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Bandwidth-tunable optical passband filter based on graphene–silicon waveguide

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ABSTRACT

A bandwidth-tunable optical passband filter based on graphene–silicon waveguide is proposed. The device is designed by utilizing a structure with four triple series-coupled microring resonators. By changing the Fermi level of graphene to lead to the variation of the modal effective index, the transmission spectra of triple series-coupled microring resonators can be coherently combined to provide the adjustable bandwidth as desired. A detailed analysis of the designed device is presented. Numerical simulations show that the effective bandwidth tuning range from 2.70 to 6.30 nm can be obtained when each microring resonator is independently controlled. With the maximum bandwidth tunability, the designed tunable filter has a minimum extinction ratio larger than 92.35 dB.

1. Introduction

Due to the emergence of bandwidth hungry services, there has been an explosive growth in Internet traffic. In order to fulfill the increased demands for bandwidth, optical networks should evolve to increase the transmission capacity and spectrum efficiency. As the prevailing technology, elastic optical networks (EONs) supporting spectrum utilization in a flexible manner have received extensive interest [1,2].

To realize the flexibility in EONs, bandwidth-tunable optical passband filters are one of the key components. Owing to the advantage of compatibility with the CMOS fabrication process, silicon photonics based on silicon-on-insulator (SOI) technology provides a promising solution [3,4]. In recent years, several bandwidth-tunable silicon filters have been demonstrated using cascaded Bragg-grating-assisted contra-directional couplers [5], silicon microrings in a Mach–Zehnder interferometer (MZI) structure [6], an unbalanced MZI with two ring resonators [7], five nearest-neighbor coupled microrings [8], and cascaded microring resonators [9]. Although the bandwidth-tunable silicon filter based on cascaded Bragg-grating-assisted contra-directional couplers (contra-DCs) can realize a large bandwidth tuning range, the designed four-stage cascade contra-DC filter has an extinction ratio (ER) larger than 49 dB. A silicon microring resonator (MRR) is regarded as an ideal element because of the compact footprint and low power consumption. However, bandwidth-tunable silicon filters based on MRRs or the integration of a MZI with MRRs have relatively narrow tunable bandwidth.

As a two-dimensional material, graphene has extraordinary electronic and optical properties, such as gate-variable optical conductivity [10], ultrahigh electron mobility [11], and wideband optical absorption [12]. It provides an attractive approach for realizing novel devices. When graphene flakes are combined with silicon waveguides, the modal effective refractive index of the graphene–silicon waveguide (GSW) can be changed by tuning the carrier density in the graphene. Previously, tunable passband filters [13], polarizers [14], optical logic gates [15], switches [16], modulators [17], and photodetectors [18] utilizing GSWs have been reported.

In this paper, a graphene-based bandwidth-tunable optical passband filter using triple series-coupled microring resonators (TSCMRRs) is proposed and designed. The functionalities and properties of the designed device are evaluated and analyzed in detail. Compared with the reported graphene-based tunable passband filters, the adjustable bandwidth can be formed as needed at the output port of the proposed device by properly adjust the Fermi level of graphene and path phase difference. Calculation results show the graphene-based bandwidth-tunable optical passband filter with the effective bandwidth tuning range from 2.70 to 6.30 nm can be achieved. When the maximum bandwidth tunability is reached, it provides a minimum ER larger than 92.35 dB.

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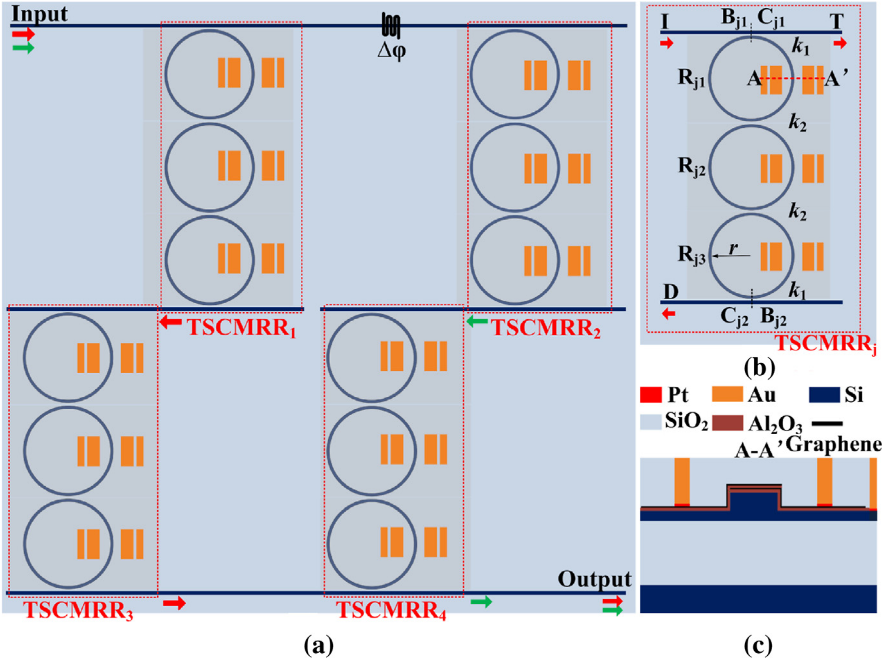

Fig. 1. (a) Schematic of the proposed bandwidth-tunable optical passband filter based on GSW (b) Structure of the TSCMRR (c) Cross-section view A–A' over the microring.

