SENSOR LETTERS
Vol. 15, 249–252, 2017

RESEARCH ARTICLE

Dispersion Characteristics and Sensitivity Properties of Graphene Surface Plasmon Sensor

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(Received: 22 December 2016. Accepted: 31 January 2017)

In this work, dispersion characteristics and sensitivity of the propagation of TM surface plasmon through the proposed waveguide sensor. The proposed sensor containing a graphene at a finite distance filled with metamaterials (MTM) from plasmonic layer and sandwiched by dielectric layers. We numerically demonstrate the proposed waveguide structure as a novel graphene surface plasmons sensor. The obtained results can be useful for enhancing the sensitivity of plasmonic—graphene devices which could be used in further application in biosensing and environmental control.

Keywords: Graphene, Metamaterial, Biosensing, Plasmonic Waves.

1. INTRODUCTION

In recent years, various waveguide containing graphene has been implemented and acted as sensors for biomedical and environmental control applications. Graphene is considered as a single-atom thick packed into a dense 2-Dimensional honeycomb crystal lattice which has attracted consideration and attention in terms of theory and experiments due to its remarkable optical, electronic, mechanical and thermal properties.[1–4] These physical properties are leading to new concepts and applications in optoelectronics technology as solar cells and integrated optical sensors. Recently, graphene has rapidly been considered as a suitable alternative candidate of generating surface plasmon to usual noble materials. This is due to the possibility of controlling and tuning generated surface plasmon through the proposed waveguide structure.

Hanson[2] had investigated the propagation characteristics of TM waves through the parallel-plate waveguide structure composed of graphene showing that the structure can guide quasi-transverse electromagnetic modes with attenuation similar to structures composed of metals. Optimization of waveguides based on surface plasmons in double-layer graphene (DLG) has been derived and achieved taking into account the effects of both extrinsic scattering and intrinsic Landau damping.[3,4] Coupled surface plasmon modes of graphene bounded a plasma substrate have been investigated showing great tunability of plasmon characteristics by changing the surrounding substrate permittivity.[3–5] Graphene-silicon waveguide structure sensors have been reported with some optimized physical parameters.[6] The dispersion characteristics of electromagnetic waves propagating in Graphene multilayered structures have been discussed and analyzed.[7]

Recently, various waveguide structures containing graphene have been implemented and acted as novel sensors for biomedical and environmental control applications. Surface Plasmon Resonance (SPR) plays a key role in the concept of sensing in waveguide sensor structure. The technique of the SPR sensors depends on a refractive index variation in the cover layer or sensing medium due to the changes of the effective wave index. Different waveguide sensor structures with graphene materials have also been reported and investigated.[6–14] El-Khozondar et al.[8] had reported the numerical investigation of an optical sensor containing graphene in more details. The fabrication of a graphene integrated waveguide sensors has also been demonstrated as a photodector for biochemical applications.[9]

Other waveguide structure with graphene bounding an isotropic dielectric media and water has been analyzed and discussed to find out the effects of some physical parameters of the considered structure.[9–15] A surface Plasmon resonance waveguide structure containing germanium nanowires bounded by three graphene layer has

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been investigated for enhancement of biosensor sensitivity with high absorbing molecules on the sensor surface.[10] Inverted surface plasmon resonance (ISPR) concept has been implemented through waveguide structure containing an absorbent metal thin films and a graphene sheet for bio sensing.[11] Waveguide sensors with low index dielectric (Teflon) and graphene in a dielectric-metal-dielectric configuration at near infrared region have been demonstrated.[12]

Metamaterials or Left Handed materials had initially been predicted more than fifty years ago by Veselego and have been realized experiemently about twenty years ago.[16–18] These artificial materials have unusual physical properties as having both negative permittivity and permeability leading to Negative index materials. They have extensively been used in some optoelectronic applications such as optical sensors. Some works had also been reported on various configuration sensors containing both metamaterials and graphene showing some high values of sensitivity.[8] Sensitivity evaluation of graphene-left handed waveguide sensors has been reported to determine the effects of artificial left handed materials on the graphene sensors.

The recipe of the work depends on the solution of the Maxwell's equations in each layer of the structure and then imposing the boundary conditions on the proposed structure to get the dispersion characteristics equation. The roots of the dispersion characteristics are computed to find out the dependence of effective index on the operating frequency. The roots of the dispersion are fed into the sensitivity standard formula to find the relation between the sensitivity and the frequency.

