Nonlinear Mixing of Two Laser Beams and THz Plasmons Generation in Graphene Coated Optical Fibre

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ABSTARCT

Graphene is a most suitable material for Terahertz (THz) radiation generation. An efficient mechanism of THz surface plasmons (THz SPs) generation in graphene coated optical fibre by nonlinear mixing of two laser beams is proposed. The graphene coated fiber supports THz SPs with plasmon resonance in the THz regime and controllable by thickness of graphene and radius of optical fibre. The laser beams exert a difference frequency ponderomotive force on the electrons of the graphene. This ponderomotive force induces a nonlinear current in graphene which driving the difference frequency THz SPs. The normalized amplitude of THz SPs decreases with frequency as the nonlinear coupling gets weaker. The efficiency of the device is around 0.01% at a laser intensity of 3×10^{14} W/cm². This scheme will be useful making the compact THz radiation source and THz plasmon sensor.

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I. Introduction

There is a substantial interest of terahertz radiation generation due to its wide applications in outer space communications, biomedical imaging, tomography, precision radar and other areas [1-7]. Due to the lack of efficient sources and detectors in THz range or so called THz gap (0.1-10THz), however, this THz gap is still remains a challenge for modern technology and poses significant limitations for further developments in this field. These limitations, arising due to the nature of light/material interaction at terahertz frequencies, are imprinted also onto the design of terahertz systems for light control, manipulation, and, most significantly, radiation guidance.

The laser based THz radiation sources are attractive due to relative simplicity and suitability for modest THz power [8-9]. However since for most applications, size is major constraints a number of techniques that exploit short pulse laser- semiconductor interaction to produce THz radiation by transient photoconductors or dc current modulation have developed [10-11]. Intense short pulse laser plasma interaction also offers potential schemes [12-15] for the generation of long pulse and high power THz, required for THz communication, remote sensing and ultrafast material characterization.

Tightly confined guided electromagnetic waves are used as a probing radiation and having large number of applications [16-24], known as surface plasmons (SPs). SPs are guided electromagnetic modes propagate along the interface between a conductor and a dielectric or conductor and air with their field amplitude falling off exponentially away from it in either medium [25-27]. The structured surfaces, also support SPs at THz frequency range are called designer plasmonic structures or ‘spoof’ SPs structures [28-30]. Two structures, an ultrathin metal film dielectric plate, and a metal coated optical fiber, are shown to support low loss THz SPs [31, 32]. These structures are shown to support THz SPs with weak attenuation. But the

metal has loss and low confinement of SPs as compared to graphene plasmons (GPs) at THz frequencies. So graphene is a most suitable candidate for THz radiation generation.

Graphene is a 2D material, which has unique properties and potential applications for making the nano devices [33–40]. The most striking feature of graphene is that all its Dirac electrons, have same speed, as energy versus momentum relation is linear, irrespective of their energy. In graphene the localized electron motion in a plane with very small electron effective mass giving rise to high in-plane conductivity. The two dimensional nature of graphene also supports plasmons with wavelengths substantially smaller than free-space electromagnetic radiation of the same frequency by approximately two orders of magnitude and generating large non-local effects. Graphene plasmons (GPs) are used for making the compact radiation sources on chip in infrared–visible–ultraviolet range [41].

The difference frequency generation (DFG) at mid-infrared is enhanced due to the presence of plasmons resonance [42–45]. The graphene holds a great promise for designing the plasmonic sensors or new THz sources. An all-optical coupling scheme is used for plasmon generation in graphene. An electron beam is used for coherent and tunable THz radiation generation from multilayer graphene deposited on a substrate [46]. Despite the recent intensive research, generation of coherent and tunable THz radiation remains a significant challenge.

In this manuscript, we put forth the new and efficient scheme of THz GPs generation via the nonlinear mixing of two laser beams in the graphene coated optical fibre. The fiber has a dielectric ripple (volume grating) of wave number q . The ripple imparts spatial harmonics to lasers shifted by q . The lasers and their spatial harmonics exert a difference frequency ponderomotive force on film electrons with wave number $k_z = k_{1z} - k_{2z} + q$, where k_{1z} and k_{2z} are the

wave numbers of the lasers. The ponderomotive force drives the THz GPs when q satisfies the phase matching condition. In section II, we developed the formalism of THz GPs in graphene coated fiber and the nonlinear mixing of lasers and THz excitation is discussed in section III. We discussed the results in section IV.

