Optics Communications 420 (2018) 72–77

Contents lists available at ScienceDirect

Optics Communications

journal homepage: www.elsevier.com/locate/optcom

# Channel hybrid plasmonic modes in dielectric-loaded graphene groove waveguides

Peng Wan, Cuihong Yang *, Zhen Liu

*School of Physics and Optoelectronic Engineering, Nanjing University of Information Science &Technology, Nanjing 210044, China*

ARTICLE INFO

*Keywords:*
Graphene
Surface plasmons
Channel waveguide
Hybrid modes

ABSTRACT

Dielectric-loaded graphene groove waveguide (DLGGW) structure is designed and the channel hybrid plasmonic modes are investigated in the terahertz domain. The proposed structure could effectively suppress the mode field confinement with relative low transmission loss due to the strong coupling between the dielectric mode and the channel graphene plasmonic mode. A typical propagation length is 37.8 μm, and optical field is confined into an ultra-small area of approximately 52 $\mu m^2$ at 1.5 THz. By changing the size of cylinder, the angle of the graphene groove, and the thickness of dielectric coating layer, the compromise between confinement and loss could be balanced flexibly. Unlike plasmons in noble metals, the propagation loss in DLGGW structure could be tuned by the graphene conductivity. Moreover, because of the imaginary part of graphene conductivity being positive, the proposed waveguide can propagate in a large terahertz frequency regime. This waveguide shows great applications in optical integrated devices, such as detectors, sensors and spectroscopy.

## 1. Introduction

As the photonic components and circuits become more integrated, it would suffer from the diffraction limit which imposes dimensions in the order of the light wavelength [1]. So it is extremely beneficial to develop highly confined waveguides, which could be applied to detectors, sensors and spectroscopy [2–5]. Surface plasmon polariton (SPP) [6–9], a way to confine and control electromagnetic waves at subwavelength scale, propagates along metal–dielectric interfaces and can be guided by metallic nanostructures beyond the diffraction limit. It is a promising candidate for highly integrated photonic devices. Various SPP waveguides within a deep subwavelength confinement have been proposed, such as plasmonic metallic gratings [10,11], gap plasmonic waveguides [12], semiconductor slit waveguides [13], hybrid plasmonic waveguides [14,15].

In contrast to these SPP waveguides that may require relatively strict fabrication condition [7], Channel plasmon polariton(CPP) waveguides in forms of a V-shaped channel [16–20] are simple to make [17] and can be adapted to mass production [16]. Moreover, CPP waveguides could balance the tradeoff between the propagation loss and mode confinement to some certain extent [21]. Several waveguide components based on these geometries have already been investigated, i.e., Mach–Zender interferometers or ring resonators [7]. CPP waveguides are usually milled on metallic substrates in the visible to near-infrared frequencies and have been studied extensively [18–20]. However in a terahertz frequency (0.1 ∼ 10 THz), only loosely bound surface waves could be supported by noble metals. Graphene surface plasmons (GSPs) have recently attracted enormous attention in optoelectronic field [22,23]. GSPs could confine electromagnetic field down to volumes that are several orders of magnitude smaller than SPP in noble metals at terahertz frequency. Moreover, GSPs could be tuned by chemical doping, electric field, magnetic field and gate bias voltage [23], which lead to novel photonic devices, such as superlens, subwavelength waveguides, and Luneburg lens [23–27]. Similar to SPP in noble metals, GSPs waveguides also suffer from high absorption loss which leads to short-range propagation at terahertz frequency. One of the promising solutions for achieving long-range propagation with tight-mode confinement is hybrid plasmonic structure [14,21,28,29]. The hybrid mode is strongly localized in the high-index dielectric and the low-index gap, which can be tuned by hybridization between the SPP modes and the waveguide modes [28]. A variety of plasmonic devices including splitters [30], couplers [31], and microring resonators [32] have been proposed and investigated. In the previous works, most researching works [14,21,28,29] adopt the noble metals in their hybrid plasmonic waveguides. These waveguides can only be tuned by adjusting the size of structure, which is the disadvantage of practical applications. Some works design hybrid plasmonic waveguides based on graphene at terahertz frequency [15,33]. To our knowledge, none

