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Low power Electro-optical filter: Constructed using silicon nanobeam resonator and PIN junction

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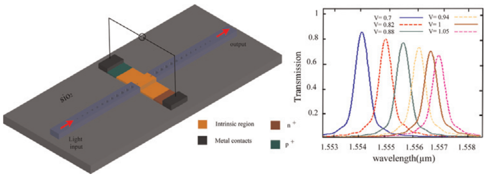
HIGHLIGHTS

- We proposed a high quality nanobeam resonator based on one dimensional photonic crystal.
- A compact and low power tunable Electro-optic filter has been proposed by using a silicon nanobeam.
- Using an active area for manipulating the free carrier density in resonance cavity.

GRAPHICAL ABSTRACT



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ABSTRACT

In this paper, a high tunable Electro-optical filter is designed and simulated with low electric power consumption. A silicon nanobeam resonator based on one-dimensional photonic crystal in the form of Fabry–Perot structure, silicon-on-insulator waveguide, is proposed with a PIN junction. In designing nanobeam resonator, "deterministic design method" is used to achieve the high quality factor and high-transmission rate. Tuning of the resonant wavelength in the output channel of the filter is achieved by manipulating the refractive index of the active area by using the free-carrier dispersion effect. The output wavelengths of designed device can be tuned for the telecom-friendly 1.55 μm range. The device shows a wavelength shift higher than 3 nm for a power consumption of only 0.9 mW. Finally, the simulation results show that the provided device can be considered as a narrowband and tunable Electro-optical filter that is suitable for DWDM communication system.

1. Introduction

Silicon nanobeam resonators are suitable for making large-scale photonic integrated circuits [1]. The kinds of devices have more applications in optical communications [2] and detection [3] systems. For first time, silicon photonics was introduced in 1980s and now it is one of the most modern technologies in the world. The main purpose of this technology is the study of electro-optic effects in silicon to create relation between electrical parameters and optical phenomena [4,5] such as refractive index, optical absorption, etc. This feature can be used to control the dispersion rate of light in certain range with changing the electron and holes carrier density in silicon with using an external electrical bias. In pioneering work, much progress has been made in this field for example, using of this technology for manufacturing of various types of optical modulators, optical switches [6], optical filters [7], waveguides [8], polarization-manipulating devices [9,10] and other Non-linear devices [11–13].

There are different ways to design optical filters, such as the use of micro-ring [14], micro-disk [15], Fabry–Perot resonator [16,17], etc. In most cases, Fabry–Perot resonators are designed using photonic crystal structure. Photonic crystal structures are made in 1D, 2D and 3D. Combining these components with dense-wavelength-division-multiplexed (DWDM) communication systems lead to achieve compact devices and at the same time low-cost and high data transfer capacity. Electro-optical filter based on

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silicon photonic represent the key components for extracting data wavelength from communication networks [18–20]. Tunable Electro-optical filter, first demonstrated in the silicon-on-insulator waveguide by Barrios et al. [21]. Another platform for electrically Tunable Resonant Filters has been considered by Shi et al. [22]. In this kind of devices, one of the important parameters is ability to adapting with DWDM systems. By increase adapting ability, the number of communication channels are expanded and thus are increased the volume of data transmission in communication systems. Range of DWDM must be around 1.55 μm and distance of each channel greater than 1 nm. So designed filters for these systems must have the listed characteristics. Several methods is used to improve the efficiency of Electro-optical filter as expanding the active area and increasing the sensitivity in passive section of photonic device, resonators based on silicon photonics enhance Controllability at the Passive photonic devices [23–27]. Resonant wavelength in Electro-optical filter is adjusted by applying an electrical voltage to the silicon cavity and changes in the optical properties of the cavity and leads to shift in the output wavelength of Electro-optical filter. High finesse resonant cavity and short length are very attractive for increased efficiency in active optical devices which can be increased the sensitivity of the cavity resonance, so with small index changes in the cavity, output wavelength will be changed more [28].

In this paper, firstly an optical filter based on nanobeam resonance cavity was designed with using of a 1D photonic crystal of ~5 μm length built into a silicon nanowaveguide. For achieve suitable quality factor in DWDM communication systems, we have calculated the scattered power in nanobeam resonant cavity. The quality factor of nanobeam cavity can be increased by reducing scattering power. According to the wavelength selection is done in resonance cavity, by placing the doped regions in the local of cavity that there is a maximum optical power, can be increased the amount of wavelength shifting at the filter output. The following, we create a silicon active area with PIN junction. In this area, for having a good response, free carrier concentration and the length of this area is designed that the most wavelength shift in resonant cavity is occurred with minimum voltage swing and low power.

