Long-range Graphene Surface Plasmon Polariton induced Tunable Optical Bistability in Terahertz Range

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Abstract

An idea towards the low threshold optical bistability and tunability of bistable thresholds at THz frequency under realistic situation is analyzed through a proposed multilayered configuration. The proposed configuration comprises a coupling prism of silicon, and monolayer graphene sheets spatially separated through 35 nm thick polymer which is sandwiched between an air gap of thickness 4.6 µm and a kerr polymer (GaAs) at 300 K temperature and at an incident light frequency of 2 THz. Utilizing the large nonlinear effect of the configuration obtained by the nonlinearity of the kerr polymer and the high local field effect due to long-range graphene surface plasmon resonance, the switching-down and switching-up threshold values for optical bistability have been markedly reduced upto 1.21×10^5 V/m and 1.24×10^5 V/m respectively thereby rendering a minimum threshold intensity of 7.2 kW/cm^2 than the articles reported till date. Tunability of the switching-down and switching-up threshold values have also been realized from 1.21×10^5 V/m to 5.18×10^5 V/m and 1.24×10^5 V/m to 1.424×10^6 V/m respectively through electrical or chemical modification of the charge carrier density and hence fermi energy of the graphene from 0.23 eV to 0.41 eV and from 1.21×10^5 V/m to 1.56×10^5 V/m and 1.24×10^5 V/m to 2.12×10^5 V/m respectively for the variation in incident angle from 70° to 88°. The effect of damping rate of graphene on optical bistability behavior has also been observed. Therefore the proposed optical bistable configuration finds potential applications in the field of all-optical switching, optical transistor, optical logic, nano-illumination and optical memory with low input threshold at THz frequency and can also be used to realize tunable optical bistable device for future THz optical communication technology.

Keywords: *Optical Bistability, Plasmonics, Graphene Plasmons, Electromagnetic optics*

1. Introduction

Certain resonant optical structures manifests two stable and steady transmission states for a single value of the input light intensity. Such an optical effect is known as optical bistability [1]. This bistability phenomenon is useful for optical storage, opto-transistors, all-optical switch elements etc [2]. Survey of recent publications in the field of optical bistability presents the interest of realizing it with a very low input threshold intensity [3,4]. The desired goal can also be achieved through graphene sheet due to its large nonlinear Kerr index and its ultra-fast nonlinear response at broad range of frequencies [5]. Graphene, which is a flat monolayer of graphite with sp^2 bonded carbon atoms packed into a dense 2D honeycomb crystal lattice, has been recognized as a promising candidate owing to the electrical tunability of its surface conductivity by varying its charge carrier density using an external gate voltage [6]. And therefore has been used for the designing of tunable optical sensors, tunable meta-materials and tunable terahertz absorbers etc. that operates in both THz and optical frequency ranges [7,8]. The optical bistability threshold value obtained through graphene sheet can further be lowered through excitation of graphene surface plasmon polaritons (SPP) also known as graphene SPP resonance [5]. As is well known SPP are evanescent electromagnetic wave created by the coupling of incident electromagnetic field with the electrons at the interface between two materials where real part of dielectric constants are opposite in sign across the interface [9]. The tunability of this bistable threshold value also proved to be significant for the all-optical devices applications [1]. For further dropping this bistable threshold value through large nonlinear effect, high local field effect of long range graphene SPP resonance can be employed. This long range graphene SPP mode is obtained by the coupling of SPPs existing at the spatially separated graphene sheets. Hence the proposed configuration comprising a kerr polymer and spatially separated graphene sheets for long range graphene SPP resonance is utilized to attain a low threshold optical bistability with a lower Fermi-enegy of graphene at terahertz ranges. The tunability of bistable threshold value is also achieved through varying the Fermi energy of graphene and adjusting the incident illumination angle. The effect of damping rate of graphene on optical bistability behavior has also been observed.

2. Proposed Scheme

This paper analytically explores a multilayer configuration consisting of Kerr polymer and spatially separated nonlinear graphene sheets to achieve low threshold optical bistability with low Fermi energy of graphene at terahertz frequency employing long range graphene SPP mode resonance and to explore tunability of the bistable thresholds. The proposed configuration comprises a coupling prism of silicon, and monolayer graphene sheets spatially separated through 35 nm thick polymer which is sandwiched between an air gap of thickness 4.6 μm and a kerr polymer (GaAs) at 300 K temperature and at a incident light frequency of 2 THz, as shown in Fig.1.

