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Special Focus on Photonic Devices and Integration

A real-time tunable arbitrary power ratios graphene based power divider

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Dear editor,

Recently, photonics integrated circuits have attracted extensive consideration for its realization of large-scale integration of various devices and functionalities on a single chip [1]. As a fundamental building block for the photonics integrated circuits, the power dividers are widely used in variaties of applications such as the optical phase arrays, the asymmetric Mach-Zehnder interferometers, and the optical computing devices. Most of the power dividers used in presenkt photonics integrated circuits are based on the directional coupler (DC), the multimode interference (MMI), and the Y-branch structures [2, 3]. However, these designs are inflexible since once fabricated, and the power split ratios could not be changed anymore with a fixed size. The graphene based silicon waveguide is considered to be suitable for wide range electro-optical applications since its transport characteristics and conductivity can be tuned conveniently by electric injection. It has been widely studied in high speed modulation and detection [4, 5]. A graphene based MMI has been reported more recently while the split ratio is not adjustable once the device structure is fixed [6]. By assembling a graphene on the conventional DC, the coupling length of the DC could be adjusted since the refractive index of the graphene-oxide-silicon (GOS) waveguides changes with different applied voltages. The tunable coupling length finally results in the different power divisions of the two output ports. Thus a wavelength insensitive real-time tunable power divider could be realized.

We proposed, to the best of our knowledge, the first real-time tunable power divider utilizing a graphene-based Si DC. Arbitrary power ratios can be achieved on a single device with change in the voltage applied to the graphene layer. Moreover, the power divider performs a wide working range of (1400–1650) nm due to the tunable electro-optical effect of graphene layer.

Principle and design. Figure 1(a) illustrates the sketch of the power divider which consists of two silicon waveguides based on graphene layer, forming the structure of DC. The distances of coupling length (W_c) and coupling gap (W_g) are separately set to be 140 μm and 0.57 μm. The variation of effective index is realized by tuning the GOS waveguides, which cross-section is shown in Figure 1(b). The interaction region is based on 220 nm rib waveguide with 500 nm width. Optical field is guided by the 10 nm alumina layer on the waveguide into the graphene layer by the way of evanescent wave. And the alumina layer also acts as the capacitance between silicon waveguide and graphene layer. The optical distribution of transverse electric (TE) fundamental mode is shown in Figure 1(c). The effective index is solved around 2.5.

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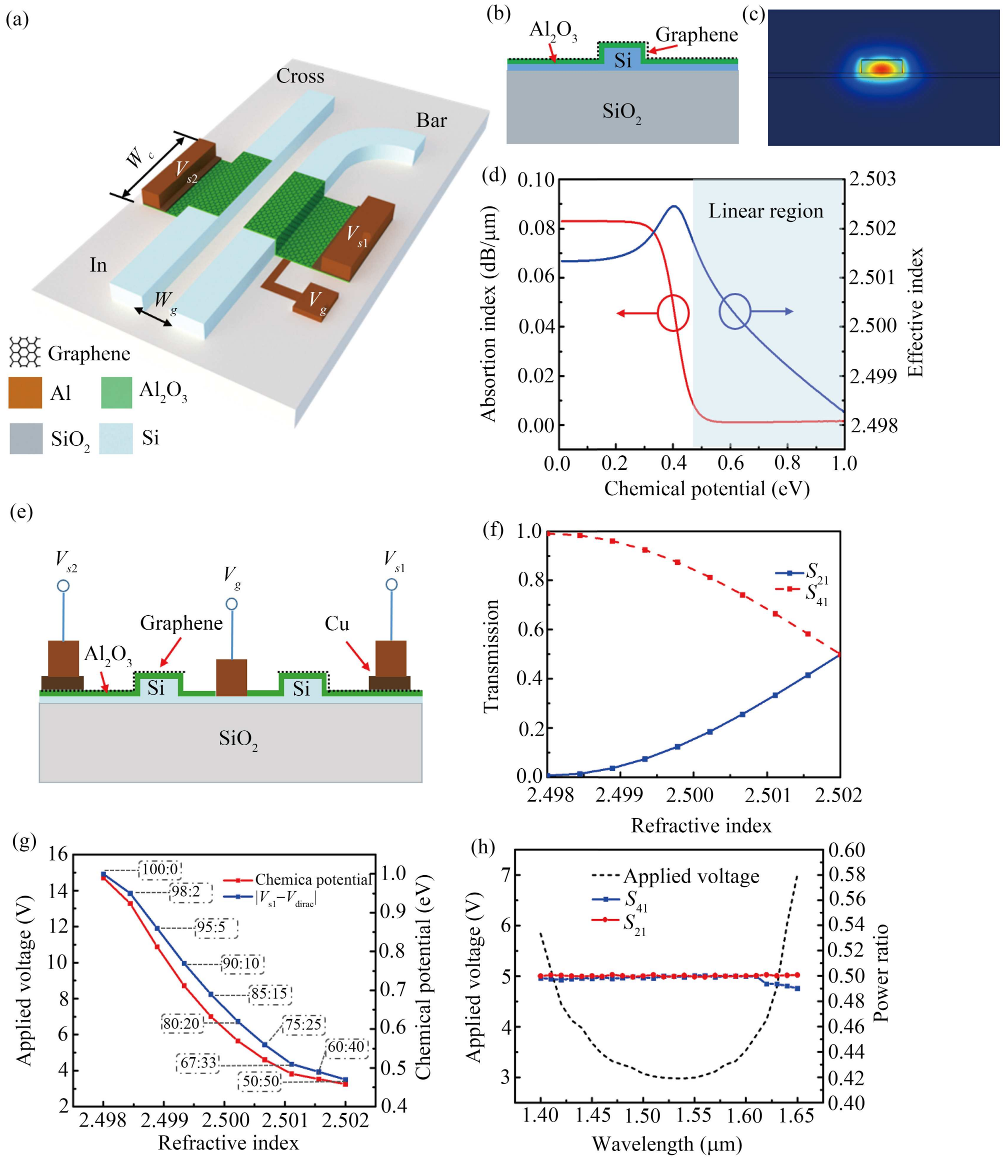