2. Materials and methods

Optical filter is usually based on passive photonic device such as fiber Bragg gratings, arranged waveguide gratings and thin film dielectric interference, etc. The kind of filters there is no ability to alter the output wavelength, so the key solution to achieve tunable filter is use of active devices in the silicon. Most of the proposed active Electro-optical devices operate the free carrier dispersion effect [4], in which the concentration of free carriers changes the real and imaginary parts of the refractive index. Soref and Bennett have calculated effect of electron and hole density to change the refractive index and optical absorption in silicon [5]. These parameters are dependent to frequency. In the wavelength of 1.55 μm, for example:

$$\Delta n = -\left[8.8 \times 10^{-22}\Delta n_e + 8.5 \times 10^{-18}(\Delta n_h)^{0.8}\right] \quad (1)$$

$$\Delta \alpha = +\left[8.5 \times 10^{-18}\Delta n_e + 6 \times 10^{-18}\Delta n_h\right] \quad (2)$$

Where Δn, $\Delta \alpha$ are real refractive index and optical absorption coefficient respectively and Δn_e is electron concentration change in cm^{-3} and Δn_h is hole concentration change in cm^{-3}. There are several methods to modulate the free carrier density in silicon, such as accumulation, injection, depletion, or inversion of carriers [13]. Injection carriers is one of the most used in a forward biased PIN junction. In injection-based structures there are recombination dynamics of minority carriers [13] and the wide width of the intrinsic region.

Fabry–Perot resonator has been composed of two Bragg mirrors facing each other. The resonant frequency in the resonator is inversely proportional to the distance between the mirrors [17]. In this resonator, resonant wavelength is given by $\omega_m = mc/2nd$. Where d is the distance between the mirrors, n is the refractive index of the medium between the mirrors, c is the light of velocity and m is an integer index. In passive mode of Fabry–Perot resonator, there is no ability to shift resonance wavelength so, the tenability of those resonators are achieved by applying an electrical voltage in the Electro-optical area and manipulating the optical properties of the cavity. The finesse of the resonator is related to the number of times that the light is reflected within the resonator and thus if high finesse is realized [6].

3. Device design

The main advantage of using a nanobeam resonator is the good performance and matching with waveguides and integrated circuits. nanobeam resonator theory is based on Fourier space analysis and mode-matching mechanisms, so for having high quality factor must be following correctly these items. There is many theoretical designs have been proposed to optimize the nanobeam cavity, such as: deterministic method, Inverse design engineering, etc. In our research we follow that presented by the Loncar group [16]. The basic block in the design nanobeam resonator is a silicon-on-insulator (SOI) photonic crystal nanobeam cavity. It is composed of two main parts: resonant cavity and feeding waveguide. A 1D photonic crystal defect was used and cavity directly

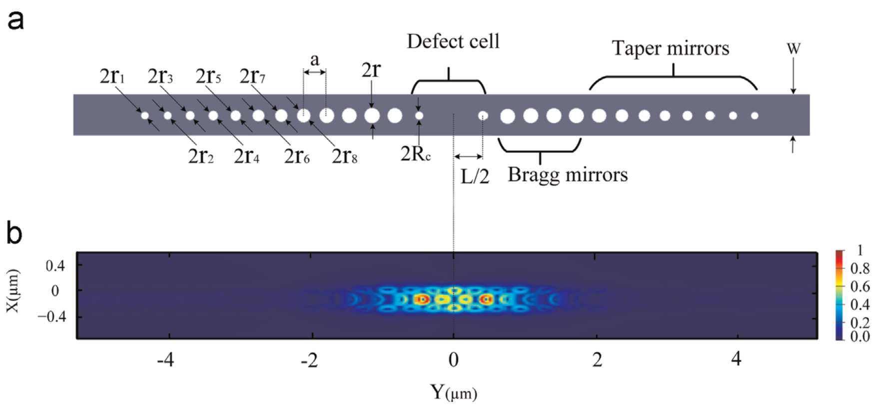

Fig. 1. (a) Schematic top-view of the nanobeam resonator based on 1D photonic crystal cavity, showing all the geometric parameters that are optimized. (b) Cross-section of the cavity with the electric field E_y of the resonance mode obtained from 3D FDTD simulations. The dashed black line is a guide to the center of the device.