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SOI PHOTONIC CIRCUITS FOR OPTICAL COMMUNICATION SYSTEMS

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Abstract. This work considers the possibility of using ring resonators as optical modulators in communication systems. Ring resonators are the major component in all-optical integrated photonic circuits due to their small size, which contributes to increasing the integration density. Controlling the light intensity through the eclectic/optic effect is the main aim of this study. Electron/optic modulation through the use of the plasma dispersion effect is studied. The plasma dispersion effect is a mechanism by which a controlled change in the effective refractive index of Silicon on Insulator (SOI) can be achieved by changing the concentration of free carriers in the silicon waveguides. In the SOI ring resonator based optical modulator, the intensity of the light passing through the resonator is controlled by changing the refractive index of the ring waveguide material, which in turn changes the resonance conditions of the resonant modes. This change in the resonance conditions can be achieved by applying an electrical field to the modulating electrodes, which are placed in the rib waveguide. In this work, the theoretical analysis and the response of the modulator are first presented, then the performance is validated using 3D simulation software. Although the work concentrates more on the intensity modulation of On-Off keying, it also opens the door for using such compact modulators for different modulation techniques such as Orthogonal Frequency Division Multiplexing (OFDM); which means high data rate modulators using small-size devices.

Keywords: optical waveguides, optical modulator, photonic circuits, ring resonator, silicon on insulator

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ФОТОННЫЕ СХЕМЫ «КРЕМНИЙ НА ИЗОЛЯТОРЕ» ДЛЯ ОПТИЧЕСКИХ СИСТЕМ СВЯЗИ

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Аннотация. В работе рассматривается возможность использования кольцевых резонаторов в качестве оптических модуляторов в системах связи. Кольцевые резонаторы являются основным компонентом полностью оптических интегральных фотонных схем из-за их небольшого размера, который способствует увеличению плотности интеграции. Управление интенсивностью света с помощью эклектического/оптического эффекта является основной целью данного исследования. Изучена электронно-оптическая модуляция с использованием эффекта плазменной дисперсии. Эффект плазменной дисперсии – это механизм, с помощью которого контролируемое изменение эффективного показателя преломления кремния на изоляторе SOI может быть достигнуто путем изменения концентрации свободных носителей в кремниевых волноводах. В оптическом модуляторе на основе кольцевого резонатора SOI интенсивность света, проходящего через резонатор, регулируется путем изменения показателя преломления материала кольцевого волновода, что, в свою очередь, изменяет условия резонанса резонансных мод. Это изменение условий резонанса может быть достигнуто путем приложения электрического поля к модулирующим электродам, которые размещены в ребристом волноводе. В этой работе представлен теоретический анализ и сначала представлен отклик модулятора, затем производительность проверяется с помощью программного обеспечения для 3D-моделирования. Хотя работа в большей степени сосредоточена на модуляции интенсивности включения-выключения, она также открывает возможности для использования таких компактных модуляторов для различных методов модуляции, таких как мультиплексирование OFDM с ортогональным частотным разделением; это означает, что модуляторы с высокой скоростью передачи данных используют малогабаритные устройства.

Ключевые слова: оптические волноводы, оптический модулятор, фотонные схемы, кольцевой резонатор, кремний на изоляторе

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Introduction

Silicon-on-insulator (SOI) waveguides are the “Occam’s Razor” of edge connectivity for integrated photonic circuits [1]. It is a simple solution to transporting light that minimizes size, weight, and cost [2]. Adding the possibility of using these waveguides to perform modulation functions to the propagated light will contribute more to the miniaturization of optical components and increase the integration density. SOI waveguide consists of a silicon layer of a high refractive index built on silicon dioxide of a lower refractive index to ensure the confinement of light in the high refractive index core region [3]. The mode confinement is highly dependent on the effective refractive index (n_{eff}) of the SOI. Manipulating the carrier concentration of the silicon material will lead to forming a p–n junction. Therefore, using a DC volt bias can cause a concentration change of the free electrons and holes and finally change the n_{eff} of the waveguide [4]. Hence, a controlled change in the effective refractive index via an external DC voltage can lead to a phase change in the propagated light. However, using a micro ring resonator will provide the possibility to control the resonance wavelength through the controlled change of the n_{eff}, and, hence, the ring resonator optical modulator can be designed.