II. THz Graphene Plasmons in Graphene Coated Optical Fibre

Consider an optical fiber (cf.1) of radius 'a' is coated by graphene sheet of conductivity σ_g . Consider the thin film of graphene is a layer zero thickness and infinite conductivity and the current density in graphene layer may be defined as

$$J = \sigma_g d\delta(r-a)E_z|_{r=a} \hat{z} = \sigma_g dE_z|_{r=a} \hat{z}. \quad (1)$$

The graphene plasmons (GPs) propagate along $\hat{z}$ direction of fiber i.e. length of fiber with variation as $\exp[-i(\omega t - k_z z)]$ is shown in Fig.1. The electric and magnetic fields of the GPs in different regions can be written as for $r < a$ (Glass) region 1

$$\begin{aligned} E_{1z} &= A_{01} I_0(\alpha_1 r) \exp[-i(\omega_1 t - k_{1z} z)], \\ H_{1\phi} &= \frac{\omega \epsilon_0 \epsilon_1}{i \alpha_1} A_{01} I'_0(\alpha_1 r) \exp[-i(\omega_1 t - k_{1z} z)], \end{aligned} \quad (2)$$

where $\alpha_1^2 = k_z^2 - \frac{\omega^2}{c^2} \epsilon_1$.

For region $r > a$ (vacuum) region 2

$$\begin{aligned} E_{2z} &= A_{02} K_0(\alpha_2 r) \exp[-i(\omega_2 t - k_{2z} z)], \\ H_{2\phi} &= -\frac{\omega \epsilon_0 \epsilon_2}{i \alpha_2} A_{02} K'_0(\alpha_2 r) \exp[-i(\omega_2 t - k_{2z} z)], \end{aligned} \quad (3)$$

where $\alpha_2^2 = k_z^2 - \frac{\omega^2}{c^2} \epsilon_2$. Using jump condition on $\vec{H}$ (at $r=a$),

$$\vec{H}_\phi|_2 - \vec{H}_\phi|_1 = \sigma_g dE_z|_{r=a}, \quad (4)$$

Putting the Eqs. (2)& (3) into Eq. (4), one may get

$$\frac{\epsilon_2}{\alpha_2} \frac{K'_0(\alpha_2 a)}{K_0(\alpha_2 a)} - \frac{\epsilon_1}{\alpha_1} \frac{I'_0(\alpha_1 a)}{I_0(\alpha_1 a)} = -\frac{i \sigma_g d}{\omega \epsilon_0}. \quad (5)$$

The Eq. (5) gives the GPs dispersion relation of SPs in graphene. In Fig. (2), we have plotted the normalized frequency ω/ω_p versus normalized wave vector $k_z c/\omega_p$ for two

normalized radii $a\omega_p/c = 10^{-2}$, $a\omega_p/c = 10^{-3}$ of optical fibre, normalized graphene sheet thickness $d\omega_p/c = 0.08$ and for typical parameters; $v_2 = 10^6 \text{ m/s}$; $c = 3 \times 10^8 \text{ m/s}$. The figure shows that with increasing the radius of optical fibre the coupling is between lasers and graphene plasmons becomes weak. As the frequency increases with wave number however; the phase velocity of graphene plasmons slows down with increasing the frequency.

III. Nonlinear Mixing of Two Laser Beams and THz Surface Plasmons Generation in Graphene Coated Optical Fibre

Let two laser beams are propagate in the azimuthally symmetric mode inside the graphene coated fiber (Fig.2). The electric fields of the laser beams inside the fiber are

$$\vec{E}_1 = A_1 \left[\hat{z} J_0(k_{1\perp} r) + i \hat{r} \frac{k_{1z}}{k_{1\perp}} J'_0(k_{1\perp} r) \right] \exp[-i(\omega_1 t - k_{1z} z)] \quad (6)$$

$$\vec{E}_2 = A_2 \left[\hat{z} J_0(k_{2\perp} r) + i \hat{r} \frac{k_{2z}}{k_{2\perp}} J'_0(k_{2\perp} r) \right] \exp[-i(\omega_2 t - k_{2z} z)] \quad (7)$$

The fiber to have a dielectric constant ripple

$$\epsilon_g = \epsilon_{g0} + \epsilon_{gq}, \quad \epsilon_{gq} = \epsilon_{g2} e^{iqz}. \quad (8)$$

The displacement vector inside the fiber is $\vec{D}_1 = \epsilon_g \vec{E}_1 = \epsilon_{g0} \vec{E}_1 + \frac{1}{2} \epsilon_{gq} \vec{E}$ and acquires a component that goes as $e^{-i[\omega_1 t - (k_{1z} + q)z]}$. This component produces an electromagnetic field (in compliance with $\nabla \cdot \vec{D} = 0$)

$$\vec{E}_{1+} \equiv -\frac{\epsilon_{gq}}{2\epsilon_{g0}} \vec{E}_1 \approx \exp[-i\{\omega_1 t - (k_{1z} + q_z)z\}]. \quad (9)$$

