Total Internal Reflection at Conductive Interfaces: Monolayer Graphene for Terahertz Modulation

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***Abstract*—We have derived the Fresnel reflection coefficients incorporating both total internal reflection (TIR) and a conductive interface. Using this result we show that the reflectance in the TIR regime has a larger dependency on the optical conductivity of the conductive layer than the transmittance in the normal incidence regime. This suggests that a TIR prism with a controllable conductive layer such as back-gated graphene could be used to create an efficient terahertz modulator.**

I. INTRODUCTION

A high performance terahertz (THz) modulator is one solution to speed up terahertz image acquisition rate. Such a modulator needs to be broadband, and ideally possess characteristics that allow the terahertz modulation to be tuned, such as controllable conductivity. Graphene, a cutting-edge 2D material with an atomically thin thickness, shows ultra-high optical conductivity in the terahertz region due to intraband transitions[1]. The optical conductivity of graphene can be tuned by manipulating its Fermi level in active terahertz modulators by applying a back-gate voltage[1, 2]. However, existing designs, that focus on controlling the transmittance of normal incidence illuminated graphene structures are not able to achieve high modulation or a large bandwidth [2].

Here, we investigate non-normal incidence and formulate the equations to describe the total internal reflection (TIR) from a conductive interface such as graphene: we find that for a given optical conductivity, the reflectance can be decreased.

II. RESULTS

Graphene can be regarded as a thin conductive film in the terahertz region due to its atomic level thickness. The optical conductivity of monolayer graphene at 1 THz can be tuned between 0.2mS and 1.5 mS by applying a back-gate voltage [1]. By increasing the quality of graphene, the optical conductivity in the terahertz region can be further increased to 2.4 mS [3]. Higher conductivity large-area graphene can hopefully be manufactured in the future. This gives graphene the potential to be used as a material in an active terahertz modulator. Based on the thin conductive film Fresnel equations[4], with an incident angle larger than the critical angle, the TIR reflection coefficients of *s*-polarized and *p*-polarized light can be interpreted as:

$$r_s = \frac{n_i\cos\theta_i - i\cdot\sqrt{n_i^2\sin^2\theta_i - n_t^2} - Z_0\sigma_s}{n_i\cos\theta_i + i\cdot\sqrt{n_i^2\sin^2\theta_i - n_t^2} + Z_0\sigma_s} \quad (1),$$

$$r_p = \frac{i\cdot n_i\sqrt{n_i^2\sin^2\theta_i - n_t^2} - n_t^2\cos\theta_i - i\cdot Z_0\sigma_s\cos\theta_i\sqrt{n_i^2\sin^2\theta_i - n_t^2}}{i\cdot n_i\sqrt{n_i^2\sin^2\theta_i - n_t^2} + n_t^2\cos\theta_i + i\cdot Z_0\sigma_s\cos\theta_i\sqrt{n_i^2\sin^2\theta_i - n_t^2}} \quad (2),$$

where n_i and n_t are the refractive indices of incident and transmitted side dielectric material. θ_i is the incident angle and σ_s is the optical conductivity of graphene.

In our calculation, two types of substrates are taken into consideration: fused silica and TOPAS (from TOPAS Advanced Polymer Company). The refractive index of fused silica and TOPAS in the THz region are ~2 and 1.56.

