Characteristics of the SPP Modes in GOLD-filled Graphene Parallel Plate Waveguide

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ABSTRACT:

Plasmonic structures which are strongly confine electromagnetic wavesat the metal-dielectric boundary investigated theoretically and experimentally, can be a possible solution of implementation of Nano photonic circuit's problem. Frequency dependent dielectric function of double negative materials and gold has substantial effect on the precision of explanation of optical properties. In this research, we proposed plasmonic parallel plate waveguide of graphene placed between double negative materials (DNM) and filled with gold (Au). Dispersion relation that defined the propagation properties below and above the cut off frequency at THz region derived using Lorentz Drude model which helped to find the permittivity of gold and DNM. Existence of Surface Plasmon Polariton (SPPs) of graphene structure and its the TM modes discussed due to highly confinement, illustrated using cutoff height by Lorentz Drude model which were the most authentic methodologies used for analysis of different lossless and lossy medium in photonics. Propagation properties of graphene structure, investigated when operation frequency near and far away from cut off frequency. The complete analysis offered some strategies for improvement to the design of sub-wavelength optical devices.

Keywords: Terahertz frequency, Propagation constant, Double negative material, Graphene plates

INTRODUCTION:

Light (electromagnetic wave) has arisen as one of the best, most powerful transporters and reliable supporters for the observation and manipulation of huge volume data at the nano-scale (Yang and Lu, 2012). Electromagnetic (EM) field confines in the form of propagating and localized Surface-Plasmons (Artar*et al*., 2009) at a metal-dielectric interface explained by the result of Maxwell equations (Zayats*et al*., 2005). A Surface Plasmon Polariton(SPP)is a strong interaction between collective charge oscillation and EM field present at the surface of noble metal (Zayats *et al*., 2004), its wavelength is much smaller than the wavelength of light (electromagnetic waves) that propagates in free space (Sharma *et al*., 2012).It is two-dimensional excitation whose EM field falling-off exponentially through distances starting from the surface. The magnetic field of an SPP is parallel to the surface and perpendicular to its direction of propagation. The SPP cannot radiate light into the dielectric medium, and cannot be excited with conventional illumination from the adjacent dielectric (Zayats *et al*., 2005) Conventional materials with real negative electric permittivity can control SPPs along metal-dielectric boundary but material with negative magnetic permeability and electric permittivity give SPPs with unique characteristics of the electromagnetic field that is not present in conventional media(Cuevas *et al*., 2016).A significant part of the investigation is to combine fields of electronics, and photonics at the nano-scale characterized vianegative dielectric function show relatively small propagation losses (Pitarke*et al*., 2008). Left-handed materials (LHMs) were first presented by Veselago in 1968 at a specific frequency range which givesa theoretical understanding interaction of the EM field with this material in 2000 assembled by Smith and his colleagues. LHMs with double negative media (Taya *et al*.,2016) at optical frequencies, known as plasmonic metamaterials (Cui *et al*.,2014),and nano-particle of gold have received much attention to planning novel devices support the SPPs mode(Derkachova *et al*.,2016).Recent interest in the investigation of grapheneapplications greatly enhanced due to its unique and interesting optical properties especially because it absorbs large amountsof white light and devices based on graphene structure operated at terahertz (THz) regime. Graphene sheet strongly supported SPPs at terahertz regime also control it by changing chemical doping or gate voltage (Li *et al*., 2016).Highly confinement, as a result of interaction between electromagnetic field and artificial guided mode propagation graphene structures depends upon how the surface of the metal is designed (Buslaev*et al.*, 2013).An artificially designed two-dimensional structure consisting of a hexagonal lattice of carbon atoms with one atom thickness, that exhibited exceptional optical properties, low losses, high carrier mobility, tunability unique conductivity which makes it valuable and provided a new path for THz and photonic applications at nano-scala (Hosseininejad and Komjani. 2016).Dispersion of localized SPPs waves by grapheme monolayer (support TE and TM modes) falling in the THz frequency range. A significant property of graphene is to efficiently control dispersion and propagation characteristics (Buslaev*et al.*, 2013).Except for electronic properties that are extensively investigated in the modern era, above all our concern is to study the photonic properties of LHM.

However, current research work has been related to the dispersion features obtained using the Lorentz Drude model of TM modes in the graphene slab waveguide filled with gold sandwich between double negative media. Propagation and dependency of propagation properties at THz frequency of SPPs field is investigated by its dispersion relation. The structured graphene surface acts as an effective medium which can lead to highly confined terahertz-guided mode propagation. The eigenvalue of TM of the graphene guide is analyzed by using continuity conditions.

