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Design of a tunable graphene plasmonic-on-white graphene switch at infrared range

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A tunable Y-branch graphene plasmonic switch operating at the wavelength of 1.55 μm is proposed in which graphene is placed on white graphene. The switch structure is investigated analytically and numerically by the finite difference time domain method. The graphene plasmonic switch considered here supports both transverse magnetic and transverse electric graphene plasmons whose propagation characteristics can be controlled by modulating the external electric field and the temperature of graphene. Our calculations show that by strong coupling between the incident waves and the graphene plasmons of the structure, a high polarization extinction ratio of 45 dB and relatively large bandwidth of 150 nm around the central wavelength of 1.55 μm are achievable. Furthermore, the application of white graphene as the substrate of graphene decreases the propagation loss of the graphene plasmons and the required applied electric field. It is also shown that the propagation mode of the graphene plasmons can be tuned by changing the temperature and the calculated threshold temperature is 650 K.

1. Introduction

Tunable optical switching plays a crucial role in advanced passive optical devices such as power splitter [1], wavelength-division-multiplexer (WDM) [2], mode-division-multiplexer (MDM) [3], polarization-division-multiplexer (PDM) [4] and polarizer [5], and also active optical devices like modulators [6] and switches [7]. Moreover, such devices exhibit great potential in the state-of-the-art fields including modern medicine [8], optical storage systems [9], and novel nanoelectronic devices [10]. It is most desirable that tunable optical switches have small footprint, low power consumption, and high switching speed. The mentioned properties attributed to optical switched are eligible for reducing the cost of fabrication process as well as improving the efficiency. To realize optical switches with optimum characteristics, various structures including free space configuration [11–13] and guided wave configuration [14] have been employed in which the switching operation can be harnessed and manipulated through different mechanisms such as electro-optic effects [11], nonlinearities effects [12,14], and thermo-optic effects [13].

Amongst different structures with various mechanisms, the Y-junction structures based on waveguide platforms can improve the input-output scalability greatly to meet the enhanced requirement of data transmission [15,16]. Such structures not only reduce the cost of the fabrication process but also significantly save the footprint. Typically, the silicon Y-branch

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structures have been extensively utilized for development of various optical switches with a number of advantageous properties such as CMOS compatibility, simple fabrication process, and low cost [17]. The major drawback of the silicon schemes is their relatively large footprint. Indeed, owing to poor tunability of silicon refractive index through external fields, long coupling lengths in the range of hundreds of microns to millimeters are expected. In addition, switching speed is limited due to low carrier mobility in silicon structures [18]. To alleviate the problems of Si-based structures, advanced materials such as polymer [19], lithium niobate ($LiNbO_3$) [20], ferroelectric materials [21], and SiGe [22] are proposed in Y-branch switches. Although polymer based switches have demonstrated good performance, their switching speed is restricted by thermo-optic effect. The proposed structures based on $LiNbO_3$ require a relatively high external voltage for switching operation resulting in high power consumption. On the other hand, structures based on ferroelectric materials suffer from poor compatibility as well as complexities in fabrication processes. To overcome the limitations of the abovementioned structures, SiGe-based schemes were proposed. Thanks to high carrier mobility and small germanium band gap, SiGe-based structures can surpass the previous structures [22]. Unfortunately, a large coupling length in the order of hundreds of microns remains a challenging issue for such configurations.

To achieve compactness for optical switches, plasmonic structures have been introduced in which light can be squeezed into a sub-wavelength space leading to enhancement of the light-matter interaction [23]. However, introduction of noble metals such as gold and silver in plasmonic structures limits the application of optical switches owing to huge amount of ohmic losses in THz and IR regime [24]. To reduce ohmic losses, hybrid plasmonic-photonic structures (HPPS) with the advantage of tight confinement at the interface of a metal and a dielectric substrate, were proposed [25]. The combination of silicon and plasmonic structures can provide a solution to the problem of large coupling length and high ohmic losses [25]. One typical mechanism to achieve switching in the abovementioned structures is to use silicon as a dielectric substrate layer and apply external field to manipulate the silicon carrier density. Although silicon-based plasmonic switches are totally compatible with CMOS technology, they suffer from limited switching speed due to low charge carrier mobility [26]. Therefore, presenting a material able to enhance the switching speed is timely.

