A Tunable THz Plasmonic Waveguide Based on Graphene Coated Bow-tie Nanowire with High Mode Confinement

Xu Wang¹, Jue Wang¹, Tao Ma¹,²* and Fang Wang¹,²

¹College of Electronic and Electrical Engineering, Henan Normal University, Xinxiang, China; ²Key Laboratory Optoelectronic Sensing Integrated Application of Henan Province, Xinxiang, China

Abstract: Background: A THz Plasmonic Waveguide Based on Graphene Coated Bow-tie Nanowire (TPW-GCBN) has been proposed. The waveguide characteristics are investigated by the Finite Element Method (FEM). The influence of the geometric parameters on propagation constants, electric field distributions, effective mode areas, and propagation lengths is obtained numerically. The performance tunability of TPW-GCBN is also studied by adjusting the Fermi energy. The simulation results show that TPW-GCBN has better mode confinement ability. TPW-GCBN provides a promising alternative in high-density integration of photonic circuit for the future tunable micro-nano optoelectronic devices. Surface plasmonpolaritons based waveguides have been widely used to enhance the local electric fields. It also has the capability of manipulating electromagnetic fields on the deep-subwavelength.

Objective: The waveguide characteristics of TPW-GCBN should be investigated. The tunability of TPW-GCBN should be studied by adjusting Fermi energy ($F_k$) which can be changed by the voltage.

Methods: The mode analysis and parameter sweep in Finite Element Method (FEM) were used to simulate TPW-GCBN for analyzing effective refractive index ($n_{eff}$), electric field distributions, normalized mode areas ($A_{norm}$), propagation length ($L_p$) and Figure of Merit (FoM).

Results: At 5 THz, $A_{norm}$ of $\lambda^2/14812$, $L_p$ of $\sim2$ μm and $FoM$ of 25 can be achieved. The simulation results show that TPW-GCBN has good mode confinement ability and flexible tunability.

Conclusion: TPW-GCBN provides new freedom to manipulate the graphene surface plasmons, and leads to new applications in high-density integration of photonic circuits for tunable integrated optical devices.

Keywords: Plasmonic waveguide, terahertz, graphene, effective mode areas, propagation length, figure of merit.

1. INTRODUCTION

Due to the capability of manipulating electromagnetic fields on the deep-subwavelength scale, metal nanostructures based on Surface Plasmon Polaritons (SPPs) have inspired a variety of potentials, such as ultra-compact optoelectronic circuits and optical sensors [1-3]. Various metal nanostructures have been proposed for guiding SPPs [4-6]. Au and Ag nanowires are typical one-dimension waveguide structures with low losses at visible and near-infrared spectral ranges [7]. The waveguiding properties of metal nanowires have been widely investigated [8], but its development and applications are limited by the inflexible substructure of the noble metal.

Graphene family nanomaterials, including single-layer graphene, multi-layer graphene, graphene quantum dots, graphene nanoplatelets, graphene oxide, and so forth demonstrate many excellent characteristics [9]. Among them, the single-layer graphene has gained much interest because of its unique electronics, photonics and plasmonic properties [10-12]. Graphene has a flat monolayer of carbon atoms tightly packed into a two-dimensional honeycomb lattice [13]. It can serve as a platform for metamaterials and support SPPs. Compared with metal plasmonic waveguides, the graphene plasmonic waveguides have three main merits: relatively low loss, tunable electromagnetic properties and strong light confinement [14-18]. Recently, novel nanofluid containing graphene and metal (silver or platinum) are proposed [19-21]. Their thermal performance, flow, heat transfer and second law characteristics are evaluated. It broadens the application of graphene.

Moreover, a series of nanoscale optical waveguide devices based on graphene have been designed, such as graphene-coated nanowire [22] and dielectric substrates contained graphene [23]. Tunable plasmonic resonance absorption characteristics have been discovered in periodic H-
shaped graphene arrays [24]. A platform using a hollow-core fiber with the integration of graphene coating has been studied to monitor the refractive index change of the surrounding air [25]. Compared with the traditional metals, SPPs based on graphene has better field confinement and could naturally be restricted on the curved graphene surfaces [26]. Hence, SPPs based on graphene provides a solution to achieve strong field enhancement on the probe component in the mid-infrared and terahertz (THz) ranges.