MATERIALS AND METHOD:

Maxwell'sequations

Maxwell's equations are playing a very crucial part in solving the theory of the field of electromagnetism and optics. James Clerk Maxwell a Scottish mathematician and physicist reformed Ampere's Law as he presented the idea of current displacement. First, in 1861, he developed a set of eight equations, and then in 1862, these equations were termed Maxwell's equations after him, the current version of Maxwell's equations contains four equations. J, Willard Gibbs, and Oliver Heaviside reorganized this set of equations. Equations set up through all these laws were experimentally confirmed by Heinrich Hertz in 1887. Hertz ensured this job. David J. Griffiths admired the work of Maxwell in the light of his equations in the following words.

SPPs in Graphene

Fig 1 shows an arrangement of Nano size graphene monolayer with thickness $d$on the upper and lower surfaces coated with LHM whose permittivity and permeability areϵ and μ respectively.The optical conductivity of graphene helps to investigate the photonic properties. Generally, two portions, inter-bands, intra-band used to definethe conductivity of Graphene and denoted as;

$$\sigma\mathrm{g} = i\frac{T\mathrm{KB}e^{2}}{\pi h^{2}\left(\omega + \frac{i}{\Gamma 1}\right)}\left(\frac{\mu}{\mathrm{KB}T} + 2\mathrm{Log}\left[10, \mathrm{Exp}\left[-\frac{\mu}{\mathrm{KB}T}\right] + 1\right]\right) + i\frac{e^{2}}{4\mathrm{Pi}h}\mathrm{Log}\left[10, \frac{2\mathrm{Abs}[\mu] - h\left(\omega + \frac{i}{\Gamma 2}\right)}{2\mathrm{Abs}[\mu] + h\left(\omega + \frac{i}{\Gamma 2}\right)}\right] \quad (1)$$

.

Here $\hbar$ is the reduced Plank constant, e electronic charge, τ momentum relaxation time, μ chemical potential,$\omega$is the optical frequency,k_BBoltzmann constant and T are temperaturesrespectively. Neglect the inter-band conductivity due to low transitions loss (Baqir and Choudhury, 2017).It has been known that the real part of the equivalent permittivity becomes negative when graphene dynamical intra-band conductivity has a positive imaginary part, resulting in the possibility of generation of the SPPs in graphene(Li *et al.*, 2016)all devices were functioning at THz frequency.

The direction of the electric field is along the x-axis and the magnetic field is along the y-axis. SPPs exponentially decay along the x-axis (+ *x* and –*x)* directions, and along the *y*-axis field were homogeneous. The wave mode propagated along the *z*-direction.

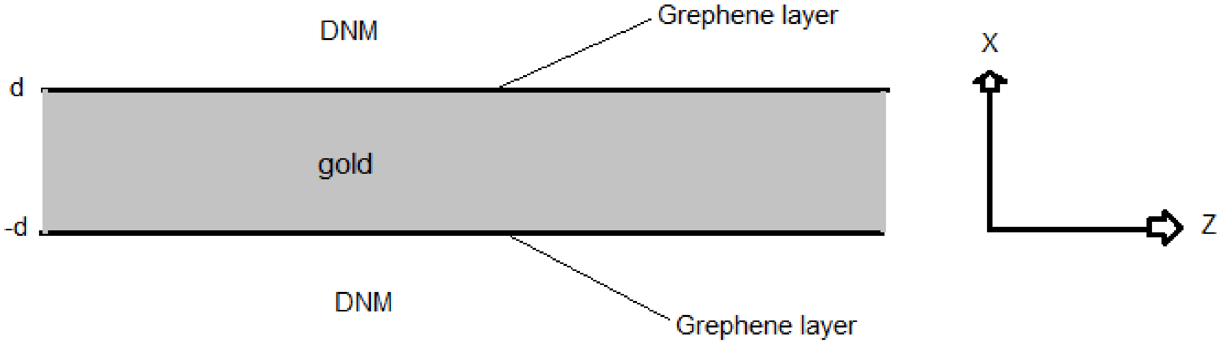

Figure 1 the parallel graphene structure placed in DNM

A surface plasmonpolariton has both transverse and longitudinal electromagnetic field components. This structure supported both transverse magnetic (TM) and transverseelectric (TE) modes. Here we discussed the TM modes due to highly confinement than TE. So, without dropping generality we have the TM field component with β (propagation constant) written as;

For x > d

$$H_y = Ae^{-\gamma x}e^{i\beta z} \qquad (2)$$

$$E_z = A\frac{-i\gamma}{\omega\varepsilon_p}e^{-\gamma x}e^{i\beta z} \qquad (3)$$

for d< x >d

Even mode

$$H_y = B(\cos\alpha x)e^{i\beta z} \qquad (4)$$

$$E_z = B\frac{\alpha}{i\omega\varepsilon_{au}}(\mathrm{Sin}\alpha x)e^{i\beta z} \qquad (5)$$