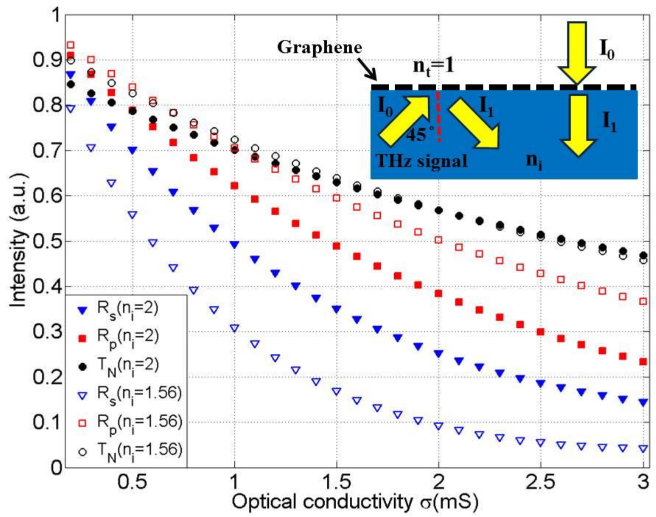

Fig. 1. Terahertz reflectance for TIR at 45° incidence and transmittance at normal incidence as a function of interface conductivity. Two different refractive indices (n_i=1.56 and 2) are considered. R*s* and R*p* represent the reflectance of *s* and *p*-polarized light in TIR. T_N represents the transmittance at normal incidence. Inset shows the TIR and transmission structure with graphene on the interface.

Using equations (1) and (2), the attenuation of an incident terahertz signal in TIR at 45° incident angle increases along with optical conductivity of graphene (Fig. 1). Using published back-gate controllable optical conductive range of graphene (0.2 to1.5 mS) [1], the modulation range of *s*-polarized light with TOPAS substrate is from 80% to 17%. If graphene's conductivity is further increased, as reported in [3], the minimum reflectance value reaches 4% at 3 mS. For *s*-polarized light with fused silica substrate, the modulation range is from 89% to 14%. The attenuation of *s*-polarized light is higher than for *p*-polarized light with the same optical conductivity due to the stronger interaction between the in-plane electric field and the graphene. For *p*-polarized light with fused silica substrate, the modulation range is from 93% to 23%. For TOPAS substrate, the modulation range of *p*-polarized light is from 96% to 37%.

Comparing with the transmittance in normal incidence, TIR reflectance shows a higher modulation range. Figure 2 shows the intensity of normal incident transmittance minus TIR reflectance (T_N - R). When the optical conductivity is lower than 0.5 mS, the T_N is lower than TIR reflectance. This is due to the reflection from air-dielectric interface in normal incidence. In TIR, the reflection is lossless when the interface is non-conductive. The attenuation of TIR reflectance over transmittance increases with increasing interface optical conductivity. For *s*-polarized light with TOPAS substrate, the intensity difference of (T_N – R) reaches a maximum value of

48% at optical conductivity of 1.8 mS. The intensity difference of (T_N – R) decreases gradually to 40% when optical conductivity continuously increases. This result could come from the more metallic-like behavior of graphene interface when its optical conductivity goes higher. Under high optical conductivity situation, the reflection from graphene interface takes dominance over absorption. For p and s-polarized light under other situations, the advantages of TIR reflectance increase with optical conductivity.

Thus, by controlling the Fermi level of a graphene layer

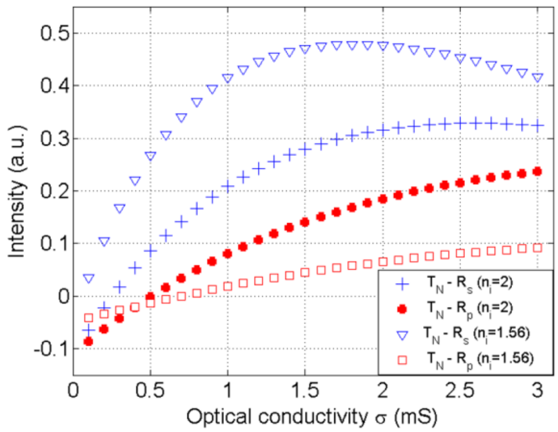

Fig 2. The intensity difference between normal incident transmittance and TIR reflectance. The equations are T_N - R*s* and T_N - R*p*.

with a back-gate voltage it will be possible to modulate a terahertz beam intensity between 80% and 4%, which is nearly a factor of two greater than that possible using a normal transmittance configuration.

III. SUMMARY

In conclusion, in this paper, we proposed a new THz modulator configuration based on total internal reflection and formulated equations to describe the absorption form a conductive interface. The theoretical results suggest that s-polarized light with TOPAS substrate has the largest modulation range, which is from 80% to 4%. Comparing with normal incident transmittance, the modulation range is increased two-fold.

IV. ACKNOWLEDGEMENTS

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