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Graphene-based plasmonic waveguide devices for electronic-photonic integrated circuit

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ABSTRACT

Graphene is a one-atom thick carbon film packed in a honeycomb structure, and because it has extraordinary optoelectronic properties, it has attracted a great deal of attention in the field of photonics. Graphene-based plasmonic photonic devices have been developed which are capable of emitting, transmitting, modulating, and detecting light wave signals using a single material. In this paper, we propose the concept of on-chip graphene electronic-photonic integrated circuits (EPICs) architecture, and present developments and perspectives on the essential graphene plasmonic-based photonic components, including the plasmonic waveguide, modulator, and photodetector, which are based on the graphene EPICs. The optical characteristics and design considerations of the graphene-based photonic devices are discussed based on experimental and theoretical investigations at telecommunications wavelengths. In parallel, we provide new device design concepts and a potential solution for further improving their operating characteristics. We also performed a numerical investigation of the characteristics of the photonic devices to explain their operating principles and to predict their operating performances. The proposed photonic components were fabricated on an organic photonic chip using an optimized fabrication process, and their optical characteristics were experimentally demonstrated. Based on these results and demonstrations, we hope to introduce new perspectives on the future direction of graphene-EPICs in graphene plasmonics and the optical telecom field.

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1. Introduction

The appearance of a new material allows us to develop novel photonic and/or electronic devices. This has certainly been the case with graphene, a carbon monolayer packed in a hexagonal structure, which is one of the presently emerging materials [1]. Numerous devices and systems based on its extraordinary mechanical, electrical, and optical properties have been demonstrated, including field effect transistors [2,3], electronic devices [4,5], mechanical devices [6,7], biosensors [8], gas sensors [9–11], optical waveguides [12,13], optical modulators [14,15], switch [16], detectors [17], light emitter [18], and optoelectronic systems [19].

In photonics technology, graphene has played an exciting role in the plasmonics field, which deals with the excitation, manipulation, and detection of light in the form of surface plasmon polaritons (SPPs) [20–25]. The SPP is a transverse-magnetic (TM)-polarization surface wave that is excited at a metal-dielectric interface [26–28]. SPPs are associated with coupling between the collective oscillation of a free electron-plasma in a metal and an electromagnetic wave, and their attractive feature is the ability to confine light within the diffraction limit. Nanoscale plasmonic devices have been demonstrated [29]. However, metal-based plasmonic devices have suffered from at limit: active control of the metal's refractive index is not possible. The manipulation of light in metal-based plasmonic devices has been dependent on changing the index of the claddings that surround the metal structures.

The most interesting characteristic of the graphene-based plasmonics is that they overcome the shortcomings of noble metal-based plasmonic waveguide devices. Graphene's complex refractive index can be tuned by adjusting its chemical potential (Fermi level) by applying a gate voltage [30–33]. The combination of the SPP's capability to confine light in the nanoscale dimension and the graphene's ability to change its refractive index means that it is possible to manipulate a plasmonic guided mode on a single-layer graphene sheet quite freely in the nanoscale [34].

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Besides applications in nano-plasmonic devices, graphene plasmonic waveguides are useful for the long-range propagation of light at optical telecommunication wavelength ranges. By exploiting its transparent thin metal-like characteristics, graphene can be used to guide light waves [12]. Like a metal strip embedded in a dielectric medium with a homogenous refractive index, a multilayer graphene strip supports the so called long-range surface plasmon polariton guided mode [35], where the surface plasmon modes excited at the upper and lower graphene-dielectric interfaces couple and form a low loss symmetric mode [13]. A 6-mm-long graphene-microribbon in polymer cladding allowed the transmission of 2.5 Gbps optical signals with a propagation loss of 2.1 dB/mm at a 1.31 μm wavelength [13].

Based on the graphene plasmonic waveguide technology and graphene's intrinsic versatile optoelectronic properties, graphene-based photonic integrated circuits (PICs) have been proposed to realize on-chip electronic-photonic integrated circuits (EPICs) [36]. A thermo-optic modulator utilizing a graphene heater concept and photo-detector based on the generation of electron-hole pairs under light illumination have also been demonstrated [37,38]. However, the optical characteristics of those devices are not yet sufficient for practical application in telecomm systems. Rigorous theoretical investigations of the graphene plasmonic waveguides are also critically important to exactly understanding the devices' operating principles.