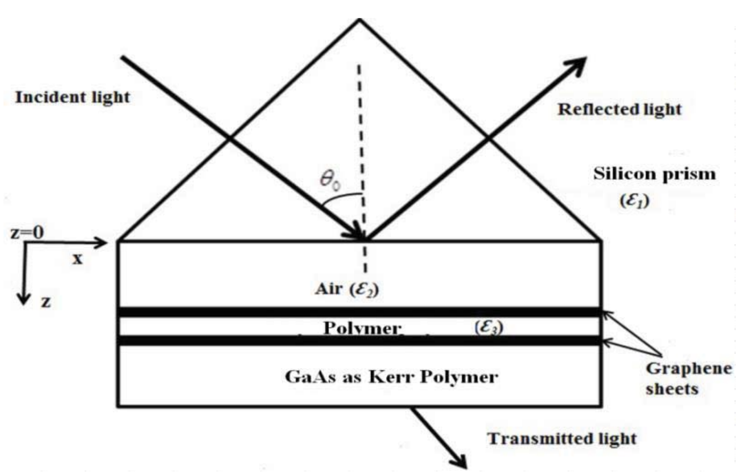

FIG 1. Proposed Configuration of optical bistability.

The surface conductivity (σ) of graphene can be expressed as $\sigma = \sigma_0 + \sigma_3 |E|^2$ where the optical-linear conductivity of graphene, σ_0 comprises of intraband, σ_{intra} and interband, σ_{inter} terms

$$\sigma_{intra} = \frac{ie^2 2k_B T}{\pi\hbar^2\left(\omega + i\tau^{-1}\right)}\left\{\frac{E_F}{2k_B T} + \ln\left[1 + \exp\left(-\frac{E_F}{k_B T}\right)\right]\right\} \tag{1}$$

$$\sigma_{inter} = \frac{e^2}{4\hbar}\left(\frac{1}{2} + \frac{1}{\pi}\tan^{-1}\left(\frac{\hbar\omega - 2E_F}{2k_B T}\right) - \frac{i}{2\pi}\ln\left|\frac{(\hbar(\omega + i\tau^{-1}) + 2E_F)^2}{(\hbar(\omega + i\tau^{-1}) - 2E_F)^2 + 4(k_B T)^2}\right|\right) \tag{2}$$

Where $$E_F = \hbar v_F \sqrt{\pi \eta_{2D}} \tag{3}$$

The carrier density for a graphene sheet (η_{2D}) can be electrically controlled through the applied gate voltage on graphene, thereby resulting in voltage controlled Fermi energy for the graphene sheet. Here T denotes the temperature in K, ω, τ , v_F, e , $\hbar$ and k_B represents the angular frequency of incident light, the electron-phonon relaxation time, Fermi velocity of electrons (=10^6 m/s), electron charge, reduced Plancks constant and Boltzmann constant respectively.

Now when an incident p-polarized beam strikes the base of the dielectric prism of the proposed configuration at the resonant angle (θ_r), then the propagation constants of the evanescent mode and the long-range graphene SPP mode gets equal thereby resulting in long-range graphene SPP mode resonance. This leads to a sharp dip in the reflected light intensity. The third order nonlinear surface conductivity of the graphene (σ_3) is expressed as

$$\sigma_3 = -\frac{9}{4}\frac{e^4 v_F^2}{\pi\hbar^2 E_F((\tau^{-1})^2 + \omega^2)(\tau^{-1} - 2i\omega)} \tag{4}$$

Therefore in nonlinear regime, as the incident light electric field rises, evanescent field (E) around nonlinear graphene increments, which lowers its surface conductivity as can be deduced from the Eq. $\sigma = \sigma_0 + \sigma_3 |E|^2$. With this decrease in surface conductivity, the propagation constant of the long-range graphene SPP mode increases; this in turn raises the resonant angle. Now for attaining the optical bistability through the proposed configuration, the incident angle (θ_0) is fixed at a value greater than the long-range graphene SPP mode resonant angle (θ_r) of the configuration. Under these circumstances, the system remains in the Total Internal Reflection (TIR) mode for very low incident electric field. When the incident electric field addresses the switching-up threshold, E_{up} , θ_r gets slightly larger than θ_0 . This switches the mode of the system from TIR mode to transmission mode. On further increasing the incident light intensity, θ_r shifts away from the θ_0 thereby decreasing the transmitted electric field. When the incident electric field gets equal to the switching down threshold, E_{down} , transmission resonance occurs due to the long-range graphene SPP mode resonance. On further lowering the incident light electric field, θ_r shifts away from the θ_0 and the mode of the system gets switched from transmission state to the TIR off resonance state. Therefore the system possesses two stable modes: TIR mode and transmission mode within the hysteresis width ($\Delta E = E_{up} - E_{down}$).

