZI is the same. However, it should be noticed that the intensity response of the ring resonator will also vary when losses are not negligible and the effective index is modified. This will introduce an additional attenuation to the signal that travels through the upper arm with respect to the one that travels through the lower arm, which could significantly degrade the extinction ratio of the modulator due to the power unbalance between both arms of the MZI. This power unbalance will be lower as the power coupling factor, i.e. the fraction of power
coupled from the waveguide into the ring, increases. Therefore, the ring does not need to be operated at the critical coupling point and just over-coupled. However, it should be realized that too high power coupling factors could increase insertion losses for a given effective index variation as the slope of the phase response will get less steep.

The fact that the ring does not need to be operated at the critical coupling factor implies that modulator robustness against fabrication deviations will be significantly improved with respect to ring based intensity modulators. Fabrication deviation could lead to both variations on the ring losses as well as variations in the designed separation between the waveguide and the ring and therefore in the power coupling factor.

Figure 12 shows the theoretical extinction ratio (ER) as a function of the coupling factor and the ring losses for the ring based intensity modulator and taking into account different effective index variations. The same plot is shown in Fig.13 for the ring enhanced MZI (REMZI) modulator although it should be noticed that in this case the range of the power coupling values is higher. Ring modeling was carried out using the analytic formula of the transmission factor [7]. Comparing the results shown in Fig. 12 and Fig. 13 it can be clearly seen the enhanced performance achieved by the REMZI modulator. High ER values in the ring modulator are only achieved when there is a correspondence between the ring losses and the coupling factor, i.e. the critical coupling condition, and therefore undesired variations in the ring losses or coupling factor significantly degrade the ER even though the effective index variation is increased. On the other hand, the REMZI modulator is much less sensitive to variations of losses and the coupling factor, especially as the effective index variation increases.

On the other hand, such mentioned values of effective index variations are achieved when a determined voltage bias is applied. An effective index variation of \(1 \times 10^{-4}\) or \(2 \times 10^{-4}\) can be achieved applying a reverse bias of 2V or 6.5 V respectively in an asymmetrical PN junction with a net doping concentration varying between 6×10^{17} cm\(^{-3}\) and 2×10^{17} cm\(^{-3}\), for N and P type respectively with resistive contacts formed by highly doped regions (1.10^{20} cm\(^{-3}\)) in order to form a good resistive contact. In such case, loss varies from 7.5 dB/cm when 2 V bias is applied and 5.5dB/cm with a reverse bias of 5 volts [8].

Finally, we can say that a similar performance is achieved for both modulators when the ring radius is modified. However, larger ring radii would imply a longer interaction length and therefore a lower drive voltage to achieve a given effective index variation. In contrast, larger ring radii could affect the modulation bandwidth owing to the higher RC constant of the device in a lumped
electrode configuration. Therefore, the ring radius yields to a trade-off between the modulation bandwidth and power consumption.

Fig. 12. Theoretical ER as a function of the coupling factor and the ring losses for the ring based intensity modulator for different effective index variation. Insertion losses are lower than 3 dB for the values shown, where the ER is higher than 5 dB (dark blue), 10 dB (light blue), 15 dB (yellow) and 20 dB (brown).

Fig. 13. Theoretical ER as a function of the coupling factor and the ring losses for the REMZI modulator for different effective index variation. Insertion losses are lower than 3 dB in the values shown, where the ER is higher than 5 dB (dark blue), 10 dB (light blue), 15 dB (yellow) and 20 dB (brown).

5. Conclusion

In this paper, we have analyzed microring tunable resonators for thermo-optic tuning and electro-optic modulation. We have reported two of the key building blocks of photonics systems: an optical tunable filter, to implement (de)multiplexer for channel transmission in wavelength division multiplexing systems (WDM) with very high extinction ratio and low insertion losses, as well as an electro-optically tunable modulator based on rings for future architectures capable of transmitting data at Tb/s. So, active rings present a versatile behavior, which allows us to adapt its response depending on the application.

Acknowledgements

Authors acknowledge funding by the European Commission under project HELIOS (pHotonics Electronics functional Integration on CMOS), FP7-224312, as well as TEC2008-06360 DEMOTEC, TEC2008-06333 SINADEC and PROMETEO-2010-087.