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Research Paper

Investigating factors affecting loss reduction in graphene-based plasmonic structures

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Abstract

In graphene-based plasmonic structures, the path length traveled by surface plasmon polaritons (SPP) or the propagation length of plasmons is very important .So that the longer the plasmon propagation length in a structure is, the better that structure will perform .Therefore, it is very important to know the factors affecting the propagation length of plasmons. One of the effective factors in increasing the propagation length of plasmons is reducing the losses of the graphene-based plasmonic structure. The losses of these structures depend on the amount of chemical potential used for graphene and the material of the substrate used in the structure. Therefore, in this work, the effect of the chemical potential and the type of different substrates on the loss of the structure in the wavelength range of 8 to 12 micrometers has been investigated. According to the results obtained in this paper, by using a chemical potential of 1eV for graphene and using glass as a substrate, it is possible to reduce the losses of the structure and thus increase the emission length.

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1. INTRODUCTION

Surface plasmon polariton (SPP) is an electromagnetic excitation that occurs at the metal-semiconductor interface [1] and is used to control light flow at nanoscale [2]. The surface plasmons of metals have TM polarization and due to surface roughness and interband absorption, they will drop a lot and have a very short emission length [3], Therefore, in order for plasmons to have a longer propagation length, graphene is used instead of metal.

Graphene is a thin material with a thickness of one atom and a network in the shape of a honeycomb [4]. This material is a Pseudo-metal or a semiconductor with zero energy gap [5], which has attracted the attention of researchers in various fields of medicine [6], electrical [7], materials [8], chemistry [9], etc. due to its unique properties.

Features such as confinement of SPPs and having both TE and TM polarizations have made graphene-based plasmonic waveguides superior to other waveguides [10]. Also, according to the investigations, graphene is the only material that can well receive SPPs in the range of 0.1 to 10 terahertz and emit them with low losses. Therefore, today, the design of plasmonic devices based on graphene, such as flip-flop [11], switch [12], biosensor [7], sensor [13], transistor [14, 15], and multiplexer [16], has attracted the attention of researchers.

The terahertz range is a part of the electromagnetic spectrum that includes the wavelength range of 1mm to 700nm and the frequency range of 300GHz to 430THz [17]. The atmosphere passes part of the electromagnetic energy and the other part is absorbed by the molecules in the atmosphere (Such as ozone, carbon dioxide and water vapor) and converted into heat. The amount of energy absorption is different in different wavelengths of the electromagnetic spectrum. So that in the terahertz range, the wavelength range of 8µm to 12µm has the least absorption and the most transmission in the earth's atmosphere [18], hence the devices made in the terahertz range usually work in this wavelength range.

One of the important points in the design of graphene-based plasmonic devices is to design the structure in such a way that SPPs have the longest propagation length (L_{spp})**,** Because the increase in the L_{spp} of SPPs (Surface Plasmon Polaritons) leads to an improvement in the performance of the structure, one of the factors affecting the propagation length of SPPs is the losses in the structure. The lower the losses in the structure, the greater the propagation length of the SPPs will be. Therefore, identifying the factors that cause losses in graphene-based plasmonic structures is of great importance. Hence, this paper will investigate the factors that cause losses in graphene-based plasmonic structures. The focus of this research is on the impact of the substrate material and the chemical potential on the amount of losses.

It seems that by using the results of this research, it is possible to design an optical structure with minimal losses and maximum propagation length, and consequently a structure with good performance, by selecting the appropriate substrate and chemical potential.

2. LOSSES

Equation (1) is used to calculate losses [19]. Where C is The speed of light in vacuum, K(w) is The imaginary part of the refractive index (n_{eff}) and w is angular frequency.

$$\alpha(w) = \frac{2\,K(w)\,w}{c} \tag{1}$$

According to this equation, the loss depends on the n_{eff}, and the smaller the imaginary part of the n_{eff}, the lower the loss.

According to the equation (2), the n_{eff} is a complex parameter whose real part is called the effective n_{eff} and its imaginary part is called the absorption coefficient and is related to the absorption of light waves [20].

$$N(\omega) = n(\omega) + jK(\omega) \tag{2}$$

According to relation (3), the n_{eff} and electrical conductivity are related to each other, so according to relations (4) and (5), the real and imaginary part of the n_{eff} can be related to the real and imaginary part of the electrical permittivity.

$$N(\omega) = \sqrt{\varepsilon(\omega)} \tag{3}$$

$$n(\omega) = \frac{\varepsilon_{real}}{2} + \frac{1}{2}\sqrt{\varepsilon_{real}^2 + \varepsilon_{image}^2} \tag{4}$$

$$K(\omega) = \frac{\varepsilon_{image}}{2n(\omega)} \tag{5}$$

The electrical conductivity of graphene consists of two parts, real and imaginary. Based on Kramers-Kronig's method, the electrical conductivity can be obtained from the following relations [21].