In this paper, a THz Plasmonic Waveguide based on Graphene-Coated Bow-tie Nanowire (TPW-GCBN) is proposed and studied. In order to study the field confinement of TPW-GCBN, Finite Element Method (FEM) is used to simulate the mode characteristics. Effective refractive index \( n_{\text{eff}} \), electric field distributions, effective mode areas \( A_{\text{eff}} \), propagation length \( L_{\text{p}} \) and figure of merit \( \text{FoM} \) of the fundamental SPPs modes supported in TPW-GCBN with different geometric parameters are investigated. To analyze the tunable properties, the influence of the Fermi energy \( E_F \) on the GPM. The real part of the GPM originates from the coupling of the two GCBN plasmonic modes (transverse magnetic mode). Fig. (2a) shows the dispersion relations of the GPM. The real part of \( n_{\text{eff}} \) \( \text{Re}(n_{\text{eff}}) \) monotonically increases with the frequency \( f_0 \) of THz wave, \( f_0=c/\lambda_0 \), where \( c \) is the speed of light in vacuum. However, \( L_0 \) monotonically decreases with an increase of \( f_0 \). In the mid-infrared and THz range, the GPM suffers from high absorption loss because the majority of the mode energy is located at the interface between the graphene layer and silicon. As shown in Fig. (2d), \( A_m \) and \( \text{FoM} \) of the GPM with respect to \( f_0 \) are illustrated. Both the normalized mode area and \( \text{FoM} \) increase

2. WAVEGUIDE STRUCTURE: MATERIALS AND METHODS

The cross-section of TPW-GCBN is shown in (Fig. 1). TPW-GCBN structure consists of two identical isosceles triangular nanowires (SiO\(_2\)) coated with graphene, an Agslab sandwiched between two nanowires, the surrounding dielectric is air. The refractive indices of SiO\(_2\) and air are 1.45 and 1, respectively.

![Cross section of TPW-GCBN](image)

Fig. (1). Cross section of TPW-GCBN. (A higher resolution / colour version of this figure is available in the electronic copy of the article).

Considering the fabrication tolerances, the three top angles of the dielectric nanowires are rounded, and the corner radius \( r=25\text{nm} \). The thickness of Agslab is \( t \), and \( g \) is the distance between the top angles of the dielectric nanowires and Agslab. The height and top angle of the rounded triangle are \( L \) and \( \theta \), respectively. The permittivity \( \epsilon_r \) of graphene can be calculated as (eq. 1) [27].

\[
\epsilon_r = 1 + \frac{i \sigma}{\epsilon_0 \omega d}
\]

where \( d \) is the thickness of monolayer graphene (in this simulation, \( d=1 \text{ nm} \)) and \( \omega \) is the angular frequency of the incident light. \( \epsilon_0 \) is the permittivity in free space. According to the Kubo’s formula [28], the surface conductivity of graphene consists of the interband and intraband contributions, that is \( \sigma(\omega)=\sigma_{\text{intr}}+\sigma_{\text{inter}} \). \( \sigma(\omega) \) is approximated as (eq. 2).

\[
\sigma(\omega) = \frac{2e^2 k T}{\pi \hbar^2 (\omega+i\tau)^2} \ln(2 \cosh \frac{E_F}{2k T})
\]

\[
-\frac{e^2}{4\hbar^2} \left[ \frac{1}{2} + \frac{\pi}{2} \right] \left( \frac{h \omega - 2 F_F}{2k T} \right) - \frac{i}{2\pi} \left[ \frac{1}{2} - \frac{\pi}{2} \right] \left( \frac{h \omega - 2 F_F}{2k T} \right)^2 \left( \frac{h \omega - 2 F_F}{2k T} + 4k T \right)
\]

where \( \tau \) and \( T \) are the relaxation time and temperature, respectively. \( h \) is the reduced plank constant, \( k_b \) is the Boltzmann constant, and \( e=1.6 \times 10^{-19} \text{ C} \). Here, \( T=300 \text{ K}, \tau=0.5 \text{ ps} \).

The permittivity of Ag is described by Drude-Lorentz model as [29] (eq. 3).

\[
\epsilon_i = \epsilon_{\infty} - \frac{\omega_p^2}{\omega^2 + i\gamma \omega}
\]

where \( \epsilon_{\infty} \) is the high-frequency permittivity, \( \gamma \) is the damping term, and \( \omega_p \) is the plasma angular frequency.

\[
\alpha_b = \sqrt{\frac{ne^2}{\epsilon_0 m_{\text{eff}}}}
\]

where, \( m_{\text{eff}}, e, \) and \( n \) are electron effective mass, the electron charge, and the carrier density, respectively.