3. Result and Discussion

With the help of computer aided simulations being performed on the proposed configuration, a set of graphs have been obtained and presented as well where Fig. 2 shows the variation of reflectance for incident p-polarized beam with the varying incident angle for E_F = 0.23 eV and τ =1 ps at very low incident electric field. The simulated graph reveals long-range graphene surface plasmon resonance at the resonant angle (θ_r) of around 55°.

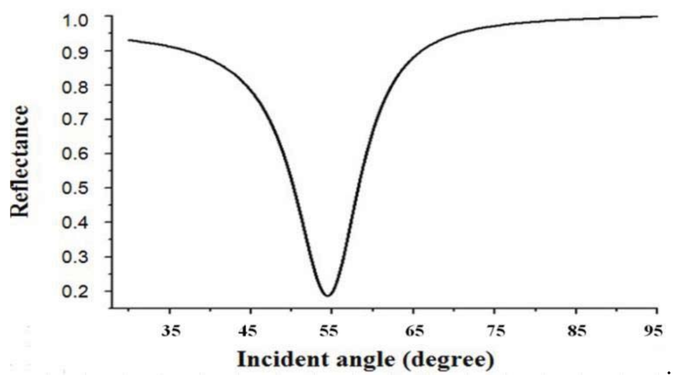

FIG 2. Reflectance versus incident angle for incident p-polarized light beam.

Now the significant role of the initial angle offset on the transmitted electric field is shown in Fig. 3.

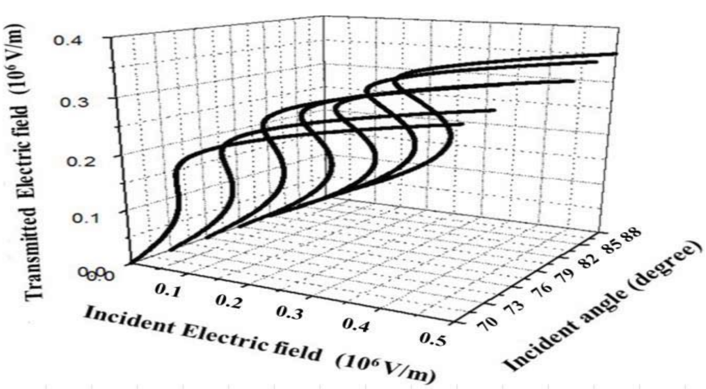

FIG 3. Dependency of transmitted electric field on the incident electric field for different incident angles.

The mentioned graph reveals that for E_F = 0.23 eV and τ =1 ps, initial angle offset broadens with the increase in incident angle of the beam, thereby demanding a larger incident electric field intensity to make the long-range graphene surface plasmon resonant angle address the fixed incident angle. The tunability of the switching-down and switching-up threshold electric fields for the occurrence of optical bistability is from 1.21×10^5 V/m to 1.56×10^5 V/m and from 1.24×10^5 V/m to 2.12×10^5 V/m respectively for the varying incident angle from 70° to 88°. It can also be concluded from the graph, that the width of the hysterical loop gets broadened with the rise in the initial angle offset on account of insignificant amount of shift in the magnitude of switching-down threshold and significant shift in the magnitude of the switching-up threshold. The nature of the graphs are found to be similar with the work presented by Xiaoyu et al. in 2015 [5]

The Fermi energy of the graphene can also influentially manipulate the thresholds of optical bistability as been shown in Fig. 4 for θ = 70° and τ =1 ps.

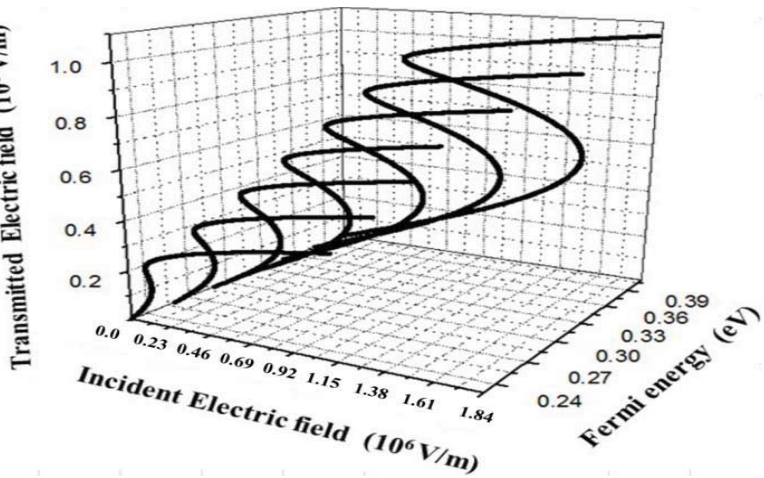

FIG 4. Transmitted electric field as a function of incident electric field for different Fermi-energies.