$$\varepsilon_{real}(E,\Gamma,\mu_c) = 1 + \frac{q^2}{8\pi E\varepsilon_0\hbar_g}\,ln\frac{(E+2|\mu_c|)^2+\Gamma^2}{(E-2|\mu_c|)^2+\Gamma^2} - \frac{q^2|\mu_c|}{\pi\varepsilon_0\hbar_g(E^2+\tau^{-2})} \tag{6}$$

$$\varepsilon_{image}(E,\Gamma,\mu_c)=\frac{q^2}{4\pi E\varepsilon_0\hbar_g}\left[1+\pi^{-1}\left\{tan^{-1}\frac{E-2|\mu_c|}{\Gamma}-tan^{-1}\frac{E+2|\mu_c|}{\Gamma}\right\}\right]+\frac{q^2|\mu_c|}{\pi E\varepsilon_0\tau\hbar_g(E^2+\tau^{-2})} \quad (7)$$

where E is Radiant photon energy, h_g=1nm is The thickness of the graphene layer, τ^{-1} is the dispersion rate of carriers which is usually considered equal to zero and μ_c is chemical potential.

The chemical potential or Fermi level is the factor that changes the conductivity of graphene. This parameter is calculated from equation (8).

$$|\mu_c|\approx \hbar\, \nu_F\sqrt{\pi a_0\mid V_b-V_0\mid} \quad (8)$$

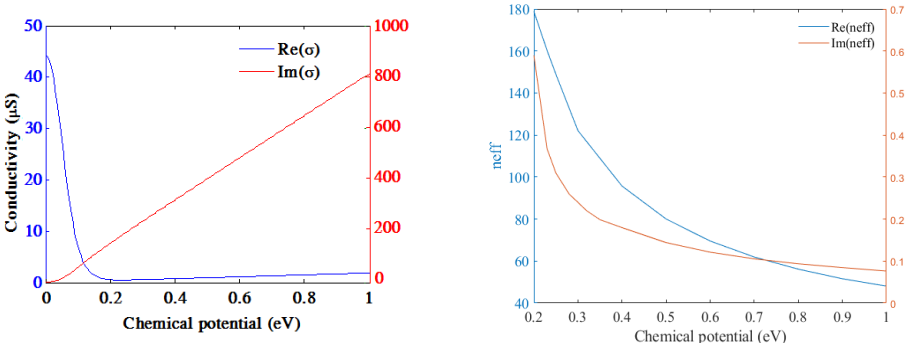
where, ħ is the Planck's reduced constant, $\nu_F = 0.9\times10^6$ ms^{-1}, $a_0=9\times10^{16}$ $m^{-2}V^{-1}$, Vb is the bias voltage and V_0 is the offset voltage caused by natural doping (V_0=0.8 V).

2.1. LOSSES IN GRAPHEN

We know that for $|\mu_c| > \hbar\omega/2$ the ε_{image} is positive and graphene behaves like an extremely thin metal and TM polarization is established. For $|\mu_c| < \hbar\omega/2$, the ε_{image} is negative and graphene behaves like an dielectric and TE polarization is established [22].

Therefore, in order to reduce the losses in graphene, the ε_{image} of the graphene surface should be positive. Therefore, according to the equation (7), it is expected that with the increase of the chemical potential, the ε_{image} of the graphene surface will become more positive and as a result, the conductivity of graphene will increase (show in Fig.1a).

In Fig. 1b, the chemical potential diagram was drawn in terms of the n_{eff} of graphene. According to this diagram, with the increase in the chemical potential, the K(ω) decreases. Therefore, according to equation (1), with the increase in the chemical potential, the amount of losses decreases.



(a) (b)

Fig.1 (a) The graphene surface conductivity versus μ_c and (b) the n_{eff} versus the chemical potential

The selected wavelength for graphene is another factor that reduces losses in graphene. In order to achieve the lowest losses in graphene, the working wavelength of the input light must be selected in such a way that it is below the limit of optical phonon emission. Therefore, the working wavelength must be greater than the optical phonon wavelength, and due to the inverse relationship between wavelength and frequency (show in equation (9)), the working frequency must be smaller than the optical phonon emission frequency [23].

$$\lambda=\upsilon/f \quad (9)$$

where v is wave speed, f is wave frequency and λ is wavelength.

2.2. INVESTIGATING LOSSES SUBSTRATE USED IN THE DESIGN OF OPTICAL DEVICES

Due to the fact that the amount of losses of the substrate used in the design of optical devices is different in the range of 8μm to 12μm wavelengths, therefore, choosing the substrate that has the lowest losses in this wavelength range is of particular importance. Therefore, in this section, the amount of losses of conventional substrates in the design of optical structures in the wavelength range of 8μm to 12μm will be investigated.

In the design of plasmonic devices based on graphene, various substrates such as Si [24, 25] SiO_2 [26], SnO_2 [27], Glass [28], Al_2O_3 [29] are used, therefore, it is very important to determine which of these substrates has the lowest losses in the range of 8μm to 12μm wavelengths. To check the amount of losses of different substrate in this wavelength range, the structure in Fig. 2 was simulated in Lumerical software, and then the loss graph was drawn in terms of wavelength for different substrate (show in Fig.3). The waveguide width used in the proposed structure is 50 nm. According to the reference [30], fabrication of

the graphene waveguides with a width of 50 nm is possible. The thickness of the graphene used for the waveguide is 2 nm [31].