---

* Corresponding author.
*E-mail address:* chyang@nuist.edu.cn (C. Yang).

https://doi.org/10.1016/j.optcom.2018.03.031
Received 3 February 2018; Received in revised form 10 March 2018; Accepted 15 March 2018

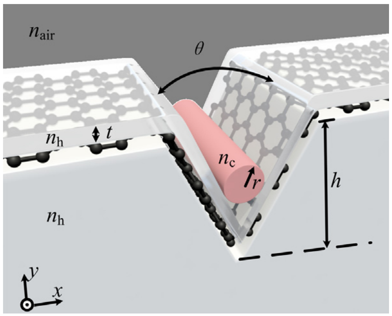

**Fig. 1.** Cross section of the hybrid graphene groove waveguide. The waveguide propagation direction is along the $z$-direction. $n_{\text{air}}$, $n_c$ and $n_h$ are refractive index of air, GaAs and HDPE respectively.

of the previous works has considered the graphene groove and the role of graphene conductivity on the waveguide. However, in the presence of the graphene conductivity, it is expected that the propagation and mode confinement of hybrid plasmonic waveguides will be modified. And the graphene conductivity is dependent on the chemical doping and the gate bias voltage. Therefore, it will provide additional degrees of freedom which can be applied to tune the SPP propagation.

In this paper, analogous to the concept of CCP and hybrid plasmonic waveguides, we proposed a channel hybrid plasmonic waveguide by integrating a high-index cylindrical rod with low-index groove embedding graphene. Owing to the coupling between the cylindrical waveguide and graphene plasmonic modes, highly efficient hybrid plasmonic modes can be obtained which exhibits strong mode confinement and long-range propagation at terahertz frequency and is different from traditional plasmonic waveguides. It can be tuned actively by graphene conductivity, which is greatly advantageous to some applications including semiconductor, space tomographic imaging, and biological sensing.

## 2. Geometry and properties of the proposed waveguide

The proposed dielectric-loaded graphene groove waveguide (DLGGW) structure is shown in Fig. 1, which consists of a high-index cylindrical rod and graphene embedded in low-index groove. Here, graphene can be laid on the performed groove [34] and be covered by a coating layer. Such sharp graphene structures have been realized by atomic force microscopy [35]. The cylindrical rod is assumed to be supported directly by the homogeneous low-index coating layer. The modal characteristics of DLGGW are investigated at 1.5 THz. The high-index cylindrical dielectric is GaAs ($n_c = 3.6$) [36] and the cladding is air ($n_{\text{air}} = 1$). High-density polyethylene (HDPE) ($n_h = 1.54$) [37] is chosen to serve as the coating layer and substrate, which has been widely employed in terahertz field and has relatively higher stability and smaller propagation loss [37,38]. Compared with the propagation loss from graphene, the loss of GaAs and HDPE can be neglected and not involved in our calculation. The graphene groove has a depth of $h = 500$ μm and a tip angle of $\theta$. The thickness of the HDPE coating layer on graphene is $t$. The radius of cylindrical GaAs is $r$. In this structure, 0.1 μm and $(0.1+t)$ μm curvature radii are applied to round all the inner and outer corners to keep a constant gap width, respectively.

The graphene surface conductivity $\sigma(\omega)$, can be derived using the kubo formula including the intraband and interband optical transition contributions [39]:

$$\sigma(\omega) = i\frac{2e^2 k_B T}{\pi\hbar^2(\omega + i\tau^{-1})}\ln[2\cos h(\frac{\mu_c}{k_B T})] + \frac{e^2}{4\hbar}[\frac{1}{2} + \frac{1}{\pi}\arctan(\frac{\hbar\omega - 2\mu_c}{2k_B T}) - \frac{i}{2\pi}\ln\frac{(\hbar\omega + 2\mu_c)^2}{(\hbar\omega + 2\mu_c)^2 + (2k_B T)^2}] \tag{1}$$