2. Device structure and operation principle

A schematic drawing of the proposed tunable filter is shown in Fig. 1(a). The device is composed of four TSCMRRs, which are denoted as TSCMRR_1, TSCMRR_2, TSCMRR_3 and TSCMRR_4. TSCMRR_1 and TSCMRR_2 in the first row are used for demultiplexing incoming signals. TSCMRR_3 and TSCMRR_4 in the second row are used to collect the demultiplexed signals passing optical paths with same length at the Output port and realize adjustable bandwidths as desired. To obtain a flat-top spectrum, the phase shifter is designed in the straight waveguide to tune the path phase difference $\Delta\varphi$. Fig. 1(b) shows the structure of the TSCMRR j ($j = 1, 2, 3, 4$). It consists of three serially coupled microrings and two straight waveguides. A cross-sectional view of the microring (along line A–A') is depicted in Fig. 1(c). As shown in Fig. 1(c), a spacer of Al_2O_3 can be uniformly deposited on the surface of the silicon waveguide by atom layer deposition (ALD). In order to realize a much wider wavelength tunable range for a given variation of chemical potential, two triple-layer graphene are used in this work. The first triple-layer graphene grown by chemical vapor deposition (CVD) can then be mechanically transferred and patterned. Similarly, the second CVD-grown triple-layer graphene can be transferred after depositing another Al_2O_3 spacer. The gold electrodes connected to platinum films can be deposited to form Ohmic contacts.

The transfer matrix method is adopted to investigate the functionalities and properties of the proposed tunable filter. The transmission function O for the Output port can be derived as:

$$O = D_1 \cdot D_3 \cdot T_4 + T_1 \cdot e^{-i\Delta\varphi} \cdot D_2 \cdot D_4 \tag{1}$$

$$T_j = C_{j1}/B_{j1} \tag{2}$$

$$D_j = C_{j2}/B_{j1} \tag{3}$$

$$\begin{aligned}\begin{bmatrix} B_{j2} \\ C_{j2} \end{bmatrix} = &\begin{bmatrix} \frac{t_1}{ik_1} & -\frac{1}{ik_1} \\ \frac{1}{ik_1} & -\frac{t_1}{ik_1} \end{bmatrix} \cdot \begin{bmatrix} 0 & e^{-i(\beta_{j3}-i\alpha_{j3})\pi r} \\ e^{i(\beta_{j3}-i\alpha_{j3})\pi r} & 0 \end{bmatrix} \\ &\cdot \begin{bmatrix} \frac{t_2}{ik_2} & -\frac{1}{ik_2} \\ \frac{1}{ik_2} & -\frac{t_2}{ik_2} \end{bmatrix} \cdot \begin{bmatrix} 0 & e^{-i(\beta_{j2}-i\alpha_{j2})\pi r} \\ e^{i(\beta_{j2}-i\alpha_{j2})\pi r} & 0 \end{bmatrix} \\ &\cdot \begin{bmatrix} \frac{t_2}{ik_2} & -\frac{1}{ik_2} \\ \frac{1}{ik_2} & -\frac{t_2}{ik_2} \end{bmatrix} \cdot \begin{bmatrix} 0 & e^{-i(\beta_{j1}-i\alpha_{j1})\pi r} \\ e^{i(\beta_{j1}-i\alpha_{j1})\pi r} & 0 \end{bmatrix} \\ &\cdot \begin{bmatrix} \frac{t_1}{ik_1} & -\frac{1}{ik_1} \\ \frac{1}{ik_1} & -\frac{t_1}{ik_1} \end{bmatrix} \cdot \begin{bmatrix} B_{j1} \\ C_{j1} \end{bmatrix}\end{aligned} \tag{4}$$

where D_j and T_j are the drop and through transmission of TSCMRR_j, respectively. $\Delta\varphi$ stands for the path phase difference. The mode propagation constant β_{jm} ($m = 1, 2, 3$) is defined as $\beta_{jm} = 2\pi n_{jm}/\lambda_{jm}$. n_{jm} is the effective refractive index of the microring waveguide, which is marked as R_{jm}. λ_{jm} is the corresponding resonant wavelength. α_{jm} is the absorption coefficient per unit length in the microring waveguide R_{jm}. r represents the radius of the microring waveguide. The field coupling coefficient k_l and field transmission coefficient t_l ($l = 1, 2$) in the coupling region satisfy $k_l^2 + t_l^2 = 1$.

The working principle for realizing the adjustable bandwidth is described in Fig. 2. When the input light goes through TSCMRR_1 and TSCMRR_2, signals at resonant wavelengths are separated. These signals passed optical paths with same length can be coherently combined in TSCMRR_4 and adjustable bandwidths can be formed as needed at the Output port. As described in Fig. 2, λ_j represents the center wavelength related to TSCMRR_j and λ_O stands for the center wavelength related to the proposed tunable filter. The resonance wavelength differences $\Delta\lambda_S$ and $\Delta\lambda_L$ are respectively defined as $2\Delta\lambda_S = \lambda_3$-$\lambda_2$ and $2\Delta\lambda_L = \lambda_1$-$\lambda_4$. Due to the symmetrical design, $\Delta\lambda_L$-$\Delta\lambda_S = \lambda_1$-$\lambda_3 = \lambda_2$-$\lambda_4$ can be achieved. To tune the resonant wavelengths of the TSCMRRs, electrical signals are applied to move the Fermi levels of graphene flakes causing the variation