The ring resonator is a basic building block in all-optical integrated circuits [5]. It consists of a straight bus waveguide coupled to a bent waveguide to form a circuit that resonates in specific wavelengths. The resonance wavelength depends mainly on the ring radius and the effective refractive index of materials. The separation between bus and ring waveguides determines the coupling efficiency and as a result, the amount of light that couples from the bus waveguide and resonates in the ring [6]. If a number of wavelengths are launched in the input port of the bus waveguide, only the wavelengths that satisfy the resonance condition will couple the ring and leave the bus waveguide. The wavelength separation between two successive wavelengths is called the free spectral range FSR which depends on the ring radius [7]. Owing to their small size, ring resonators have been used widely in all-optical integrated circuits in different applications such as add-drop multiplexers, and sensors [8, 9].

In the ring resonator-based optical modulator, the intensity of the light passing through the resonator is controlled by changing the refractive index of the waveguide material, which in turn changes the resonance conditions of the resonant modes. This change in the resonance conditions can be achieved by applying an electrical field to a modulating electrode that is placed near the waveguide. Ring resonator-based optical modulators have several advantages over other types of optical modulators, including high modulation efficiency, low power consumption, low insertion loss, and compact size [4]. In recent years, there has been significant research and development in ring resonator-based optical modulators, particularly in the areas of silicon photonics and integrated photonics [10, 11]. These advances have led to the development of new and more advanced modulators, including high-speed modulators, low-loss modulators, and modulators with improved bandwidth and modulation depth. The possibility of controlling the resonance wavelength through the electro-optic change of the effective refractive index can be used to control the intensity of output light [12]. A linear change of the Δn through the applied DC volt provides an optical modulator with a high speed of response for the conventional non-return to zero NRZ and also for advanced modulation techniques such as OFDM transmission [13]. In this work, an optical modulator based on a ring resonator is presented. The mathematical analysis for the electro-optic effect is discussed and numerical modelling of the proposed design is performed using 3D simulation software [14]. The results show the output frequency response of the design that can be used as a modulator in optical communication systems.

Theoretical Modelling of the Proposed Design

Mathematical analysis

Starting from the first Maxwell's equation, the Laplacian of the electrical field is expressed as [15]

$$\nabla^2 E = \omega^2 \mu \varepsilon E - j\omega\mu J. \tag{1}$$

But $J = \dfrac{\partial P}{\partial t}$, where P is the polarization

$$\nabla^2 E - \frac{\omega^2}{c^2} = \mu \frac{\partial^2 P}{\partial t^2}; \tag{2}$$

$$P = \varepsilon_0 \left(\chi^1 \cdot E + \chi^2 \cdot E^2 + \chi^3 \cdot E^3 \right), \tag{3}$$

where χ^1 is the electrical linear susceptibility.

Given that

$$\varepsilon = 1 + \chi^1;$$

$$\varepsilon = \left(n + j\alpha\frac{c}{2\omega}\right)2n + j\alpha\frac{\lambda}{2\pi} = 1 + \chi^1 = 1 + \mathrm{Re}\left(\chi^1\right) + j\,\mathrm{Im}\left(\chi^1\right).$$

So that,

$$n = 1 + \mathrm{Re}\left(\chi^1\right); \quad (4)$$

$$\alpha = j\frac{2\pi}{\lambda}\mathrm{Im}\left(\chi^1\right). \quad (5)$$

The above analysis is valid for low electric fields where only linear susceptibility is used. For high-intensity optical fields, high-level susceptibility (χ^2 and χ^3) needs to be taken into account. However, χ^2 is not included in the calculations because the silicon is a center-symmetrical material [14]. Therefore, only χ^3 will be introduced. χ^3 is the main source of nonlinearity that is excited by the intensity [16]. It can be understood through two effects, i.e. Kerr effect and the Two-Photon Absorption TPA [17]. Generally, Kerr effect can manifest as an intensity-induced phase change while the TPA phenomena is responsible of the material refractive index change due to the generation of free carriers in the waveguide. The effect of χ^3 (both the Kerr effect and TPA) can be modelled mathematically through γ (the complex nonlinear parameter):

$$\gamma A_{eff} = \frac{2\pi}{\lambda}n_2 + j\frac{\beta_{TPA}}{2};$$

$$\gamma A_{eff} = \frac{\omega}{c}\cdot\frac{3\chi^3}{4\varepsilon_0 n^2} + j\frac{3\omega\chi^3}{4\varepsilon_0 c n^2};$$

$$\gamma A_{eff}\left(\frac{4\varepsilon_0 c n^2}{3\omega}\right) = \mathrm{Re}\left(\chi^3\right) + j\,\mathrm{Im}\left(\chi^3\right);$$

$$\left(\gamma_{\mathrm{Re}} + j\gamma_{\mathrm{Im}}\right)A_{eff}\left(\frac{4\varepsilon_0 c n^2}{3\omega}\right) = \mathrm{Re}\left(\chi^3\right) + j\,\mathrm{Im}\left(\chi^3\right).$$