The focus of this paper is on TM surface plasmon-graphene technology. It will discuss and evaluate the dispersion characteristics and the sensitivity of waveguide structure composed of graphene at distance from plasma substrate. In the next section, the proposed structure and theory will be presented followed by results and discussion. Then, the conclusion is given.

2. PROPOSED STRUCTURE AND THEORY

Figure 1 displays a 4-layer waveguide sensor composed of a graphene thin film having conductivity (σ) placed at a distance d_2 above a plasma surface with thickness d_1. The plasma layer is laying above a dielectric with permittivity (ε_1) and the graphene layer is covered with dielectric material having permitivity ε_3 and permeability μ_3. The plasma layer has permitiviy constant (ε_p) which can be described by the following formula

$$\varepsilon_p = \varepsilon_0\left(1 - \frac{\omega^2}{\omega_p^2}\right) \tag{1}$$

where ε_0 is the vacuum permittivity and ω_p is the plasma frequency, and ω is the angular frequency of the applied field. The space between the graphene layer and the plasma layer is filled with metamaterials (MTM) with negative permitivity ε_2 and negative permeability μ_2. In this structure, the value of $\varepsilon_2\mu_2 = 4$.[19]

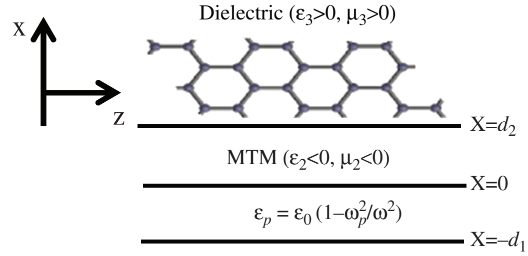

Fig. 1. The proposed structure. The field is assumed to travel a long the *x*-axis.

The dispersion Eq. (2) can be derived by solving Maxwell's equations and applying the boundary conditions.

$$\frac{\gamma_2\gamma_p\varepsilon_1 + \gamma_1\gamma_2\varepsilon_p\tanh(\gamma_p d_1)}{\varepsilon_2\gamma_2\Gamma + \gamma_3\varepsilon_2\tanh(\gamma_2 d_2)} + \frac{\gamma_1\gamma_p\varepsilon_p + \gamma_p^2\varepsilon_1\tanh(\gamma_p d_1)}{\gamma_3\varepsilon_p + \Gamma\gamma_2\varepsilon_p\tanh(\gamma_2 d_2)} = 0 \tag{2}$$

Where $\Gamma = (\varepsilon_3/\varepsilon_2) + i(\sigma q/\omega\varepsilon_2)$, $q^2 - \gamma_i^2 = \varepsilon_i\omega^2/(\varepsilon_0 c^2)$ $(i = 1, 2, 3, p)$, c is the speed of light, and σ is the optical conductivity of the graphene sheet which is considered constant. The dispersion equation can be simplified by ignoring the retardation effect since c is much lager than the Fermi velocity of the graphene. Therefore, Eq. (2) can be rewritten as follows

$$\varepsilon_p\frac{\varepsilon_1 + \varepsilon_p\tanh(qd_1)}{\Gamma + \tanh(qd_2)} + \varepsilon_2\frac{\varepsilon_p + \varepsilon_1\tanh(qd_1)}{1 + \Gamma\tanh(qd_2)} = 0 \tag{3}$$

The sensitivity is defined as the change in effective index with respect to the cladding index.[20] The sensitivity is derived from the above equation by differentiating q with respect to ε_3 as follows

$$S = \frac{dq}{d\varepsilon_3} = \frac{D_1}{D_2} \tag{4}$$

where

$$D_1 = \frac{X}{\varepsilon_2 X_2} + \frac{Y}{\varepsilon_2 Y_2}\tanh(qd_2)$$

$$D_2 = \frac{\varepsilon_p^2 d_1 \sec h^2(qd_1)}{X_2} - d_2\sec h^2(qd_2)\frac{X}{X_2} + \frac{\varepsilon_1\varepsilon_2 d_1\sec h^2(qd_1)}{Y_2} - \frac{Y}{Y_2}\Gamma d_2\sec h^2(qd_2)$$

$$X = \varepsilon_p\frac{X_1}{X_2}, \quad Y = \varepsilon_2\frac{Y_1}{Y_2}$$

$$X_1 = \varepsilon_1 + \varepsilon_p\tanh(qd_1), \quad X_2 = \Gamma + \tanh(qd_2)$$

$$Y_1 = \varepsilon_p + \varepsilon_1\tanh(qd_1), \quad Y_2 = 1 + \Gamma\tanh(qd_2)$$

To calculate the sensitivity, we first solve Eq. (3) for q then these values are used to solve Eq. (4).