where $k_B$ is the Boltzmann constant, $T = 300$ K is the temperature, $\omega$ is the frequency and $e$ is the electron charge. $\mu_c$ is the chemical potential which can be tuned by chemical doping, electric field, and gate bias voltage. At different values of $\mu_c$, certain desired graphene conductivity can be achieved. The carrier relaxation lifetime $\tau$ is determined by the carrier mobility $\mu$ in graphene, according to $\tau = \mu_c\mu/(eV_F^2)$, where $V_F = 10^6$ m/s is Fermi velocity. The carrier mobility $\mu$ ranges from ∼1000 $\text{cm}^2\text{V}^{-1}\text{s}^{-1}$ [40] in chemical vapor deposition (CVD) grown graphene to 230 000 $\text{cm}^2\text{V}^{-1}\text{s}^{-1}$ [41] in suspended exfoliated graphene. When the chemical potential $\mu_c$ is tuned to 0.15 eV, the carrier relaxation lifetime located from 0.015 to 3.45 ps. In our calculation $\tau = 0.5$ ps was taken. In Eq. (1), when the imaginary part of the graphene conductivity is positive, the graphene is capable of supporting a transverse-magnetic (TM) SPP surface wave which is similar to the case of metal SPP [42]. When the imaginary part is negative, a weak transverse-electric (TE) SPP surface wave can be supported and propagated [43,44].

The equivalent permittivity of graphene is given by

$$\varepsilon_g = 2.5 + i\sigma(\omega)/(\omega\varepsilon_0 d) \tag{2}$$

where $d = 0.5$ nm is the effective thickness of graphene [45]. The modal properties are investigated by finite-element-method-based mode solver using COMSOL. The eigenvalue solver is used with the calculation region in the $x$- and $y$- direction which is assumed to be sufficiently infinite. Convergence tests are executed to ensure an accurate eigenvalue [46].

For DLGGW we proposed in the present paper, the high-index dielectric GaAs mode coupling with higher order channel GSPs mode will be obtained under certain geometries [21]. However, we will only discuss the fundamental mode, which is more preferred for expected applications. The classical control variable method is adopted. We fix some parameters and sweep the other two to find the relationship between the mode property and the geometrical parameters, which includes the HDPE coating layer thickness on graphene ($t$), the radius of cylindrical GaAs ($r$), the tip angle of groove ($\theta$), and the graphene chemical potential ($\mu_c$).

SPP mode properties in DLGGW are mainly determined by three physical parameters, which are mode effective index ($N_{eff}$), propagation length ($L_m$) and normalized mode area ($A_m/A_0$).

$$L_m = \lambda/(4\pi\text{Im}(N_{eff})) \tag{3}$$

where $\lambda$ is the working wavelength, $\text{Im}(N_{eff})$ is the imaginary part of the mode effective refractive index $N_{eff}$.

The mode area $A_m$ is defined as [47]

$$A_m = \frac{\int_s p(x,y)dxdy}{\max[p(x,y)]} \tag{4}$$

where $p$ $(x,y)$ is the energy flux density, $p(x,y) = E(x,y) \times H(x,y)$. The normalized modal area is defined as $A_m/A_0$, where $A_0 = \lambda^2/4$ is the diffraction limited mode area.

Figure of merit ($FoM$) provides an appropriate measurement for the trade-off between the propagation length ($L_m$) and mode area ($A_m$) [48].

$$FoM = \frac{L_m}{2\sqrt{A_m/\pi}} \tag{5}$$

The electric field distributions at $\theta = 30°$ and $\mu_c = 0.5$ eV are shown in Fig. 2. The dominant electric component is $E_x$. Because the fundamental plasmonic modes in the graphene groove exist in the apex [34], most electromagnetic energy is localized at the bottom of the graphene groove and the HDPE coating layer for a small radius [see Fig. 2(a), (e), and (i)]. It is worth noting that in this situation, the mode field size is smaller than counterparts in hybrid metal plasmonic waveguides [21], which results from the strong interaction between the incident light and the free electrons in graphene. A combination of graphene plasmon and high-index contrast effect at rod/groove interface will lead to a deep-subwavelength mode confinement [28], so with increasing the radius of rod, the mode field tends to shift toward the