Odd mode

$$H_y = C(\mathrm{Sin}\alpha x)e^{i\beta z} \qquad (6)$$

$$E_z = C\frac{-\alpha}{i\omega\varepsilon_{au}}(\cos\alpha x)e^{i\beta z} \qquad (7)$$

For x < d

$$H_y = De^{\gamma x}e^{i\beta z} \qquad (8)$$

$$E_z = D\frac{i\gamma}{\omega\varepsilon_p}e^{\gamma x}e^{i\beta z} \qquad (9)$$

Whereωis the incident frequency $k_0 = \omega\sqrt{\epsilon_0\mu_0}$is the free-space wave number the attenuation constant and A, B, C, and Dare undetermined coefficients. The boundary conditions are given by the continuity *atx* = d and Ampere's law(Gu, 2013).

First boundary condition

$$E_z|_{x=d^+}{}^- = E_z|\,|_{x=d^-} \qquad (10)$$

2nd boundary condition is

$$H_y|_{x=d^+} - H_y|_{x=d^-} = \sigma = E_z|_{x=d} \qquad (11)$$

This is the required dispersion relation in account DNM of the TM mode written as;
We get

$$\mathrm{B}\sin\alpha\mathrm{d} = \mathrm{A}\frac{\gamma\varepsilon_{\mathrm{au}}}{\alpha\epsilon\mathrm{p}}\mathrm{e}^{-\gamma\mathrm{d}} \qquad (12)$$

$$\mathrm{B}\cos\alpha\mathrm{d} = \mathrm{A}\mathrm{e}^{-\gamma\mathrm{d}}\left(1+\frac{\mathrm{i}\sigma\gamma}{\omega\epsilon\mathrm{p}}\right) \qquad (13) \qquad \mathrm{C}\cos\alpha\mathrm{d} =$$

$$-\mathrm{D}\frac{\gamma\varepsilon_{\mathrm{au}}}{\alpha\varepsilon_{\mathrm{p}}}\mathrm{e}^{\gamma\mathrm{d}} \qquad (14)$$

$$\mathrm{C}\sin\alpha\mathrm{d} = \mathrm{D}\mathrm{e}^{\gamma\mathrm{d}}\left(1+\frac{\mathrm{i}\sigma\gamma}{\omega\varepsilon_{\mathrm{p}}}\right) \qquad (15)$$

For Odd Mode cos kx convertsin kx for the above four equations

Dispersion relation for even mode

$$\mathrm{Tan}[\alpha\mathrm{d}] - \frac{\gamma\epsilon\mathrm{au}}{\alpha\epsilon\mathrm{p}\left(1+\frac{\mathrm{i}\sigma\mathrm{g}\gamma}{\omega\epsilon\mathrm{p}}\right)} \qquad (16)$$

For odd mode

$$\cot[\alpha\mathrm{d}] + \frac{\gamma\epsilon\mathrm{au}}{\alpha\epsilon\mathrm{p}\left(1+\frac{\mathrm{i}\sigma\mathrm{g}\gamma}{\omega\epsilon\mathrm{p}}\right)} \qquad (17)$$

where

$\alpha = \sqrt{\epsilon\mathrm{au}\mathrm{k}_0^2 - \beta^2}and\gamma = \sqrt{\beta^2 - \epsilon\mathrm{p}\mathrm{k}_0^2}$

The Lorentz-Drude model is used for determining optical properties

$$\epsilon = \epsilon_0\left(1 - \frac{(\omega_{\mathrm{ep}})^2 - (\omega_{\mathrm{eo}})^2}{(\omega)^2 - (\omega_{\mathrm{eo}})^2 + i\Gamma_{\mathrm{e}}\omega}\right)$$

$$\mu = \mu_0\left(1 - \frac{(\omega_{\mathrm{mp}})^2 - (\omega_{\mathrm{mo}})^2}{(\omega)^2 - (\omega_{\mathrm{mo}})^2 + i\Gamma_{\mathrm{m}}\omega}\right)$$

$\boldsymbol{\omega_{\mathrm{ep}}}$=electronic plasma frequency,$\boldsymbol{\omega_{\mathrm{eo}}}$=electronic resonance frequency,$\boldsymbol{\omega_{\mathrm{mp}}}$=magnetic plasma frequency,$\boldsymbol{\omega_{\mathrm{mo}}}$ =magnetic resonance frequency,$\boldsymbol{e\omega}$= electronic damping and$\boldsymbol{m\omega}$= magnetic damping.

RESULT AND DISCUSSION:

The SPPs modes at the boundary amid dielectric, metal, mode confinement of effective mode index is defined by real part. The higher the mode confinement the larger is real part effective mode index. Through investigation resulting TM SPP modes that modes have propagation constant β much higher than k_o if graphene conductivity is imaginary purely with the positive part which is also imaginary. Also, the conductivity part which is real is introduced a loss of the mode. With improvements in technology, the loss was considerably high here, but as mentioned above it can be reduced if the quality of graphene is improved.