Similarly,

$$\vec{E}_{2+} \equiv -\frac{\epsilon_{gq}}{2\epsilon_{g0}} \vec{E}_2 \approx \exp[-i\{\omega_2 t - (k_{2z} + q_z)z\}]. \quad (10)$$

Here, the phase matching conditions demands that

$$\omega_{SPHz} = \omega_1 - \omega_2, \quad k_{SPHz} = k_{1z} - k_{2z} + q. \quad (11)$$

The lasers impart oscillatory velocities to the electrons, given as

$$\vec{v}_{1+} = \frac{e\vec{E}_{1+}}{m\omega_1}, \quad \vec{v}_{2+} = \frac{e\vec{E}_{2+}}{m\omega_2}. \quad (12)$$

These laser beams also impart the ponderomotive force F_{pz} on electrons at beat frequency given by

$$F_{pz} \approx \frac{mi(k_{1z} - k_{2z} + q)}{2} \vec{v}_1 \vec{v}_2^* \frac{\epsilon_{gq}}{2\epsilon_{g0}}. \quad (13)$$

This ponderomotive force also imparts oscillatory velocity to electrons at frequency $(\omega_1 - \omega_2)$ and may be written as

$$\vec{v}_\omega = \frac{\hat{z}F_{pz}}{-im\omega}, \quad (14)$$

the nonlinear current in graphene sheet may be written as

$$\vec{J}_\omega^{NL} = -\hat{z} \frac{n_0 e (k_{1z} - k_{2z} + q)}{2\omega} \vec{v}_1 \vec{v}_2^* \frac{\epsilon_{gq}}{2\epsilon_{g0}} \equiv \hat{z} F d\delta(r) \exp[-i(\omega_{sp}t - k_{sp}z)]. \quad (15)$$

$$\text{where } \vec{F} = \frac{n_0 e k_{sp}}{4\omega} \frac{e^2 |E_1| |E_2|}{m^2 \omega_1 \omega_2} \frac{\epsilon_{gq}}{\epsilon_{g0}}. \quad (16)$$

This nonlinear current density is localized in graphene sheet, which is the source of THz graphene plasmons. The electric and magnetic field vectors for GPs are given as

For $r < a$ (glass)

$$\begin{aligned} \vec{E}_1 &= A_1 \left[\hat{z} \tilde{I}_0(\alpha_1 r) - i \hat{r} \frac{k_z}{\alpha_1} I'_0(\alpha_1 r) \right] \exp[-i(\omega_1 t - k_1 z)], \\ \vec{H}_\phi &= \frac{i\omega\epsilon_0\epsilon_1}{\alpha_1} A_1 I'_0(\alpha_1 r) \exp[-i(\omega_1 t - k_1 z)]. \end{aligned} \quad (17)$$

For $r > a$ (vacuum)

$$\vec{E}_2 = A_2 \left[\hat{z} \vec{K}_0(\alpha_2 r) - i \hat{r} \frac{k_z}{\alpha_2} K'_0(\alpha_2 r) \right] \exp[-i(\omega_2 t - k_2 z)],$$

$$\vec{H}_\phi = -\frac{i\omega\epsilon_0}{\alpha_2} A_2 K'_0(\alpha_2 r) \exp[-i(\omega_2 t - k_2 z)]. \quad (18)$$

The nonlinear current density manifests itself in the jump condition on the $\vec{H}_\phi$ component of the GPs at $\mathbf{r} = \mathbf{a}$, gives

$$DA_0 = \frac{-iFd/\omega\epsilon_0}{K'_0(\alpha_2 a)}, \quad (19)$$

$$D = \frac{\epsilon_1}{\alpha_1} \frac{I'_0(\alpha_1 a)}{I_0(\alpha_1 a)} - \frac{1}{\alpha_2} \frac{K'_0(\alpha_2 a)}{K_0(\alpha_2 a)} - \frac{\sigma_g d}{i\omega\epsilon_0}. \quad (20)$$

Solving Eq. (19), it yields the amplitude of THz GPs

$$A_0 = \frac{FdL/\omega\epsilon_0}{K'_0(\alpha_2 a)\partial D/\partial k_{sp}}. \quad (21)$$