In this paper, we propose a schematic concept, of graphene-based electronic-photonic integrated circuits (graphene-EPICs), and provide perspectives on recently reported technological progress in developing graphene-based plasmonic waveguide devices at telecom wavelengths. We discuss on the experimental and theoretical characteristics of graphene-based photonic components, including the waveguide, modulator, and photodetector, which are based on the graphene-EPICs. In parallel, we provide new device design concepts to further develop their operating characteristics. Numerical investigations of the characteristics of the proposed graphene-based photonic devices were performed to explain their operating principles and predict their expected performances. In the numerical investigation, we considered graphene as an isotropic and as an anisotropic material. We then suggested an optimized fabrication process and procedures to realize the proposed graphene-based photonic device. We fabricated the photonic components on an organic photonic material-based photonic chip and demonstrated the characteristics of the photonic devices. Finally, we discuss how graphene-EPICs can lead to the improvement of next-generation on-chip photonic systems.

2. Concept of graphene-based electronic-photonic integrated circuit

With recent increases in operating signal frequency, electrical lines have reached their limits, leading to high power consumption, time delays, skew, and electromagnetic interference (EMI). On-chip electronic–photonic integrated circuits (EPICs) have been proposed as a promising technology to overcome these shortcomings [39]. The development of hybrid chip enabling optical computing and signal processing requires the development of certain precursor technologies. In this regard, both monolithic integration technologies for optical components such as waveguides, lasers, modulators, and detectors, and technologies allowing compatibility with conventional electronic circuits have been being achieved using Silicon, GaAs and indium phosphate (InP) materials [40–41]. Recently developed silicon photonic technologies allow the building of numerous photonic components on complementary meta l–oxide–semiconductor (CMOS) wafers to produce CMOS-compatible electronic-photonic integrated devices [42,43]. Beyond data communication technologies, these EPIC chips have been used in radio frequency integrated optoelectronics, integrated radio transceivers, and high-speed microwave signal processing [44–46]. However, silicon photonic circuits must be incorporated into not only silicon-incompatible semiconducting optical materials such as GaAs and/or InP, but also the metallic features of the CMOS device.

Fig. 1 displays one design schematic concept of the graphene plasmonics-based electronic-photonic integrated circuits (graphene-EPICs) on a chip. The concept of the on-chip graphene plasmonic EPICs has been updated based on our previous proposal [36]. The proposed graphene-EPICs can be easily realized with the aid of conventionally developed planar light wave circuit (PLC) technologies using silica, silicon nitride, InP, or silicon. The resulting graphene-EPICs can be used for ultra-broad bandwidth and high-performance information processing, and the graphene-integrated photonic devices can be integrated with electronic components such as field-effect transistors, gas sensors, and memory components.

In this design, a light wave is launched in the upper graphene plasmonic waveguide (the continuous wave (CW) source port) and propagates through the graphene strip, which has a micron-sized width. The guided mode is called a long range-surface plasmon polariton (LR-SPP) strip mode, and is excited by an ultra-thin metal strip embedded in a dielectric medium with a homogenous refractive index. A graphene-based planar waveguide photodetector receives the optical data from optical data input port and converts them into electrical signals. Meanwhile, a vertical graphene photodetector located at the center of the chip receives the external optical data from a vertically incident light wave and/or microwave and then, converts them into a second set of electrical signals. The two sets of electrical signals from the two different graphene photodetectors are intermodulated by a graphene field effect transistor (FET). The intermodulated electrical signals are then converted into optical signals by the graphene modulator, which is placed at the bottom of the chip. Finally, new electronic-photonic processed optical signals are generated at the optical data output port (left bottom in Fig. 1). The optical data from the internal optical data input could contain high frequency video signals and the external optical data (or THz or microwave data) could contain sound signals. Both signals would be mixed by the FET device and transmitted to another graphene-based optoelectronic device on the same platform or an external chip. Although the operation scenario of the graphene EPIC chip shown in Fig. 1 is generalized, the similar approach can be used on a scenario by scenario basis for designing application chips for processing specific target electronic and photonic hybrid signals.

3. Graphene-based plasmonic waveguide

The proposed graphene-based electronic-photonic integrated circuits use a graphene-based plasmonic waveguide to guide the lightwave signal and interconnect all graphene-based photonic devices. To theoretically investigate the optical characteristics of the guided modes in the graphene strip, we first investigate the optical properties of graphene. In optics, graphene is a conductive, transparent, and gapless semiconductor with linear conical energy-momentum dispersion [2,18]. L.A. Falkovsky used dynamical conductivity $\sigma(\omega)$ to study the optical properties of graphene [30,31]. The dynamic conductivity σ can be expressed as a function of frequency ω, temperature T, and chemical potential μ_c. Altering the dynamic conductivity and applying the appropriate boundary conditions at interfaces, he calculated the reflection and transmission coefficients of graphene under various charge carrier

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