Graphene, a unique two-dimensional one-atom-thickness material, is an excellent candidate in harnessing of light due to its ultra-high mobility and low carrier scattering rate at room temperature [27,28]. Besides, the special linear band structure around Dirac point allows inter-band absorption modulation by tuning the Fermi level through its tunable surface conductivity [29,30]. Therefore, graphene has been utilized in plasmonics due to its metallic behavior at THz to near infrared range [31]. It can harness, squeeze, and manipulate electromagnetic waves simply by applying an external electric or magnetic field, leading to propagation of graphene plasmons at the graphene-dielectric interface [32,33]. Compared to the conventional plasmonic materials such as silver or gold, graphene plasmons present significant benefits including high mobility, tunability, ultra-low ohmic losses, higher mode confinement due strong light-matter interaction, and easy integration with the CMOS technology [34,35]. These remarkable properties stem from the tunable surface conductivity of graphene as well as the electronic states in the valence and conduction bands of graphene that can be expressed by a linear dispersion relation [36]. This relation strongly depends on the Fermi energy of graphene.

Furthermore, the ability to transfer graphene onto silicon, opens an avenue to potential applications of graphene-based plasmonic structures such as hybrid graphene plasmonic-photonic structures (HGPPS) [37–39]. Due to high integrity of silicon with CMOS technology, HGPPS have been the focus of attention. On the other hand, since interlayers play a vital role in controlling the speed of carries on graphene sheet and thus the switching speed, the choice of interlayer material is of prime importance in graphene plasmonic switches [40]. Therefore, an efficient control of the graphene optical properties can be achieved by selecting a high quality-resistive interlayer. More recently, to obtain a high switching speed and low power consumption, Aznakayeva et al. proposed a new dielectric material namely Hafnium oxide (HfO_2) as a substrate for free space graphene-based structure [40]. They experimentally demonstrate that SiO_2 can be supplanted by Hafnium oxide dielectric due to its high k value and large band gap energy (5.68 eV). Although the mobility in the proposed structure is enhanced by an order of two compared to the conventional graphene/SiO_2 structures, there is a possibility of raising the switching speed with other advanced optical materials.

Monolayer hexagonal boron-nitride (h-BN) which is commonly called as white graphene (WG) is a unique two-dimensional dielectric material displaying a new platform for supporting graphene plasmons. The application of WG reduces graphene scattering loss, resulting in higher propagation length as well as high switching speed [41,42]. Benefited from compact device length, graphene/WG switches prove to have exceptional performance in terms of power consumption. Additionally, owing to relatively similar carrier mobility of graphene and WG, graphene/WG switches exhibit higher carrier mobility than that of the silicon-based structures.

In this paper, we propose a Y-branch graphene plasmonic switch wherein graphene is placed on white graphene. By modulating the external electric field along with the temperature, we can tailor the propagation of graphene plasmons in the output arms of the switch. Excellent ability of selecting the transmitted polarization, through tuning the temperature or applying an external electric field, combined with tuning the amplitude of the transmitted wave, result in very high polarization extinction ratio (PER) of 45 dB and relatively large bandwidth (BW) of 150 nm around the central wavelength of 1550 nm.

The rest of this paper is organized as follows. In Section 2, the Y-branch graphene plasmonic switch is proposed and the dispersion properties of its graphene plasmons are studied analytically and numerically. Also, the switching mechanism of the TE-TM graphene plasmons in the presented structure is investigated for a certain set of physical parameters by using the Kubo and mode coupled methods. The effect of variations in the temperature and chemical potential on the propagation and

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