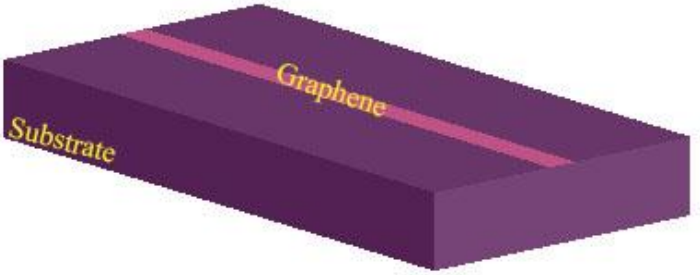


Fig. 2 A view of the structure used for simulation

According to the obtained results, in the wavelength range of 8μm to 12μm, glass has the lowest losses and SiO_2 has the highest losses, so it seems that using a glass substrate in graphene-based plasmonic structures is the best choice.

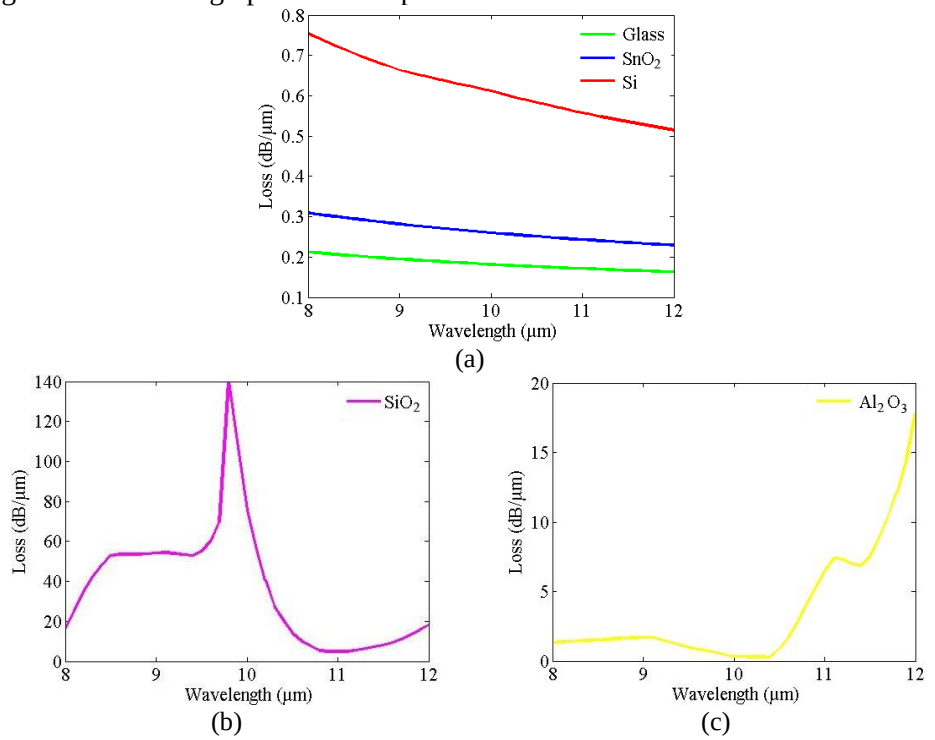


Fig. 3 Loss versus the wavelength for different substrates at μ_c =1eV

One of the important points in the design of graphene-based plasmin structures is to have the maximum possible propagation length.

For the practical measurement of the propagation length, one can use the far field microscopes, PSTM-microscope, LRM-microscope [32], and equation (10) can be used to calculate it theoretically [33]:

$$L_{SPP} = \frac{\lambda_0}{2\pi\ Im(n_{eff})} \tag{10}$$

Where λ_0 is Input wavelength. To ensure the results obtained in this article, the structure presented in Fig 2 was simulated for the glass substrate and the constant chemical potential of 1eV, and for the wavelength range of 8μm to 12μm graphs related to losses and propagation length were drawn. According to this diagram, as the wavelength increases, the loss decreases and the propagation length increases.

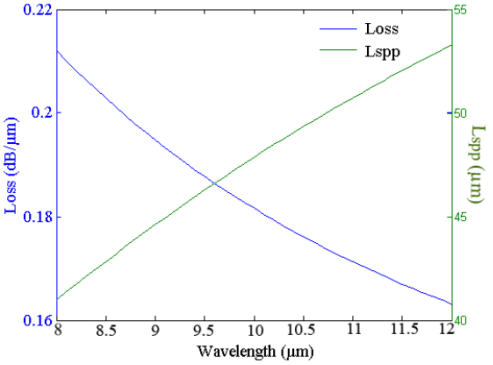


Fig. 4 Propagation length and loss versus the wavelength at a chemical potential of 1eV

3. CONCLUSION

One of the effective factors in increasing the propagation length of plasmons in graphene-based plasmonic structures is the reduction of losses. The losses of these structures depend on the amount of chemical potential applied to graphene and the type of substrate used. According to the results obtained in this article, by setting the chemical potential of graphene on 1eV and using glass as a substrate, the losses of graphene-based plasmonic structures can be minimized.

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