At exact phase matching condition, D vanishes. However due to finite length of interaction $L = 2r_0$ where r_0 is laser spot size, so D can be replaced by region $D \cong -i(\partial D/\partial k_z)(\partial/\partial z)$, Eq. (19) can be written as

$$\frac{\partial D}{\partial k_z} = -k_z \left[\frac{\epsilon_1}{\alpha_1^3} \frac{I'_0(\alpha_1 a)}{I_0(\alpha_1 a)} - \frac{1}{\alpha_2^3} \frac{K'_0(\alpha_2 a)}{K_0(\alpha_2 a)} \right]. \quad (22)$$

Solving and rearranging the terms in Eq. (22), we have

$$\left| \frac{A_0}{A_1} \right| = \frac{1/(\omega/\omega_p)(\omega/4\omega_1)(k_{sp}/k_z)(|v_2|/c)(\epsilon_{gq}/\epsilon_{g0})(d\omega_p/c)(L\omega/c)}{K'_0(\alpha_2 a) \left(\frac{\epsilon_1}{(k_z^2 - (\omega^2/c)\epsilon_1)^{3/2}} \frac{I'_0(\alpha_1 a)}{I_0(\alpha_1 a)} - \frac{1}{(\omega^2/c)^{3/2}} \frac{K'_0(\alpha_2 a)}{K_0(\alpha_2 a)} \right)}. \quad (23)$$

Eq. (23) gives the amplitude of terahertz graphene plasmon. For following parameters: $v_2 = 10^6 \text{ m/s}$; $c = 3 \times 10^8 \text{ m/s}$; $\omega = 10^{13} \text{ rad/s}$; $k_z^2 c^2 / \omega^2 = 2.6$; $\omega_1 = 2 \times 10^{12} \text{ rad/s}$; $\omega_p \approx 2.5 \times 10^{12} \text{ rad/s}$, normalized thickness $d\omega_p/c = 0.08, 0.10, 0.12$, normalized radius of optical

fibre $a\omega_p/c = 10^{-2}, 10^{-3}$ $L\omega/c = 10^3$, $\varepsilon_{g2}/\varepsilon_{g0} = 0.2$. For CO₂ laser, $e|E_2|/m\omega_2c = 10^{-2}$, corresponds to an intensity $3 \times 10^{12} \text{ W/cm}^2$ and power $\sim 8 \text{ MW}$. For $1 \mu\text{m}$, wavelength it corresponds to an intensity of $3 \times 10^{14} \text{ W/cm}^2$. Fig. 4, 5 and 6, show that as the frequency raises, the normalized amplitude of THz SPW decreases. It is due to the weakening of the nonlinear coupling of SPs at higher frequencies.

IV. Conclusion

In conclusion, the graphene coated fiber offers the promise of producing phase matched THz graphene plasmons using laser moderate power (MW range) and intensity. The nonlinearity arises through the ponderomotive force and phase matching is provided by the volume grating of suitable wave number inside the fiber. The efficiency is one order of magnitude smaller than the ideal efficiency given by Manley Rowe relations. The thickness of the graphene sheet and radius of an optical fibre are important parameters to influence the THz graphene surface plasmons resonant frequency. The normalized amplitude of THz GPS decrease with frequency as the nonlinear coupling gets weaker. The fiber configuration is more suitable as the grating structures in optical fibers are routinely available. The efficiency of the device is around 0.01% at a laser intensity of $3 \times 10^{14} \text{ W/cm}^2$.

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Figure Captions

Fig.1 THz GPs propagation in graphene coated optical fiber.

Fig.2. Dispersion relation for graphene plasmons.

Fig.3. THz GPs excitation via nonlinear mixing of lasers in graphene coated optical fiber.

Fig.4 .Normalized THz graphene surface plasmons amplitude variation with normalized frequency for different two different normalized radii of optical fibre and fixed thickness of graphene sheet.

Fig.5. Normalized THz graphene surface plasmons amplitude variation with normalized frequency for different normalized thickness of graphene sheet and fixed normalized radius of optical fibre.

Fig.6. Normalized THz graphene surface plasmons amplitude variation with normalized frequency for different normalized thickness of graphene sheet and fixed normalized radius of optical fibre.

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Fig.5. Normalized THz graphene surface plasmons amplitude variation with normalized frequency for different normalized thickness of graphene sheet and fixed normalized radius $a\omega_p/c = 10^{-2}$ of optical fibre.

Fig.6. Normalized THz graphene surface plasmons amplitude variation with normalized frequency for different normalized thickness of graphene sheet and fixed normalized radius $a\omega_p/c = 10^{-3}$ of optical fibre.