# Amplitude and Phase modulation Designs at 300 GHz Exploiting Graphene Based Waveguide Configurations

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**Abstract:** *Dispersion equations for waveguide modes of rectangular metal waveguide, and planar metal waveguide with graphene were presented here. It is demonstrated that the modes propagation constants can be substantially modulated by the graphene Fermi level modulation. This enables the potential for future designs of amplitude and phase modulators for electromagnetic waves in metal waveguides with integrated graphene structure. Particular examples and modulator designs will be discussed for f= 0.3 THz. This paper highlights the unique advantage of using graphene together with dielectrics for sub-THz waves propagating in a planar and rectangular metal waveguide with a monolayer of graphene.*

## I. Introduction

The potential to manipulate the flow of electromagnetic waves is very important for information processing and communication. The remarkable electrical and optical properties of graphene which include inherent reconfiguration capabilities by simply applying an electrostatic biasing field makes this material suitable for a highly efficient modulator for complex modulation formats[1]. Latter research on graphene has shown the potential to deal with all modulator's challenges [2]. Coupled graphene-metal plasmons and waveguide modes for planar metal waveguide behavior were described at the sub-THz range [3, 4]. Furthermore, the dispersion equation of waveguide modes of rectangular metal waveguide has been derived in the approximation of perfectly conducting waveguide metal walls [5].

## II. Model

In our work, we focused on *EMW* propagation in the rectangular waveguide that shown in Fig. 1.

As the graphene layer can be characterized by a surface electron concentration $n_s$ and a surface conductivity. At room temperature, intraband transitions give the largest contribution to the optical conductivity of graphene for low terahertz frequencies $f < 30\ THz$ and Fermi levels $E_F > 0.05\ eV$. The intraband graphene conductivity is given as:

$$\sigma^{intra}(\omega) = i\,\frac{2Te^2 \ln\left[2\cosh\left(E_F/2T\right)\right]}{\pi\hbar^2\omega\left[1+i/\omega\tau\right]} \qquad (1)$$

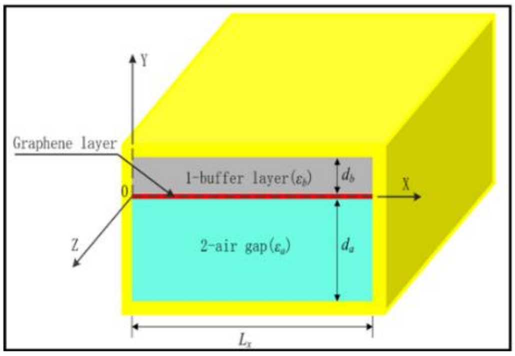



Fig. 1. Schematic view of the considered waveguide structures: rectangular left.

Where $\omega$ is angular frequency, $e$ is the electron charge, $E_F$ is the Fermi energy level of graphene, $\tau$ is electron relaxation time, $T = k_B t$ are the graphene electron energy, Fermi energy and temperature ($k_B$ is Boltzmann constant and $t$ is temperature in Kelvin) [7]. The dispersion equation for rectangular waveguide structure is given as follows:

$$Q_2 + \left(Q_1 \cot(Q_1 d_b) - i\,\frac{\sigma(\omega,q)\omega}{c^2\varepsilon_0}\right)\tan(Q_2 d_a) = 0 \qquad (2)$$

*TE* modes of planar metal layered waveguide can be easily calculated, but without vertical metal walls at $x=(0,L_x)$). The dispersion equation for *TE* modes of planar metal layered waveguide is given as:

$$\left(1+\frac{Q_2}{Q_m}\right)\left(Q_2+\beta Q_1-\frac{\sigma k_0}{c\varepsilon_0}\right)+\exp(-2iQ_2 d_a)\left(1-\frac{Q_2}{Q_m}\right)\left(Q_2-\beta Q_1+\frac{\sigma k_0}{c\varepsilon_0}\right)=0 \quad (3)$$

where $\beta = \left(1+\frac{iQ_1\tan(Q_1 d_b)}{Q_m}\right)\Big/\left(\mathrm{i}\tan(Q_1 d_b)+\frac{Q_1}{Q_m}\right)$, $Q_m = \sqrt{k_0^2\varepsilon_m - q^2}$ , $Q_1 =$