We plot the dispersion relation propagation constant β and frequency

When

$Z0 = 120\,\pi\,\Omega$
m0=$4*p*10^{-7}$
m0=$4*p*10^{-7}$
Gm=$1000*10^{9}$
e=$1.6*10^{-19}$
G1=$1.66\ *10^{-12}$
KB=$1.38*10^{-23}$
h = $(6.62*10^{-34})/\ (2p)$

e0=$8.85*10^{-12}$
e0=$8.85*10^{-12}$
Ge=$1000*10^{9}$
wp=$2*p*0.1*10^{9}$
m=0.2e
G2=$200\ *10^{-12}$
T=300

The PROFESSIONAL MATHEMATICA SOFTWARE PACK was used to find the result.

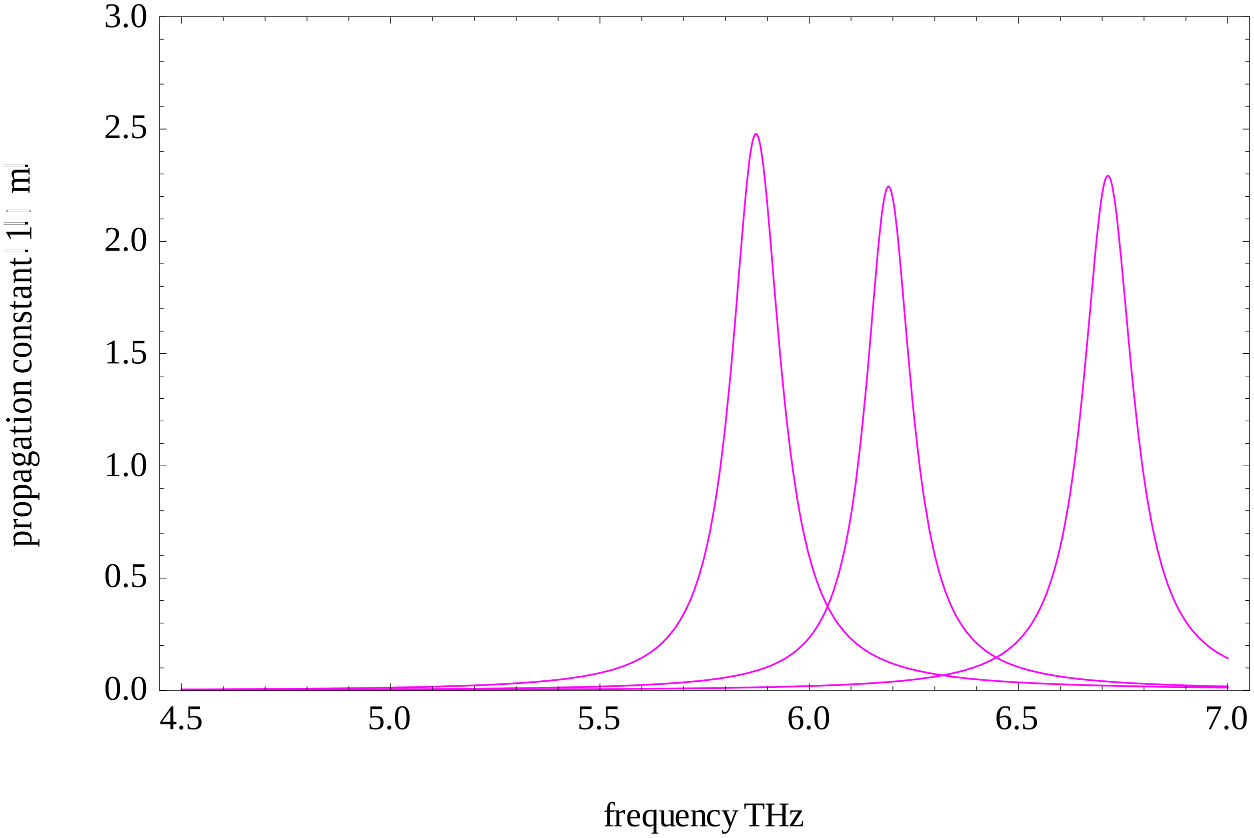

Fig1. Dispersion of the parallel graphene structure placed in DNM at increasing plasma frequency $\boldsymbol{\omega}_{\mathbf{ep}}$

Lorentz Drude medium model helped to define the magnetic permeability and electric permittivity of DNM and gold. Graphically representation of dispersion relation with cutoff frequency at THz region illustrated in Fig 1-6. The value of chemical potential decreased, intensity also decreased while cutoff frequency shifted toward a higher THz region (Fig 1). Increasing electronic resonance frequency cutoff frequency decreased without any change in peeks intensity (Fig 2). Increasing the number of oscillations n peeks shifted toward the lower or zero point of THs regions with continuously increasing intensity (Fig 3). The result shows the small change in chemical potential gave a large difference in their cutoff frequency (Fig 4). Due to decreasing plasma frequency of Gold cutoff frequency increased while decreasing sharpness, damping constant increased (Fig 5). Fig 6 shows that variation in oscillator strength increased, damping and cutoff frequency will be decreased.

