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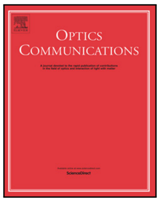

Design of a compact high-speed optical modulator based on a hybrid plasmonic nanobeam cavity

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ABSTRACT

A hybrid plasmonic electro-optic modulator based on a polymer-filled one dimensional photonic crystal nanobeam (1D PhCNB) cavity is proposed here. In the proposed structure the optical intensity modulation is realized by shifting the resonant wavelength of the cavity through electrically tuning the refractive index of the electro-optic polymer in the hybrid plasmonic waveguide. As a result of the subwavelength light confinement in the hybrid plasmonic waveguide and the compact footprint of the 1D PhCNB cavity, the designed modulator has the small overall footprint of 3.6 μm^2 and the required wavelength shift can be achieved by applying very small actuating power. Three dimensional finite-difference time-domain (3D-FDTD) simulations show that the modulation depth of 10.9 dB, and insertion loss of 1.14 dB, along with very high modulation speed of 224 GHz can be achieved in the proposed modulator with very low modulation energy of 0.75 fJ/bit. A comparison between the performance parameters of the proposed modulator and those of previously reported PhCNB based modulators reveals the superior performance of the proposed structure in terms of modulation speed, energy consumption and overall footprint.

1. Introduction

Optical modulators are key elements of integrated optical systems for optical communication. Achieving high modulation depth (MD), low insertion loss (IL), low power consumption, high speed and small footprint are main challenges in designing these modulators [1,2]. Usually, optical intensity modulation is achieved in one of these two schemes; direct intensity modulation by modifying absorption coefficient (and therefore the propagation loss) of an optical structure, or phase change dependent intensity modulation in an optical interferometer by introducing refractive index changes. The second scheme usually results in higher modulation speed and smaller IL and therefore is widely adopted in designing optical modulators [3]. Two categories of optical elements are mainly used to realize phase change based optical modulators; non-resonance interferometry structures such as Mach–Zehnder interferometers (MZIs) [4,5], and resonance interferometry structures such as coupled waveguide–resonator structures [6–13]. In the first category, the refractive index change is used to initiate a phase shift in the propagating waves in an interferometer structure and thusly produce a constructive or destructive interference. MZI structures are usually used for this purpose [4,5]. This type of modulators offer broadband operation, but have relatively large footprints [5,14]. In the second category of structures, the refractive index change is used to shift the resonance wavelength of a resonant structure such as micro-ring resonator (MRR) [6,7] or photonic crystal (PhC) resonator [8–13]. The shift in the resonance wavelength results in the variation of the transmission intensity of the coupled waveguide–resonator structure [1]. Compared to MZI based modulators, resonant modulators have much smaller footprint and lower power consumption [15–18], but at the cost of narrower optical bandwidth [14]. Because of their interesting properties i.e. small footprint and low power consumption, resonator based modulators have been vastly studied in literature [6–13]. Among different resonant structures, one-dimensional (1D) PhC nanobeam cavities because of their unique capabilities such as high-quality factor along with very small mode volume, small footprint and ease of integration [19–21], are a promising candidate for realization of optical modulators.

Aside from modulator structure, different physical mechanisms can be used to produce the required refractive index change. Commonly used methods include free carrier plasma dispersion (FCPD) effect in semiconductors [8–10], and the nonlinear effects such as Pockels effect in electro-optic (EO) polymers [6,7,11–13,22–24]. While it is widely used in realization of silicon optical modulators, carrier lifetime and

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refractive index change induced by FCPD effect, set some constraints on the highest achievable operation speed and the required footprint of the modulator [23–25]. In contrast, large electro-optic coefficient and fast response of the EO polymers, promise the possibility of reaching higher modulation speed and lower power consumption with smaller device footprint [26]. Different structures have been proposed to employ the large EO coefficient of polymers for realization of optical modulators [6,7,11–13,22–24]. Among these structures, coupled waveguide–resonator structures based on hybrid plasmonic waveguides (HPWs), present superior performance parameters because of the ability of the HPWs to provide a good tradeoff between subwavelength mode confinement and propagation length [27,28].

The performance of HPW-based optical modulators can be further improved by implementing a 1D photonic crystal nanobeam (PhCNB) cavity in a properly designed HPW. This way, the transversal light confinement of the optical wave in the HPW cross section can be combined with the longitudinal confinement of optical modes of the nanobeam resonator and result in optical resonance modes with extremely small mode volume [29]. In such a structure, small footprint of the PhCNB reduces the overall footprint of the modulator while extremely low mode volume of optical modes increases the sensitivity of the resonance wavelength of these modes to small variations of refractive index of the EO polymer [10]. As a result, large resonance wavelength shifts can be achieved by introducing very small refractive index variations or equivalently applying very small voltages. Small overall footprint of the proposed modulator on the other hand, reduces the resistive–capacitive (RC) time delay of the structure which in turn increase the modulation bandwidth and speed of the proposed modulator. One dimensional hybrid plasmonic PhCNB cavities have been employed in different applications, including nanolasers [30], optical switches [31], optomechanical devices [29], and sensors [19], in the recent years. But to the best of our knowledge, application of 1D hybrid plasmonic nanobeam resonators in realization of electro-optical modulators has not been studied so far. Here, we propose a hybrid plasmonic electro-optical intensity modulator based on polymer-filled 1D PhCNB resonator, which operate at telecommunication wavelength. The modulator is based on SOI platform. As mentioned above, through proper design of the nanobeam structure, optical modulators with high modulation depth, compact footprint, and high modulation speed can be achieved. Furthermore, the compact footprint of the device decreases the overall energy consumption.