It can be inferred from the graph that with the elevation in the Fermi energy of the graphene, threshold requirement to achieve optical bistability increases. Both the switching-down and switching-up bistable threshold values get enhanced alongwith the widening of the hysteresis width, by incrementing the Fermi energy, thereby indicating a tunability of threshold electric fields from 1.21×10^5 V/m to 5.18×10^5 V/m and 1.24×10^5 V/m to 1.424×10^6 V/m respectively for the variation in E_F from 0.23 eV to 0.41eV. Compared to the reported articles, this work presents the feasibility to obtain hysteresis with a much less switching threshold of about 1.21×10^5 V/m and 1.24×10^5 V/m for E_{down} and E_{up} respectively at a E_F = 0.23 eV under the realistic situation thereby rendering a minimum threshold intensity of 7.2 kW/cm^2 [1,3,5].

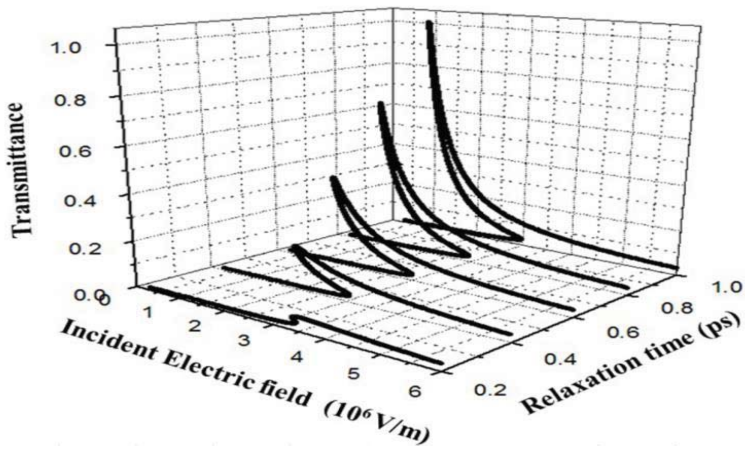

FIG 5. Dependency of transmitted electric field on the incident electric for different damping rate of graphene.

The damping rate (τ^{-1}) of graphene can also modify markedly the behavior of optical bisability as shown in Fig. 5 for θ = 70°, E_F = 0.4 eV. As perceptible from the graphs, with the increase in the damping rate, the transmitted electric field decreases on account of increase in the energy losses in graphene. Moreover increased damping rate of graphene demands larger incident electric field threshold due to the significantly reduced nonlinear surface conductivity. For much larger damping rate, the bistability graph may even straighten out thereby displaying much higher bistable threshold requirement to achieve optical bistability.

4. Conclusion

A multilayered configuration has been analytically explored to achieve optical bistability with low switching-down and switching-up threshold values of about 1.21×10^5 V/m and 1.24×10^5 V/m thereby rendering a minimum threshold intensity of 7.2 kW/cm^2 respectively by employing the large nonlinear effect of the configuration obtained by utilising the nonlinearity of the kerr polymer and the high local field effect due to the long-range graphene SPP resonance. Tunability of the respective bistable threshold values have also been realized from 1.21×10^5 V/m to 5.18×10^5 V/m and 1.24×10^5 V/m to 1.424×10^6 V/m through electrical or chemical modification of the charge carrier density and hence fermi energy of the graphene from 0.23 eV to 0.41 eV and from 1.21×10^5 V/m to 1.56×10^5 V/m and 1.24×10^5 V/m to 2.12×10^5 V/m for the variation in incident angle from 70° to 88° . The effect of damping rate of graphene on optical bistability behavior has also been observed. Therefore the proposed optical bistable configuration finds potential applications in the field of all-optical switching, optical transistor, optical logic, nano-illumination and optical memory with low input threshold at THz frequency and can also be used to realize tunable optical bistable device for future THz optical communication technology.

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