Figure 1 (Color online) (a) Sketch of the power divider utilizing the graphene-based DC; (b) cross-section of the interaction region in graphene based silicon waveguide; (c) the fundamental TE mode distribution in graphene based silicon waveguide; (d) Re($n_{\rm eff}$) and absorption of GOS waveguide as functions of the chemical potential; (e) cross-section of the interaction region with its drive scheme using two static signals; (f) normalization optical power of cross port and bar port as functions of different refractive index; (g) the values of applied voltages, refractive index of the bottom waveguide and the chemical potential of the graphene layer under several specific power ratios; (h) working performance of the device under a wide wavelength range (from 1400 to 1650 nm), as the applied voltage of graphene layer tuned to make sure a 50:50 split ratio.

Figure 1(d) shows the Re($n_{\rm eff}$) and absorption of GOS waveguide as functions of the chemical potential. In the range of (0.47–1) eV, the GOS waveguide is suitable for Re($n_{\rm eff}$) tuning, as the absorption is low and the effective index exhibits a linear change.

Results and discussion. Figure 1(e) shows the driving scheme of the graphene-based DC. Silicon waveguide is slightly p-doped and is connected to the analog ground by a copper electrode. Two static voltages, V_{s1} and V_{s2}, are applied to the top and bottom waveguide of DC, respectively. The length of the coupling region and the gap distance between the waveguides are pre-designed to make sure of a 50:50 power distribution when no voltage applied. An asymmetric power ratio can be realized by first tuning V_{s2} to set the refractive index of the top waveguide to the start point of linear region. Then the different power ratios, from 100:0 to 50:50 can be achieved with the variations of V_{s1}, as shown in Figure 1(f), the S_{21}/S_{41} represents the normalized optical power ratio between cross/bar port and input port. When the input port changes, the power ratio reverses, showing a tunable ratio from 50:50 to 0:100. Thus a 100:0 to 0:100 tunable power ratio was demonstrated. The relationship between chemical potential and applied voltage is described by

$$\mu = \hbar v_F \sqrt{\eta\pi |V_g - V_{\mathrm{dirac}}|}, \tag{1}$$

where $v_F = 3 \times 10^6$ m $\cdot$ s^{-1} denotes the Fermi velocity, $V_{\mathrm{dirac}} = 0.8$ V the voltage offset caused by natural doping, V_g the driving voltage, and $\eta = 5.531 \times 10^{16}$ m$^{-2} \cdot$ V^{-1} as per the GOS capacitor model. As shown in Figure 1(g), when the applied voltage varies from 3.4 to 15 V, corresponding with the chemical potential of graphene layer ranging from 0.47 to 1 eV, several specific power ratios can be obtained, which shows a flexible adjustment of power division. From Figure 1(g), the power divider needs about 15 V applied voltage to tune the graphene layer to 1 eV for a 100:0 split ratio. Such a high voltage may result in the breaking down of the 10 nm alumina layer. The solutions of such problem can be thickening the alumina layer or re-designing the device length for a lower working voltage. Furthermore, the change of the fermi level influences the loss of the waveguide. While in our design, the device studies in the linear region as shown in Figure 1(d). Within this area, the graphene has a relatively low transmission loss, which is almost transparency material. And the fluctuation of the absorption index around the working region is about 0.0009 dB/μm, which can be negligible.

The device can also work as a fixed 50:50 power beam splitter within a wide wavelength range. For the conventional DC, the coupling length would be changed with different working wavelength. In our design, by tuning the voltages of the DC arms, the specific (50:50) coupling length could be set to make sure the input power divided evenly. More details are exhibited in Figure 1(h). With the applied voltage changing from 3 to 7 V, the power ratios of two outputs maintain 50:50 stably, under a wide working wavelength range (1400–1650) nm. The normalization coupling loss, described by $|1 - (S_{21} + S_{41})|$, is calculated to be quite small ($\leqslant$0.01) since the transparency of the graphene layer in linear region. For the wavelength beyond 1650 nm, loss may increase due to the fixed waveguide structure, which no longer suitable for the light transmission of such wavelength. Moreover, other power ratios would also exhibit the wide working wavelength with different driving schemes. Generally, the results demonstrate a strong ability of refractive index adjustment in graphene layer with low loss and wide working range, making the device suitable for large scale on-chip integration.

Conclusion. We proposed a novel power beam splitter utilizing a graphene based Si DC. The device is real-time tunable on chip for arbitrary power ratio due to the electro-refractive effect of graphene layer. A wide working wavelength range from 1400 to 1650 nm is also obtained by tuning the applied voltage on graphene based silicon waveguide. The results show great potential of the graphene based device in the field of integrated optical circuits and silicon photonics.

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