So that

$$\chi^3 = \frac{4}{3}\varepsilon_0 c n^2 n_2 + j\frac{2}{3}\frac{c}{\omega}n^2\beta_{TPA};$$

$$\mathrm{Re}\left(\chi^3\right) + j\,\mathrm{Im}\left(\chi^3\right) = \frac{4}{3}\varepsilon_0 c n^2 n_2 + j\frac{2}{3}\frac{c}{\omega}n^2\beta_{TPA}.$$

Therefore, the intensity-induced phase change coefficient is:

$$n_2 = \frac{2\,\mathrm{Re}\left(\chi^3\right)}{4\varepsilon_0 c n^2}.$$

While the TPA loss coefficient is:

$$\beta_{TPA} = \frac{3\omega\,\mathrm{Im}\left(\chi^3\right)}{2\varepsilon_0 c n^2}.$$

However, there is another nonlinear induced phenomenon is called the free carrier effects (FC) which are the main effects of interest in the waveguide modulators, i.e. FCA (free carrier absorption α_f) and FCD (free carrier dispersion n_f).

Finally, the nonlinear Schrödinger equation can be written as:

$$\frac{\partial A}{\partial z}=\left(-\frac{1}{2}\alpha_0-\frac{1}{2}\alpha_f\frac{n_0}{n}-\frac{1}{2}\frac{\beta_{TPA}}{A_{eff}}|A|^2\right)A-j\left[\beta_2\frac{\partial^2 A}{\partial t^2}+\frac{\omega_0 n_0}{cn}n_f A-\frac{\omega n_2}{cA_{eff}}|A|^2 A\right]. \qquad (6)$$

For silicon waveguide modulators, more consideration is given for n_f and α_f [18]:

$$n_f(\omega, N_e, N_h)=-\frac{q^2}{2\epsilon_0 n_0\omega^2}\left(\frac{N_c}{m_e^*}+\frac{N_h}{m_h^*}\right), \qquad (7)$$

where N_h and N_e are the free holes and electrons concentration, respectively; μ_h and μ_e are the mobility of holes and electrons, respectively, while m_e^* and m_h^* are the electrons and holes effective mass, respectively. Based on the Drude model [19], the expressions derived above provide a useful description of the free carriers' dynamics in silicon waveguides. This analysis shows the possibility of controlling the effective refractive index n_f by the presence of the intensity-induced free carriers.

Electro-Optic Effect

In the equations (7) and (8), the two parameters n_f and α_f are proven to be a function of the free carrier concentration. Therefore, any manipulation with this concentration definitely leads to a phase change as well as loss change of propagated light. This fact revealed a way to exploit the ongoing light propagation to be modulated while travelling through the silicon waveguide. Changing the N_e and N_h can be achieved through applying the electric field which leads to an electro-optic effect.

To achieve a controlled change of the effective refractive index in SOI waveguide for the communication window (1.55 and 1.3 nm), either the thermo optic effect or the plasma dispersion effect is used. While, the thermo optic coefficient provides sufficient value of modulation depth, the speed of change is not sufficient for high data modulators, therefore, it is used to switch configuration [20]. Hence, for fast conversion modulation, plasma dispersion-based modulators are the good choice.

Based on Soref and Bennett [21], the change in Δn owing to the change in the free carrier concentration in the silicon material is called the plasma dispersion effect. Mathematically,

$$\Delta n=\Delta n_e+\Delta n_h, \qquad (8)$$

where Δn_e and Δn_h represent the change in free electrons and holes, respectively. Therefore, manipulating free carriers concentration in silicon waveguide using electric field results in a modulator that relies on the plasma effect.