One degree change in temperature showsthe small change in cutoff frequency with little increase in intensity Thickness between slabsis also affected bythe propagation of TM mode .0.13 to 0.17 sharpness or damping as well as THz frequency remainsthe same. butthe large gap between the slab and these factors changed discontinuously.

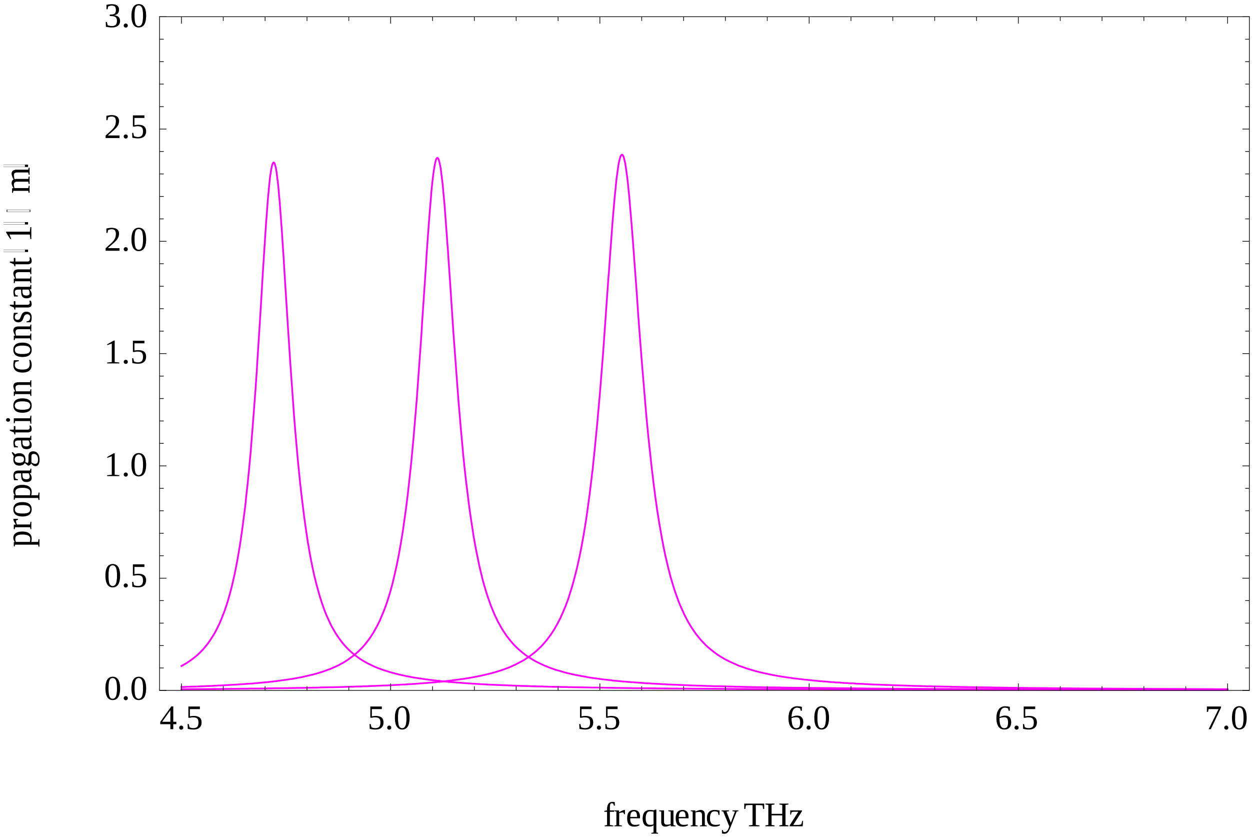

Fig2. Dispersion of the parallel graphene structure placed in DNM at the electronics resonance frequency