$\sqrt{k_a^2\varepsilon_b - (\pi n/L_x)^2 - q^2}$ , $Q_2 = \sqrt{k_a^2\varepsilon_a - (\pi n/L_x)^2 - q^2}$, $k_0 = \omega/c$ ,

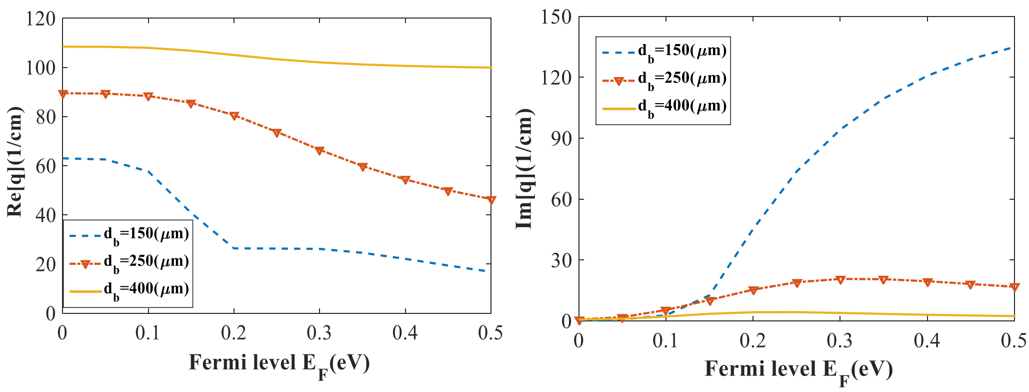
$q$ is the waveguide mode propagation constant, $c = 1/\sqrt{\varepsilon_0 \mu_0}$ is the light speed in vacuum, $\varepsilon_0$ and $\mu_0$ are the permittivity and permeability in vacuum. In the approximation of perfectly conducting metal waveguide walls, (3) reduces to (2). Solutions of dispersion (2) and *TE* modes field distributions for planar metal waveguides are almost coincident with *TE* modes of rectangular metal waveguide if $|\varepsilon_m| \gg 1$, see [4,5].

## III. Numerical results and discussions

We consider in more detail the structure of the *TE* modes of the rectangular waveguide, and planer, described by dispersion (2) & (3). All *TE* modes of the rectangular waveguide are labeled as $TE_{0m}$ modes where subscript index *0* means that these modes are the solutions for *n=0* and the index *m* identifies the solution number; the modes in the absence of graphene layer are denoted as $TE_{0m}^{0}$ modes. Solutions of (2) are given by the well-known dispersion relations for $TE_{0m}^{h}$ modes of a hollow rectangular waveguide (h corresponds to its height) in the absence of buffer layer when $d_b=0$:

$$q^2 = k_0^2 \varepsilon_a - m^2\pi^2 / d_a^2 \quad (4)$$

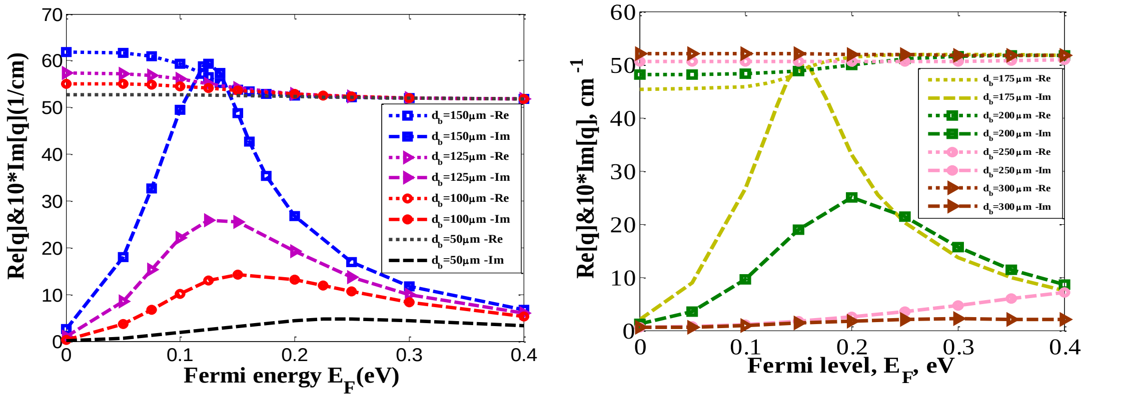
Where m=1,2,3,…Numerical calculations were performed for the waveguide structures the material parameters were taken from references [7,8]. Therefore dispersion relations for $TE_{0m}$ modes of the planar and rectangular waveguides are very close to each other. The dependences of the first *TE* waveguide mode propagation constant versus Fermi level for planar metal waveguide are shown in (Figs. 2(a) & 2(b)).