Silicon Waveguides

In general, there are two major types of silicon waveguides, namely the rib and slab waveguide structures, as shown in Fig. 1. For electro-optic modulators, rib waveguides are preferable because of their geometry that allows adding the DC bias terminals on the sides. Biased *p-n* junction-based rib waveguides are found in different configurations depending on the doped regions as shown in Fig. 2.

Plasma dispersion effect is commonly used in the electro optic modulators where the electro-refractive nature of this effect allows the doped silicon waveguides to function as phase modulators. In fact, most of the optical transmitters are intensity modulators, therefore, a special photonic design is required to exploit this effect to control the output intensity of light. The Mach–Zehnder interferometer was used to achieve intensity modulation of light through the controlled refractive index of the waveguide

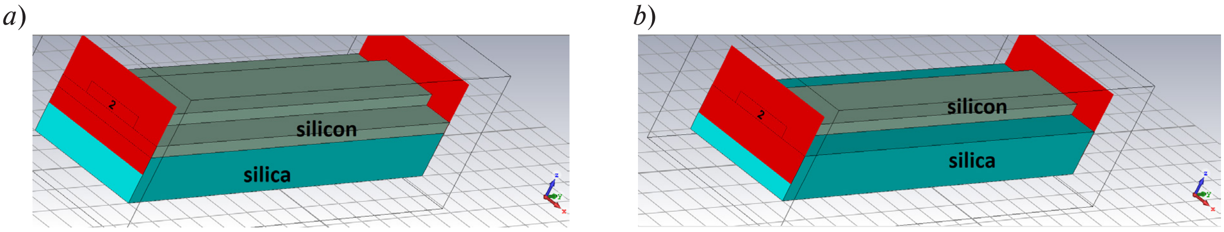

Fig. 1. Silicon on Insulator waveguide structures. Rib type waveguide (*a*) and Slab type waveguide (*b*)

Fig. 2. Cross section of a doped rib waveguide (*a*) showing the metal vias and (*b*) showing the doping level

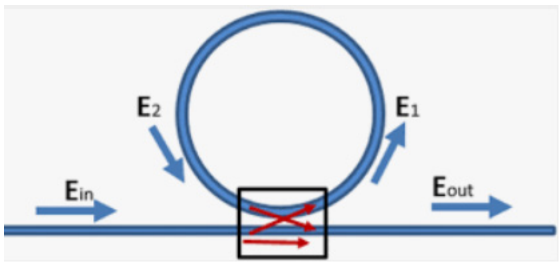

Fig. 3. Layout of a single ring resonator

section [22]. An intensity modulation of light passing through the waveguide is achieved without the need for optical-electrical optical conversion. Ring resonator is proposed to be used to perform the intensity modulation of light through the use of electro-optic effect as will be discussed in the next section.

Ring resonator based optical modulator

Ring resonator is a basic building block in the integrated photonic circuits. It consists of a straight bus waveguide coupled to a ring waveguide to produce a resonant device that is used to select a specific wavelength based on the resonance condition.

The resonance condition depends mainly on the effective refractive index and the ring radius. Ring resonators have been used in different applications ranging from add/drop multiplexing, sensors, and recently as optical modulators. Since the main aim in this study is to manipulate the resonance condition of the ring through the change of the free carrier concentration, it is useful to study the ring resonator response shown in Fig. 3, and explain the resonance condition.

Based on Fig. 3, the electric fields E_{in}, E_{out}, E_1 and E_2 are used to extract the transfer function of this configuration. The transfer function of this device depends mainly on the coupling region (that is the region where the bus and ring waveguide are close to each other). This region is defined by the cross-coupling and through coupling coefficients k and t, respectively. Where $k^2 + t^2 = 1$. Therefore, the relation between electric fields in each point is defined by the following matrix:

$$\begin{bmatrix} E_{\text{out}} \\ E_1 \end{bmatrix} = \begin{bmatrix} t & k \\ -k^* & t^* \end{bmatrix} \begin{bmatrix} E_{\text{in}} \\ E_2 \end{bmatrix}. \tag{9}$$

Also, the relation between the electric fields inside the ring which describes the round-trip propagation of the light is given by:

$$E_2 = \alpha e^{-j\phi} E_1.$$

Here, α represents the attenuation inside the ring waveguide, while ϕ is the phase shift accumulated along the round trip. ϕ is related to the wavelength of the light λ, the length of ring l as well as the mode effective refractive index n_{eff}, and can be expressed mathematically through the following equation:

$$\phi = \frac{2\pi}{\lambda} \ln_{eff}.$$

Therefore, the output field can be expressed as:

$$E_{\text{out},1} = \frac{t - \alpha e^{-j\phi}}{1 - \alpha t e^{-j\phi}} E_{\text{in},1}. \tag{10}$$