3. RESULTS AND DISCUSSION

Equation (3) is solved numerically for $d_1 = d_2 = 5$ μm, and $\sigma = 6.089\text{E–}6$ Siemens using Maple at different values of ε_2. Figure 2 shows the real part of propagation constant ($Re(q)$) as a function of frequency at $\varepsilon_2 = -1$ (red curve), $\varepsilon_2 = -2$ (blue curve), and $\varepsilon_2 = -4$ (black curve). It can be seen from Figure 2 that when the absolute value of ε_2 increases the value of $Re(q)$ decreases as expected from Eq. (3).

Moreover, at certain frequency (around 1.43E14 Hz), q has a maximum value. For $\varepsilon_2 = -1$, q has another maximum around 2.14E14 Hz. At low frequency, Γ becomes pure imaginary. This implies that $Re(q)$ approaches zero as ω gets smaller. At $\omega = \omega_p$, $\varepsilon_p = 0$ and the solution of Eq. (3) is zero. The previous calucation is repeated keeping all the variables the same and changing σ to have the value of 6.089E–5. The $Re(q)$ is plotted as a function of frequency in Figure 3. It is observed from Figure 3 that when $\varepsilon_2 = -1$ a third peak appears at which the value of ($Re(q)$) increased dramatically.

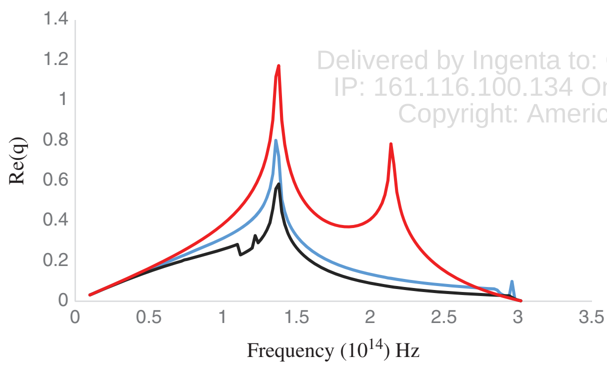

Fig. 2. The real part of the propagation constant as function of frequency at $\sigma = 6.089\text{E–}6$ at different values of ε_2. The red curve is for $\varepsilon_2 = -1$, the blue curve is $\varepsilon_2 = -2$, and the black is for $\varepsilon_2 = -4$.

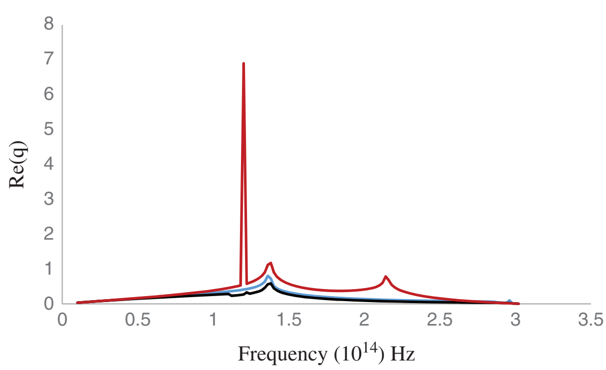

Fig. 3. The real part of the propagation constant as function of frequency at $\sigma = 6.089\text{E–}5$ at different values of ε_2. The red curve is for $\varepsilon_2 = -1$, the blue curve is $\varepsilon_2 = -2$, and the black is for $\varepsilon_2 = -4$.

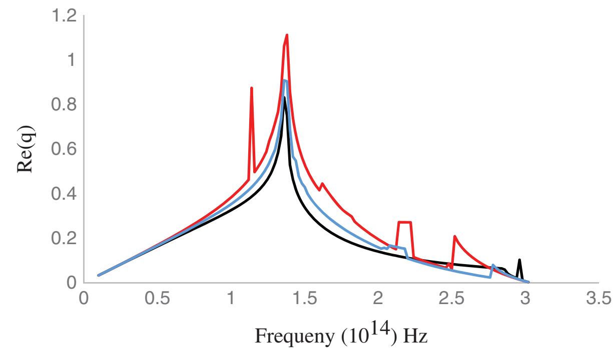

Fig. 4. The real part of the propagation constant as function of frequency at $\sigma = 6.089\text{E–}6$, $\varepsilon_2 = -1$, $d_1 = 5$ μm, and at different values d_2. The red curve is for $d_2 = 1$ μm, the blue curve is for $d_2 = 3$ μm, and the black curve is for $d_2 = 5$ μm.