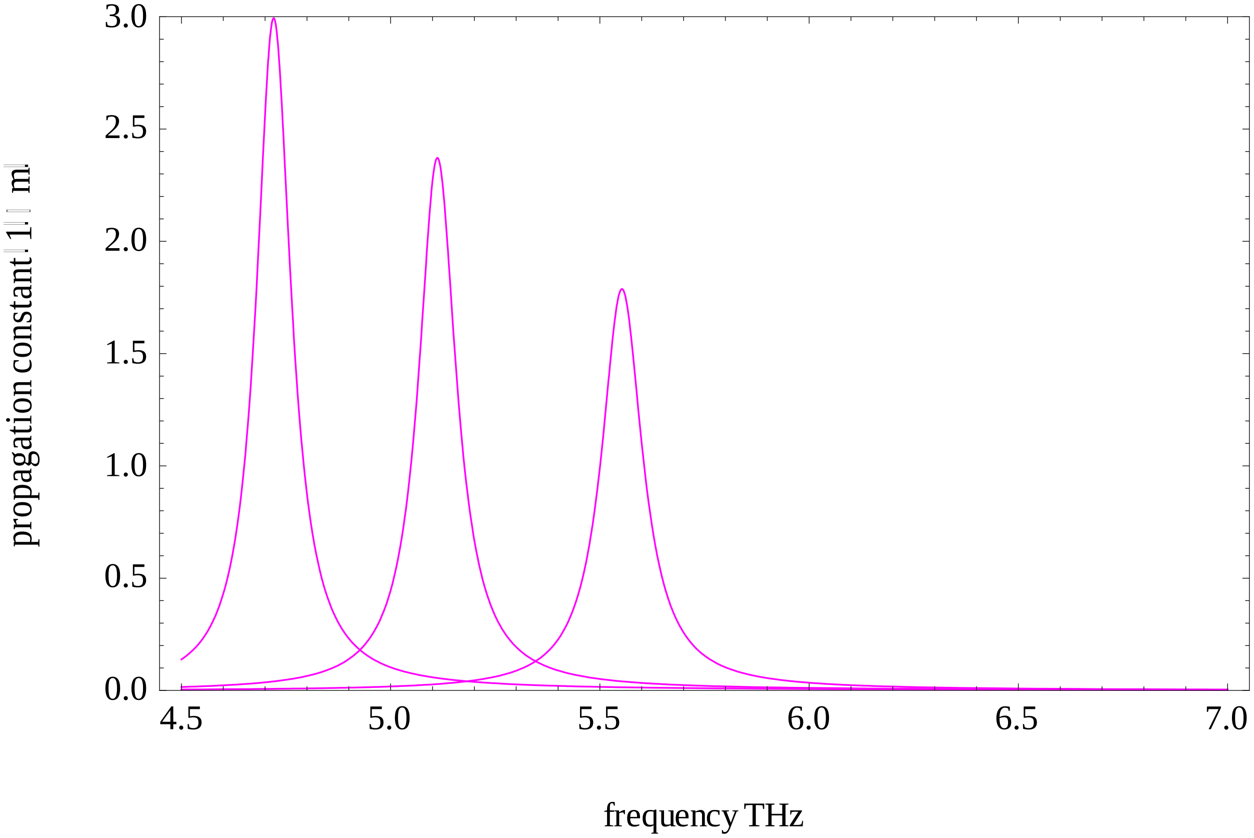

Fig3. Dispersion of the parallel graphene structure placed in DNM at increasing no of oscillation n