The behavior of such device is obtained by calculating the transfer function that relates the output filed E_{out} to the input field E_{in} where the intensity and phase information are defined by relation $\left|\frac{E_{\text{out}}}{E_{\text{in}}}\right|$. Also, the optical intensity transfer function is obtained as [4]:

$$I_{\text{out}} = \frac{|t|^2 + \alpha^2 - 2\alpha|t|\cos(\phi + \theta)}{1 + \alpha^2 |t|^2 - 2\alpha|t|\cos(\phi + \theta)} I_{\text{in}}. \tag{11}$$

Plotting this function with respect to the wavelength shows a periodic change at specific wavelengths that are coupled from the straight waveguide to the ring and resonate inside the resonator as shown in Fig. 4. There, $S_{2,1}$ represents the power intensity I_{out} at port 2, and $S_{1,1}$ is the power reflection coefficient at port 1. The separation between two successive wavelengths is called the Free Spectral Range (FSR, Fig. 4, *b*), and defined as:

$$FSR = \frac{\lambda^2}{n_g L}. \tag{12}$$

Here, n_g is the group refractive index of the device.

The most important consideration in the design of the resonator ring based optical modulator is the incorporation of the DC bias terminals in the bent waveguide to manipulate n_{eff}. Application of voltage on the bent waveguide will induce a change in the effective refractive index, which will lead to a shift in the resonance wavelength as shown in Fig. 5. Therefore, this effect can be used to design a ring resonator based optical modulator that performs all optical intensity modulation of light with a small size ring resonator providing high density integration of devices with high data rates of transmission. The results shown in Fig. 5 are calculated based on a MATLAB code. However, in the next section, a numerical simulation of the small size optical modulator is presented using a 3D simulation software to validate the design.

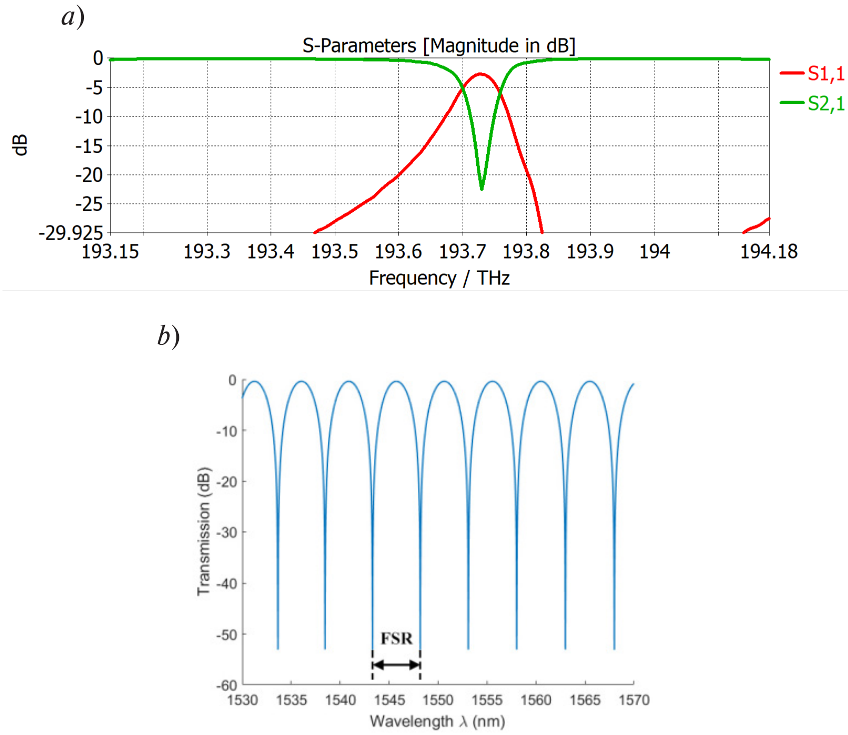

Fig. 4. Transmission of a single ring resonator CST representation (*a*), the representation of the FSR of a single ring (*b*) calculated using MATLAB