The dependence of $Re(q)$ on frequency is exhibited in Figure 4 at values of $d_1 = 5$ μm, $\sigma = 6.089\text{E–}6$, $\varepsilon_2 = -1$ for different values of thickness d_2. The values of d_2 are: 1 μm (red curve), 3 μm (blue curve), and 5 μm (black curve). It can be seen from Figure 4 that as d_2 increases the value of $Re(q)$ decreases. Comparing Figure 4 with Figure 2, we can see that the changes in the value of $Re(q)$ is small.

Further, we calculated the sensitivity at different values of d_2 using the following values: $\sigma = 6.089\text{E–}6$, $\varepsilon_1 = 3.9$, $\varepsilon_2 = -1$, $\varepsilon_3 = 1$, $d_1 = 5$ μm and at $\omega = 1.36\text{E}14$ Hz. The values of $Re(q)$ is obtained from Eq. (3) and substituted into Eq. (4) to get the sensitivity. The variation of the sensitivity (S) with d_2 is illustrated in Figure 5. The sensitivity has a maximum value at $d_2 = 861$ nm and decrease as the values of d_2 increases. S reaches its minimum value at $d_2 = 4401$ nm.

Figure 6 displays the sensitivity (S) as a function of ε_2. It is obvious from Figure 6 that the sensitivity changes its value as ε_2 changes. Moreover, S has positive and negative values indicating that the proposed sensor is sensitive to both positive and negative changes.

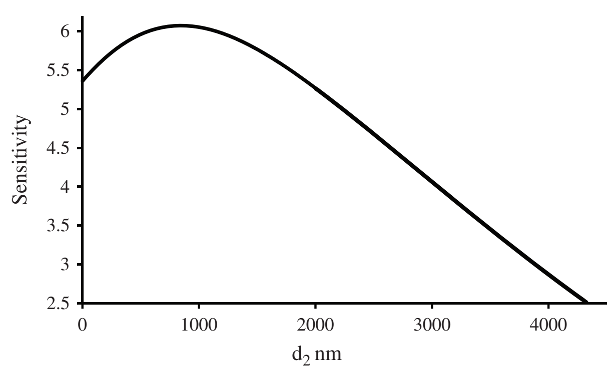

Fig. 5. The sensitivity is plotted as function of d_2. Calculation is performed for $\sigma = 6.089\text{E–}6$, $\varepsilon_1 = 3.9$, $\varepsilon_2 = -1$, $\varepsilon_3 = 1$, $d_1 = 5$ μm, $\omega = 1.36\text{E}14$ Hz, and at different values of d_2.

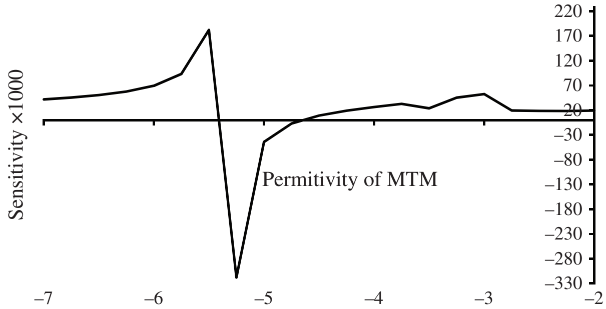

Fig. 6. The sensitivity is plotted as function of ε_2. Calculation is performed for $\sigma = 6.089\text{E–}6$, $\varepsilon_1 = 3.9$, $\varepsilon_3 = 1$, $d_1 = d_2 = 5\ \mu\text{m}$, $\omega = 1.36 \times 10^{14}$ Hz.

4. CONCLUSION

We have studied the influence of the Graphene on the sensitivity enhancement of the proposed sensor which is composed of Graphene, MTM, plasma and dielectric substrate and cladding. The results reveal that the Graphene plasmon concepts. Inaddition, the considered configuration is a promising candidate for further improvement of the optical sensors performance.

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