The remainder of this paper is organized as follows. In Section 2, the design of the modulator structure including HPW and 1D PhCNB cavity is described. In Section 3, the results of 3D-FDTD simulations are investigated and the modulator parameters, such as insertion loss, extinction ratio, modulation speed, and energy consumption are discussed. Finally, the conclusions are made in Section 4.

2. Modulator design

2.1. Proposed modulator structure

The schematic view of the proposed modulator is given in Fig. 1, which shows that, the nanobeam resonator is formed by introducing a nonuniform defect in a 1D periodic waveguide. Each period of the periodic waveguide, is made by perforating a hole of radius r in the silicon layer of a HPW section of length a, and filling this hole with the polymer (low index material of the HPW). The resonance wavelength and quality factor of the PhCNB modes can be tuned by proper design of the periodic waveguide lattice constant; a, and radius of the polymer-filled holes in the HPW; r. According to the cross section in Fig. 1(b), the HPW itself is made by sandwiching an EO polymer layer between a silicon rib waveguide and a metallic (silver) cover. This metallic layer is assumed to be one of the electrodes needed for applying the actuating voltage of the modulator. The other electrode is formed by depositing a metallic pad on a highly doped (with the doping concentration of $10^{21}\,\mathrm{cm}^{-3}$) region of the rib waveguide pedestal (see Fig. 1(b)). To increase the electrical conductivity of Si, the Si rib waveguide is assumed to be doped with donor impurity atoms with concentration of 10^{18} cm^{-3}. Although this doping increases the propagation loss of the waveguide (through increasing Si conductivity) but this excess loss is much smaller than the propagation loss of the HPW which is mainly caused by the high conductivity of the top metallic layer in HPW [6], and therefore can be neglected.

The proposed structure is in the form of a direct-coupled waveguide–resonator structure (see the schematic view of Fig. 1(c)) and the transmission spectrum of the structure in the vicinity of each resonance frequency of the PhCNB is similar to the output spectrum of a band-pass filter (where the center frequency of the filter is equal to the resonance frequency of the corresponding PhCNB mode). Therefore, the overall structure composed of the input and output HPWs and the PhCNB, works as a band-pass filter whose center frequency and bandwidth can be tuned by adjusting the resonance frequency and quality factor of the PhCNB modes. By applying an appropriate voltage to the two electrodes of the structure, the refractive index of the EO polymer can be slightly changed. The change in refractive index of the polymer in turn shifts the resonance wavelength of the PhCNB modes, and therefore the center frequency of the overall structure. As a result, the intensity of an optical wave passing through the structure with the specific wavelength range of $\Delta\lambda$ around the center wavelength of the structure can be modulated.

The refractive index change of the EO polymer, due to an external electric field E is given by [11]:

$$\Delta n = \frac{1}{2}\gamma_{33} n_p^3 E \tag{1}$$

where n_p and γ_{33} are the refractive index and electro-optic coefficient of the polymer, respectively. In the following analysis, the refractive indices of the Si, SiO$_2$ and the polymer layer are considered to be $n_{Si} = 3.476$, $n_{SiO2} = 1.444$ [32] and $n_p = 1.6$, respectively (for wavelengths near $\lambda = 1550$ nm). We use molecular glasses based on the reversible self-assembly of aromatic/perfluoroaromatic dendron-substituted nonlinear optical chromophores as the EO polymer, which has an EO coefficient equal to 200 pm/V with good alignment stability [33]. Also, silver is modeled as a low-loss Drude metal with the parameters: background dielectric constant $\varepsilon_\infty = 3.3651$, plasma frequency $\omega_p = 1.3779\times 10^{16}$ rad/s, and collision frequency $\gamma = 4.9719\times 10^{12}$ s^{-1} [34].

In the rest of this section, we first optimize HPW dimensions to minimize both propagation loss and effective mode area of the waveguide. This waveguide will then be used to design the PhCNB resonator. Simulation results for the performance parameters of the designed PhCNB modulator will be provided in the next section.

2.2. Hybrid plasmonic waveguide design

As mentioned above, the operation mechanism of the modulator to be designed is the effective index change of the HPW (and therefore the resonance wavelength shift of the PhCNB) in response to an electric field applied to the electro-optic polymer layer. To increase the sensitivity of the structure to the applied electric field or equivalently reduce the required voltage for achieving the required effective index change, the geometrical parameters of the HPW should be optimized. According to the cross section view of the HPW in Fig. 1(b), the design parameters of the HPW are the thickness of the silicon layer h_{Si}, thickness of the silver layer h_{Ag}, width of the waveguide W, thickness of the polymer layer h_p, and thickness of the silicon pedestal layer t. The waveguide characteristics are mainly determined by the parameters h_p, W and h_{Si}, and the other two parameters have less significant effects on the HPW dispersion behavior. Here, the thickness of the pedestal layer is set to be $t = 50$ nm for balancing of the propagation loss and resistive–capacitive (RC) time delay of the overall structure [35]. Also the thickness of the silver layer is set to be $h_{Ag} = 100$ nm, which is typical value in HPW literature [6,7,22,23]. As mentioned, the optical amplitude modulation in the structure of Fig. 1 is realized by introducing a change in the