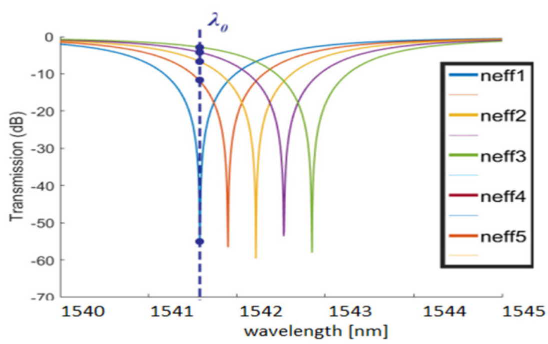

Fig. 5. A MATLab calculated response of a single ring resonator for different values of the effective refractive index. $n_{eff1} = 0$, $n_{eff2} = 1\times10^{-4}$, $n_{eff3} = 2\times10^{-4}$, $n_{eff4} = 4\times10^{-4}$, $n_{eff5} = 5\times10^{-4}$

CST simulation results and discussion

In this section, the silicon on insulator based ring resonator is modeled using a 3D simulation software as shown in Fig. 6. The CST studio suite is used to model a ring resonator with a radius of 16 μ*m* coupled to a straight bus with dimensions of 0.48 μ*m* width ×0.25 μ*m* height, to ensure a single mode propagation. The material of the ring and bus waveguide is made of silicon (Si) with refractive index 3.45 which is built on silicon dioxide layer (SiO_2) of a 1.45 refractive index to achieve a high refractive index contrast. This ensures the guidance of light, the high refractive index region with the high confinement, Fig. 7. The upper clad was set to be air with $n = 1$.

The time domain solver result of the CST simulation is shown in Fig. 8. Different values of the effective refractive index are calculated numerically by using the doped silicon-based rib waveguide as shown in

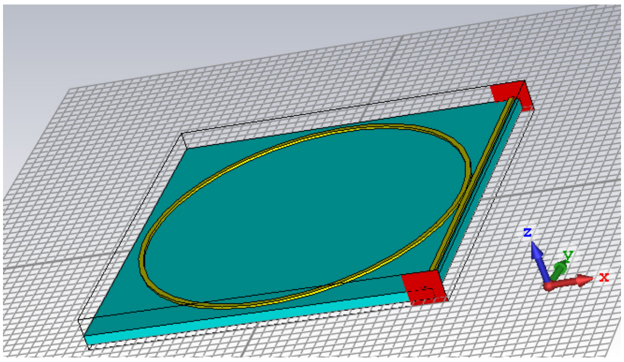

Fig. 6. CST representation of a ring resonator

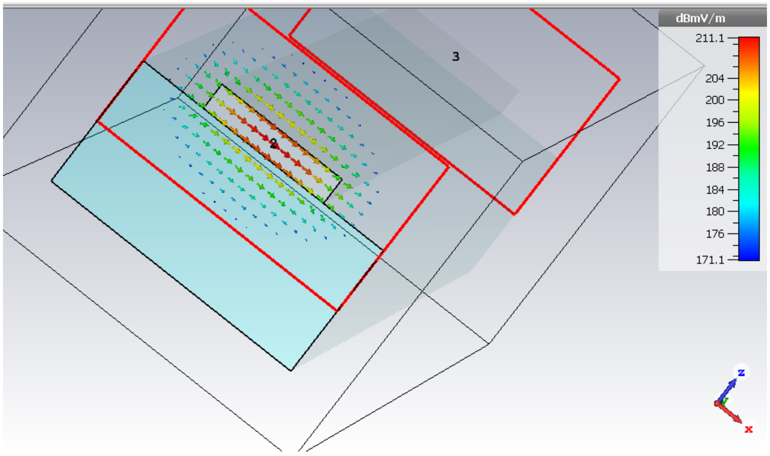

Fig. 7. CST mode profile representation in the rib waveguide

Fig. 2. The ring resonator response shown in Fig. 8 shows a good agreement with that calculated in Fig. 5, which supports the concept of using the effective refractive change to obtain intensity modulation.

The idea in Fig. 8 is that the resonance wavelength is changing every time the effective refractive index changes. Therefore, for no change in n_{eff1} the resonance wavelength (1542.7 nm) will face an attenuation of almost –40 dB. Changing n_{eff} (caused by the applied filed) will lead to a shift in resonance frequency to a longer wavelength and expose the reference wavelength (1542.7 nm) to another attenuation level as shown in Fig. 8 (see the linear dotted line).

