# Effect of nonlinearity on surface plasmon polaritons in graphene in the Terahertz region

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***Abstract*—The effect of a strong electric field ($\geq 4kV/cm$) on the properties of surface plasmon polaritons (SPP's) is investigated. It is found that when a strong enough field is applied, the TM SPP dispersion can move up into the light cone. It is further found that when considering the problem of exciting SPP's using a prisim (ie. excitation from evanescent waves), optical bistability is possible as a sufficiently high field.**

## I. Introduction and Background

WHILST the study of surface plasmon polaritons (SPP's) has been going for around one hundred years, there has been renewed intrest in this field of plasmonics due to the discovery that a graphene sheet is capable of enhancing the SPP response. Graphene is a two-dimensional allotrope of carbon that exists as a hexagonal lattice. Graphene is found to have a linear dispersion around the Dirac points, which gives rise to a number of unusual effects.

### A. Nonlinear SPP dispersion relation

By matching the electric and magentic fields either side of a graphene sheet sandwiched between two dielectrics, the transverse magnetic (TM) mode from SPP's is found to be [1]

$$\frac{\varepsilon_1}{\tilde{\kappa}_1} + \frac{\varepsilon_2}{\tilde{\kappa}_2} + \frac{4i\alpha}{\omega}\tilde{\sigma} = 0 \qquad (1)$$

Where

$$\tilde{\sigma} = \frac{1}{\gamma - i\omega}\left[\mathcal{I}_1 + \frac{3}{4}\phi^2 E^2 \frac{\gamma^2 - 6\omega^2 + 5i\gamma\omega}{(\gamma^2 - 6\omega^2)^2 + 25\gamma^2\omega^2}\mathcal{I}_3\right], \qquad (2)$$

$\tilde{\kappa}_j^2 = (\hbar c)^2 q^2 - \omega^2 \epsilon_j$, and

$$\mathcal{I}_1 = \mu + 2k_B T \ln\left[\exp\left(-\frac{\mu}{k_B T}\right) + 1\right]$$

$$\mathcal{I}_3 = \int_0^\infty \left(\frac{1}{p}\frac{\partial f_0}{\partial p} - \frac{\partial^2 f_0}{\partial p^2} - p\frac{\partial^3 f_0}{\partial p^3}\right) \mathrm{d}p$$

where $f_0 = f_0^+ - f_0^-$.

For finite relaxation time ($\gamma$), and strong field, the SPP dispersion relation crosses into the light cone.

### B. Reflectivity and bistability

If we consider the Otto configuration (prism set up above dielectric-graphene-dielectric stack), we can match the electric and magnetic fields, and find a nonlinear system of equations. By solving this numerically we can find the reflection coefficient as well as the field strength at the location of the graphene sheet. Excitation occurs when there is a dip in the reflectivity, as well as a spike in the field strength at the graphene sheet. This occurs at a frequency of about 1THz. This corresponds to a match of the wavevector and frequency, thus allowing excitation of the SPP's. A similar optical bistability effect has been observed in a system without the prism, indicating that the phenomenon is not unexpected in this system [2].

## II. Results

Figure 1 shows the effect of the increase in the field on the reflection coefficient. When the electric field is increased, the dip in the reflection begins to bend, and at a sufficiently high field ($\gtrsim 4kV/cm$) an onset of bistability is found to occur. The field strength at the graphene interface also exhibits bistability. The onset field for bistability is expected to be a function of the chemical potential.

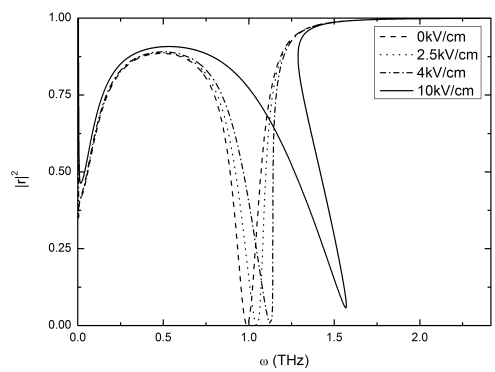


Fig. 1. Reflection coefficient with increasing field and frequency

## III. Conclusion

We found that as well as allowing for the dispersion relation to raise up into the light cone [3], optical bistability is also able to occur when exciting SPP's by using a prism.

## References

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