(a) (b)

Fig. 2. Dispersion dependences of the first *TE* waveguide mode propagation constant versus Fermi level for *f=0.3 THz*, for $d_2=(150,250,400)$ *μm*, for planar metal waveguide (a) the real part, (b) the imaginary part.

The modes propagation constants versus Fermi level $E_F$ for $TE_{0m}$ modes grouped around $TE_{01}^{0}$ modulation by graphene electrons concentration are shown in (Figs. 3(a) & 3(b)) for different buffer thicknesses. It is clear that the mode propagation constants modulations shown in (Figs. 3(a) & 3(b)) are similar.




(a) (b)

Fig.3. (a) Dependences of $TE_{01}$ modes propagation constant versus Fermi level for different buffer thickness $d_b$; real parts (*Re[q]*), and imaginary part multiplied by 10(*Im[q]*), for *f=0.3 THz*. (b) Dependences of waveguide modes propagation constants q versus Fermi level for different buffer thickness $d_b$; real parts (*Re[q]*), and imaginary parts multiplied by 10 (*Im[q]*), for *f=0.3 THz*.

## Conclusion

Dispersion equation for waveguide modes of rectangular metal waveguide with graphene has been presented in the approximation of perfectly conducting waveguide metal walls. Dispersion dependences of these modes are close to the ones for TE modes of planar metal waveguide with graphene.

## References

[1] K. Novoselov, A. Geim, S. Morozov, D. Jiang, Y. Zhang , S. Dubonos, I. Grigorieva and A. Firsov, “Electric field effect in atomically thin carbofilts,” Science, 2004, 306, 666–669.G. T. Reed, Silicon Photonics (Wiley, 2008

[2] E. Carrasco and J. Perruisseau-Carrier, “Reflectarray antenna at terahertz using graphene,” IEEE Antennas Wireless Propag. Lett.12, 253–256, 2013.

[3] H. Alkorre, G. Shkerdin, J. Stiens and R. Vounckx, “Coupled TM plasmon-polaritons features of graphenemetal layered structure in the sub-THz frequency range,” J. Opt., 17 045003, 2015.

[4] G. Shkerdin, H. Alkorre, J. Stiens and R. Vounckx, “Modified TM & TE waveguide modes and reflectivity by graphene layer in coupled-graphene-metal multilayer structure in sub-Terahertz frequency,” J. Opt., 17, 055006.20117, 055006, 2015.

[5] G. Shkerdin, H. Alkorre, H. Guoqiang and J. Stiens, “Modified TE modes of metal waveguide with integrated graphene structure in the sub-terahertz frequency range,” IET, to be publish.

[6] L. A. Falkovsky, “Optical properties of graphene and IV-VI semiconductors Phys. Usp., 51, 887-897, 2008.

[7] R. Kitamura, L. Pilon and J. Miroslaw, “Optical constants of silica glass from extreme ultraviolet to far infrared at near room temperature,” Appl. Opt, 46 8118–33, 2007.

[8] A. Ordal, J. Bell, W. Alexander, L. Long and R. Querry, “Optical properties of fourteen metals in the infrared and far infrared: Al, Co, Cu, Au, Fe, Pb, Mo, Ni, Pd, Pt, Ag, Ti, V, and W,” Appl. Opt., 24, 4493-4499, 1985.