The propagation length \( L_p \) is defined as \( L_p=\lambda_0/\left[4\pi \text{Im}(n_{\text{eff}})\right] \), where \( n_{\text{eff}} \) and \( \lambda_0 \) are the effective refractive index and wavelength of the incident light, respectively. \( \text{Im}(n_{\text{eff}}) \) is the imaginary part of \( n_{\text{eff}} \). The effective mode area \( A_{\text{eff}} \) is defined as:

\[
A_{\text{eff}} = \frac{\int W(r)dr}{\max \{W(r)\}}
\]

where \( W(r) \) is the energy density (per unit length flowed along the direction of propagation). Here, the normalized mode area \( A_m/A_0=\lambda_0/4 \) is used, \( A_0=\lambda_0^2/4 \) is the diffraction-limited mode area.

3. RESULTS AND DISCUSSION

The waveguide characteristics of TPW-GCBN are investigated by using the mode analysis in FEM. A THz wave with frequencies ranging from 1 THz to 18 THz is used as the incident source. Fig. 2 shows the Electric Field distributions and mode properties of the fundamental mode in TPW-GCBN. Here, \( L=600 \text{ nm}, r=80\text{nm}, \) and \( g=5\text{nm} \). In Fig. (2a), the optical energy is mainly confined in the gap between the isosceles triangular nanowires and Ag slabs. The fundamental Graphene Plasmon Mode (GPM) is approximately linearly polarized. As shown in Fig. (2b), the normalized electric field in \( x \) direction has the maximum value at the graphene surface in air. The GPM originates from the coupling of the two GCBN plasmonic modes (transverse magnetic mode). Fig. (2c) shows the dispersion relations of the GPM. The real part of \( n_{\text{eff}} \) \( \text{Re}(n_{\text{eff}}) \) monotonically increases with the frequency \( f_0 \) of THz wave, \( f_0=c/\lambda_0 \), where \( c \) is the speed of light in vacuum. However, \( L_0 \) monotonically decreases with an increase of \( f_0 \). In the mid-infrared and THz range, the GPM suffers from high absorption loss because the majority of the mode energy is located at the interface between the graphene layer and silicon. As shown in Fig. (2d), \( A_m \) and \( \text{FoM} \) of the GPM with respect to \( f_0 \) are illustrated. Both the normalized mode area and \( \text{FoM} \) increase.
with \( f_0 \). As \( f_0 \) increases, mode energy is gradually dispersed along with the graphene layer, which increases \( A_m \). It also increases the absorption, then causes \( L_p \) to decrease.

To understand the effects of geometric parameters on mode characteristics, \( \text{Re}(n_{\text{eff}}), L_p, A_m \) and \( \text{FoM} \) with different \( g \) and \( t \) are simulated by mode analysis. In the following simulations, \( f_0 \) of 5 THz and \( L \) of 600 nm are chosen. The influences of \( g \), \( t \) and \( F_E \) on mode characteristics are investigated.

The impact on the GPM of \( t \) is shown in (Fig. 3). Here, \( g \) is set as 5 nm, and \( t \) varies from 20 nm to 140 nm. In (Fig. 3a), \( \text{Re}(n_{\text{eff}}) \) and \( L_p \) change slowly with different \( t \). As shown in (Fig. 3b), \( A_m \) increases slightly with the increase of \( t \). However, \( \text{FoM} \) hardly changes when \( t \) increases. Hence, for the fundamental GPM, the thickness of Ag slab has less effect on the propagation length and effective mode area of the TPW-GCBN.

Due to the electric field energy is mainly concentrated in the gap between the graphene layer and Ag slab, \( g \) has a strong impact on the mode field distribution of the GPM. The influences of \( g \) on the GPM is shown in (Fig. 4). Here, \( t=80 \) nm, and \( g \) ranges from 2 nm to 20 nm. (Fig. 4a) presents the changes of \( \text{Re}(n_{\text{eff}}) \) and \( L_p \) with different \( g \). For increasing \( g \), \( \text{Re}(n_{\text{eff}}) \) moderately decreases as the solid red line shown in (Fig. 4a). Meanwhile, \( L_p \) has the same changing trend with \( \text{Re}(n_{\text{eff}}) \). The field enhancement and confinement are able to improve with decrease of the slot width in the slot waveguide. Hence, \( \text{Re}(n_{\text{eff}}) \) and \( L_p \) decrease due to the field enhancement and confinement weaken when \( g \) increases. The increasing also causes \( A_m \) to increase approximately linearly, as shown in (Fig. 4b). Then the \( \text{FoM} \) of TPW-GCBN increases slightly, and then remains almost no change when \( g \) exceeds 14 nm.
In order to investigate the tunability of TPW-GCBN, mode characteristics of the GPM with different $F_E$ are illustrated, as shown in (Fig. 5). Due to the presence of graphene involved in TPW-GCBN, mode characteristics are affected not only by the geometric parameters but also by $\varepsilon_g$ which can be changed by $F_E$. $F_E$ can be adjusted by the voltage applied to graphene. Here, $t=80$ nm, $g=5$ nm, and $F_E$ varies from 0.2 eV to 1.0 eV. As shown in (Fig. 5a), $\text{Re}(n_{\text{eff}})$ decreases with an increase of $F_E$. But $L_p$ increases with $F_E$. The highly doped graphene ($F_E=1.0$) make it exhibit good metallic properties, which is conducive to the propagation of GPM. In (Fig. 5b), both $A_m$ and FoM increase with an increase of $F_E$. $A_m$ enlarges about 27% when $F_E$ ranging from 0.2 eV to 1.0 eV, thus $F_E$ has an obvious influence on $A_m$. Then, the performance of the GCBN can be improved by simply enlarging the Fermi energy.