A linear relation between the electric-filed change (information signal) and the resonance change is crucial in considering the efficiency of the proposed modulator. This relation needs to be as linear as possible in order to have a real intensity modulation at the output of the ring resonator. Fig. 9 shows almost linear relationship between the output intensity of the modulator with the change of the effective refractive index induced by the electric field. Achieving a linear change means light can be easily modulated with the required information signal that is used as the drive voltage for the metal vias.

Conclusion

In a ring resonator-based optical modulator, the intensity of the light passing through the resonator is controlled by changing the refractive index of the waveguide material, which in turn changes the resonance conditions of the resonant modes. This change in the resonance conditions can be achieved by applying an electrical field to modulating electrodes which are placed near the waveguide. This work

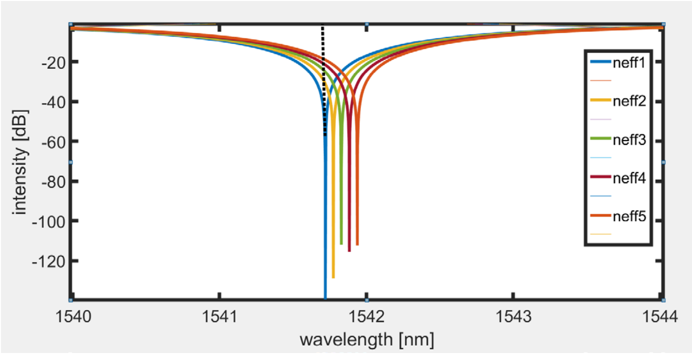

Fig. 8. CST calculated transmission of a single ring resonator for the same values of the effective refractive index in Fig. 5

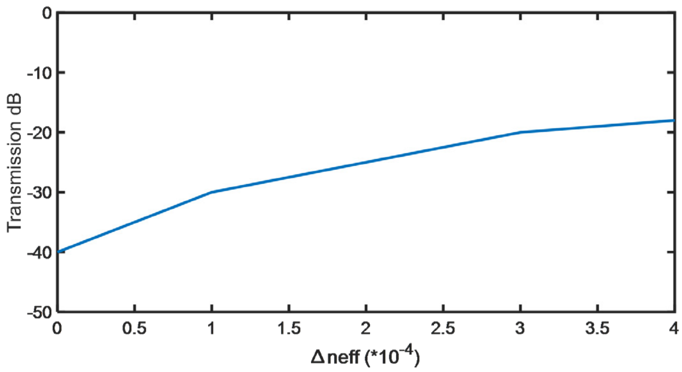

Fig. 9. The relation between the output intensity of the modulator with the effective refractive change

examined, theoretically and numerically, the possibility of achieving a modulator like behavior using a small size ring resonator to support the search for the high integration density in all optical photonic circuits. The frequency response of the single ring resonator is presented first with a stronger emphasis on the effect of changing the effective refractive index on the resonance wavelength. Using doped silicon-based rib waveguide provides the possibility of adding copper vias around the circumference of the ring. Via these vias, a voltage change produced by the information signal can be used to alter the free carrier's concentration in the waveguide. This, in turn, will change the propagation constant through the change in the effective refractive index and finally produce a controlled intensity for the pumped CW light at the input of the ring. A theoretical calculation is presented and the response of the proposed modulator is first presented using MATLab, then the performance was validated using 3D simulation software. Ring resonator-based optical modulators have several advantages over other types, including high modulation efficiency, low power consumption, low insertion loss, and compact size.

Future work

This work is part of an ongoing project that aims to design an integrated photonic circuit of a transceiver (Comb generator and modulator) based on SOI ring resonators. Multiple carrier wavelengths transceiver that can achieve >100 Gb/s capacity is drawing researchers' attention. A significant interest is devoted to the concept of using a single laser input fed to an optical wavelength comb generator instead of using distributed feedback lasers. Comb generators find implementations in WDM transceiver environments. Appropriate shaping of the spectrum around the optical carrier by means of electro-optic modulation of a Continuous Wave (CW) source is the basis of a modulator-based comb generator. The comb shape is determined mainly by two factors: the applied electrical signal waveform and achieved modulation depth. In the ring resonators, the modulation depth is determined by the coupling coefficient and the *p-n* junction operating condition (modulation regime).

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