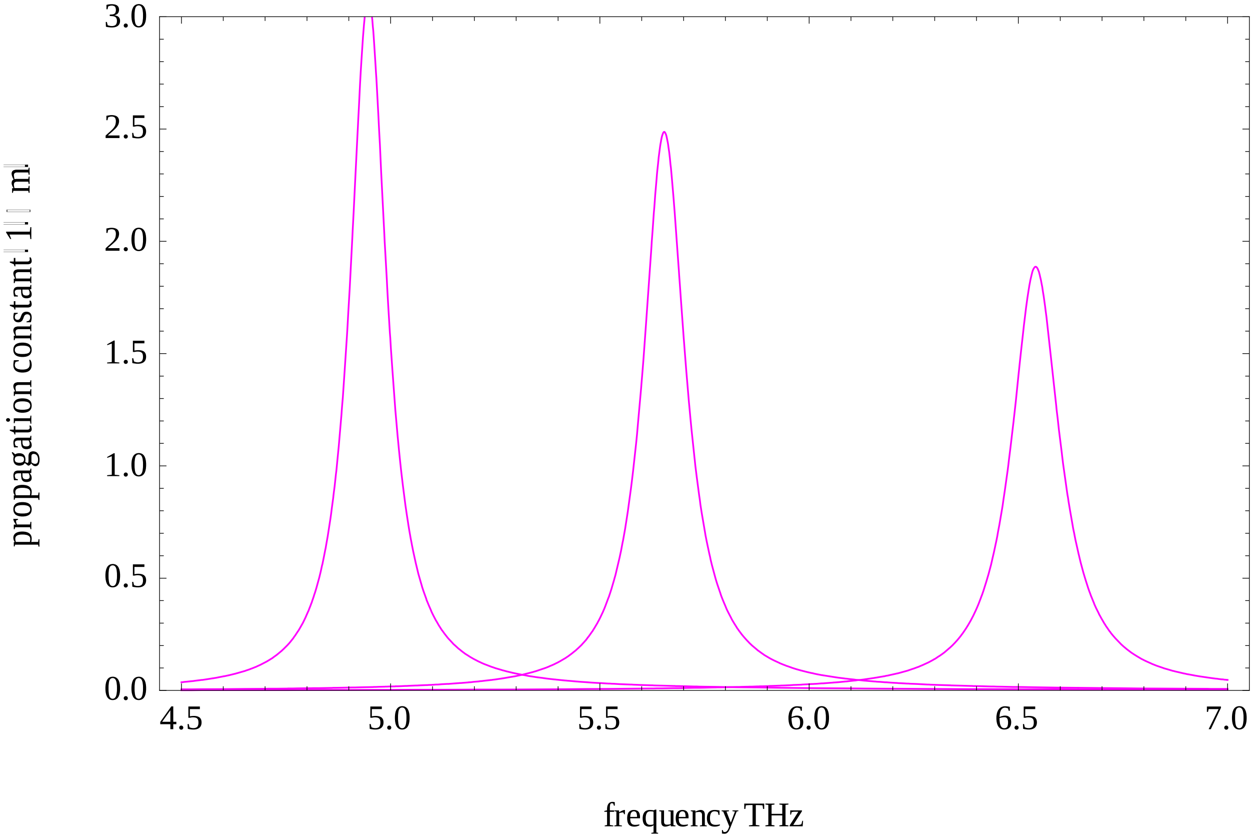

Fig4. Dispersion of the parallel graphene structure placed in DNM at increasing chemical potential

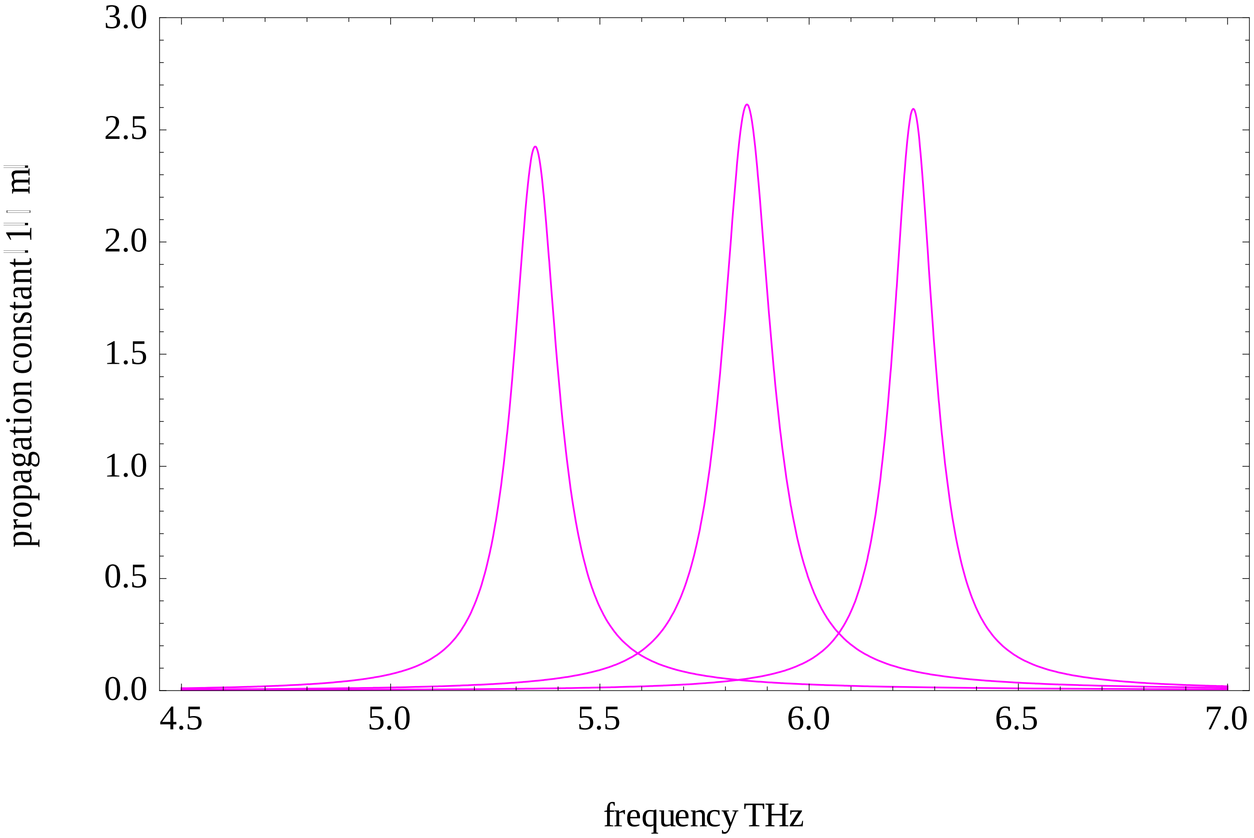

Fig 5. Dispersion of the parallel graphene structure placed in DNM at 8 t0 10 THs region