The comparison between TPW-GCBN and several other similar waveguide structures is listed in Table 1. Compared to other TPWs, TPW-GCBN has minimum $A_{\text{eff}}$. It is of great significance in the field of nonlinear optics. Although $L_p$ reduces due to the addition of graphene, $L_p$ of TPW-GCBN is larger than that of the cylinder based TPW. Moreover, the performances of TPW-GCBN can be adjusted by the voltage applied to graphene.

<table>
<thead>
<tr>
<th>Nanowire Shape</th>
<th>Core</th>
<th>Cladding</th>
<th>Coating Material</th>
<th>Substrate</th>
<th>$L_p(\mu m)$</th>
<th>$A_{\text{eff}}$</th>
<th>$\text{FoM}$</th>
<th>References</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cylinder</td>
<td>Si</td>
<td>SiO$_2$</td>
<td>-</td>
<td>Ag</td>
<td>11000</td>
<td>$\lambda^{2}/205$</td>
<td>117</td>
<td>[31]</td>
</tr>
<tr>
<td>Cylinder</td>
<td>SiO$_2$</td>
<td>Air</td>
<td>graphene</td>
<td>Si</td>
<td>12.1</td>
<td>-</td>
<td>113.4</td>
<td>[32]</td>
</tr>
<tr>
<td>Bow-tie</td>
<td>Si</td>
<td>SiO$_2$</td>
<td>-</td>
<td>Ag</td>
<td>1196</td>
<td>$\lambda^{2}/2353$</td>
<td>-</td>
<td>[33]</td>
</tr>
<tr>
<td>Bow-tie</td>
<td>SiO$_2$</td>
<td>air</td>
<td>graphene</td>
<td>Ag</td>
<td>20</td>
<td>$\lambda^{2}/14812$</td>
<td>25</td>
<td>This work</td>
</tr>
</tbody>
</table>
Compared with the plasmonic waveguides without graphene, the waveguide performances can be adjusted by changing the gate voltage of the transparent electrodes. It can be used as electro-optic modulation, optical attenuation and optical switching.

CONCLUSION

In summary, mode characteristics of TPW-GCBN in the THz frequency band are investigated by FEM. The influence of the geometric parameters on propagation constants, electric field distributions, effective mode areas, and propagation lengths are obtained numerically. Meanwhile, the performance tunability of TPW-GCBN is also studied by adjusting $F_E$. The simulation results show that, the proposed TPW-GCBN has better mode confinement lengths obtained numerically. Meanwhile, the performance tunability of TPW-GCBN is also studied by $A_{eff}$ of $\lambda^{2}/14812$ and $L_p$ of 20um at $f_0 = 5$THz are obtained, the FoM is $\sim 25$. The proposed TPW-GCBN has better mode confinement ability because of the small $A_{eff}$. The performances of TPW-GCBN can be adjusted by voltage applied to graphene. TPW-GCBN has potential applications in high-density integration of photonic circuits for future tunable micro nano optoelectronic devices.

CONSENT FOR PUBLICATION

Not applicable.

AVAILABILITY OF DATA AND MATERIALS

Not applicable.

FUNDING

This work is supported in part by the National Natural Science Foundation of China (No. 61627818), the scientific and technological project of Henan province (182102210367), the Key Project of Henan Education Department (19A510002), the Cultivation Foundation for National Project of Henan Normal University (2017PL04), and the Ph. D. Program of Henan Normal University (HNU) (gd17167 and 5101239 170010).

CONFLICT OF INTEREST

The authors declare no conflict of interest, financial or otherwise.

ACKNOWLEDGEMENTS

We gratefully acknowledge Heng Liu for her invaluable contributions in figures improvement.

REFERENCES