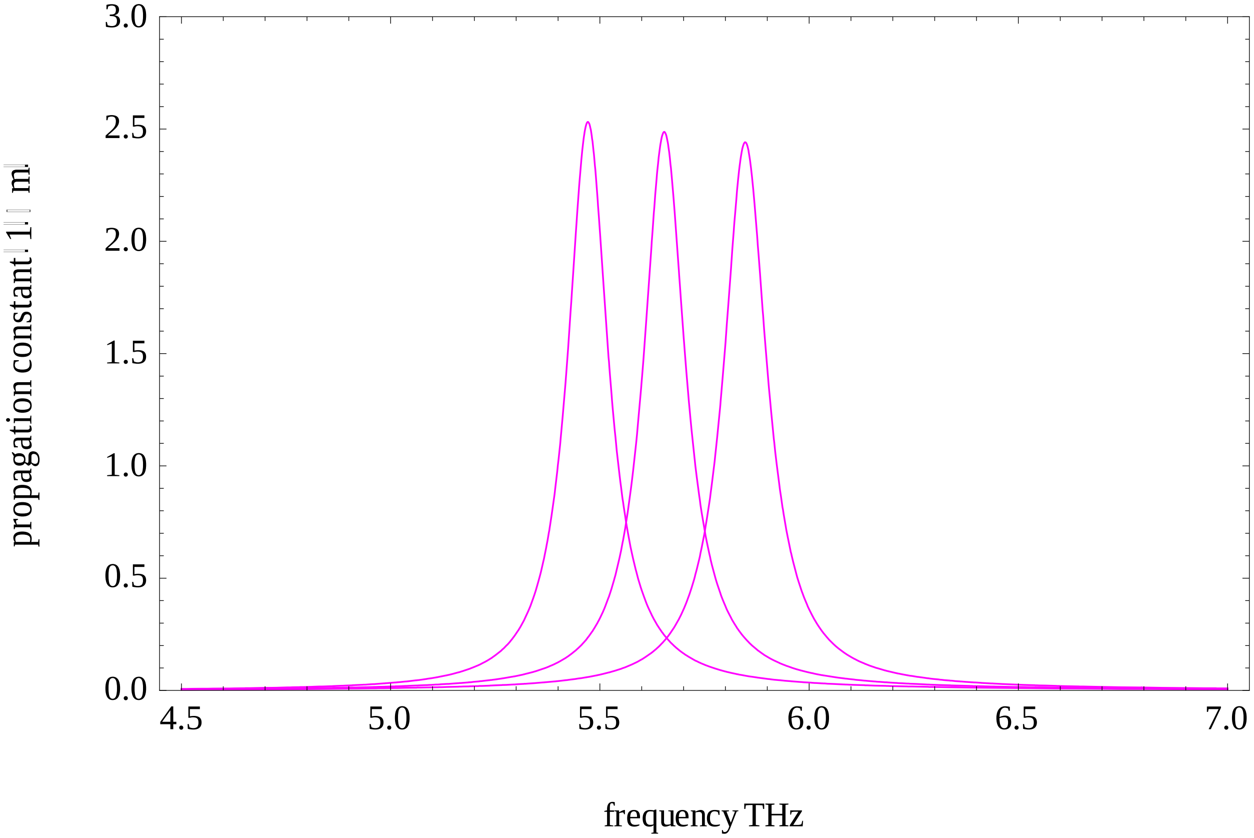

Fig6. Dispersion of the parallel graphene structure placed in DNM with an oscillating frequency of gold ωn

CONCLUSION:

In this study, we studied confined SPPs modes in parallel plates of graphene placed in double negative material (DNM) filled with gold. This examination aims to drive a well-organized method to excited waveguide modes at the THz region. Theoretically investigated SPPs modes supported by presented structure established and especially TM modes supported waveguides.The features of graphene-based were found through different chemical methods.

It is concluded that graphene plasmonic waveguide-filled gold may be exhibited as ultra-thin metal like a waveguide. Also, graphene-based SSPs waveguidesare exploited for the growth of next-generation communication devices integrated with photonic chip circuits.

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Conflict of interest

The author declares no conflict of interest

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