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Research Article

Conversion efficiency by circularly polarized laser pulse with two different spin states in magnetized quantum plasma

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ABSTRACT

Second harmonic generation due to the effect of two different spin states of electron on the propagation of a circularly polarized laser pulse in homogenous high density, quantum plasma is studied using the quantum hydrodynamic (QHD) model. The effects associated with the Fermi pressure, the Bohm-potential and the electron spin-up and spin-down have been taken in to account. The efficiency of the Second harmonic radiation is derived and the effect of spin polarization on the conversion efficiency has been analyzed.

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INTRODUCTION

Numerous theoretical and experimental research groups have expressed keen interest in investigating the physics of laser-plasma interaction, driven by its direct relevance to a range of practical applications. These applications encompass areas such as laser-driven fusion, plasma-based accelerators and the generation of higher harmonics [1–5]. When a strong laser interacts with plasma, it can cause a number of nonlinear phenomena, including self-focusing, scattering instabilities and harmonic production [6–11]. To find out more regarding the complex characteristics of intense laser interaction with plasma, researchers are studying these instabilities through theory as well as experiment [12–15]. Harmonic production is the most important field of study in the process of laser-plasma interaction. The most probable medium for producing harmonics actually consists of plasma. As a result, several harmonics are generated from the fundamental frequency of the laser beam. In the plasma medium, harmonic generation has an important effect on the transition the laser beams. A variety of plasma characteristics, such as electrical conductivity, opacity and local electron density, can be evaluated with the help of harmonic generation [16, 17]. Second harmonic generation (SHG) provides a simple approach to observe a beam's transit through a plasma medium. It was Sodha and Kaw [18] which made earlier work on SHG. Harmonic radiations were extremely significant in spectroscopy [19-22]. Several mechanisms, including plasma wave excitation electron plasma wave (EPW), plasma instabilities and resonant absorption, may generate harmonics [8, 23–27]. A study by Nitikant and Sharma [28, 29], the wiggler magnetic field

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must be present for phase matching and has a kinematical function in generating the transverse harmonic current.

Quantum effects become essential for studying in high-density plasma, when the de-Broglie wavelength of particles is of the order of greater than the inter-particle distance. Particle degeneracy joins the picture when the temperature of the plasma is less than the Fermi temperature. Considering its important applications in nanoscale and nanoelectronic devices [30-31], superdense astrophysical objects [32-34] (such as white dwarfs, neutron stars, magnetostars, and supernova), quantum plasma echoes [35], quantum X-ray free electron laser [36] and intense laser-solid density plasma experiments [37–38], studying quantum plasma has been focused throughout the last decade. The most earlier research on SHG has employed a laser beam with uniform irradiance or the classical regime. But the irradiance from a Gaussian beam is not uniform. Due to the focusing and defocusing characteristics of these beams, the second harmonic amplitude is significantly impacted.

The analysis of the role of electron spin in quantum plasma is crucial with potential persistence even in the presence of macroscopic variations on scales exceeding the de Broglie wavelength. Particularly in high-temperature plasmas, the quantum characteristics stemming from the intrinsic magnetic moment of electrons become prominent, resulting in distinct spin effects [39-41] that diverge from those observed in non-spin quantum plasma phenomena [42-44]. Over the past decade, numerous scholarly articles have explored the influence of electron spin on plasma dynamics [45-46]. Unlike the conventional view of plasma electrons as a single fluid, a paradigm shift proposes the treatment of spin-up and spin-down electrons as seperate plasma species as the magnetic fields application results a concentration between the electron species resulting in spin polarization. The separation of spins remains well-defined, assuming that the force associated with spin flip [47-48] can be reasonably neglected.

The current study focuses on the propagation of circularly polarized electromagnetic wave through quantum plasma under the influence of an external magnetic field featuring two distinct spin states of electrons. This investigation takes into consideration various quantum effects like Fermi pressure, Bohm potential and discrepancies in spin-up and spin-down electron concentrations arising from an external magnetic field. The first order velocities, electron density and spin angular momentum for the two electron spin states have been evaluated in Sec-II. Section III is devoted to the analysis of the second harmonic generation and its corresponding conversion efficiency. Finally, Section IV presents the concluding remarks.

LASER-PLASMA INTERACTION

We consider a circularly polarized wave propagating along the z- direction through uniform cold plasma. An axially directed magnetic field $\vec{B}_0 = b\hat{z}$ is applied to the system with the fields of the incident e. m. wave given as

$$\vec{E}(x,y) = E_0(\hat{x} + i\hat{y})e^{i(kz-\omega t)} + c.c, \tag{1}$$

$$\vec{B}(x,y) = \frac{c(\hat{k}\times\vec{E})}{\omega}. \tag{2}$$

where c is the vacuum speed of light, k is the propagating wave vector, wave frequency ω, and E_0 is the slowly changing amplitude of the circularly polarized wave inside the plasma. The current density at 2ω develops and acts as a source for the second harmonic when the pulse progresses through magnetized plasma. The electromagnetic field and plasma's interaction is governed by the QHD equations, which are [49-51],

$$\left(\frac{\partial}{\partial t} + \vec{v}_\alpha.\nabla\right)\vec{v}_\alpha = -\frac{-e}{m}\left[\vec{E} + \frac{1}{c}\left(\vec{v}_\alpha \times \vec{B}\right)\right] - \frac{\nabla\vec{P}_\alpha}{mn_\alpha} + \frac{\hbar^2}{2m^2}\nabla\left(\frac{1}{\sqrt{n_\alpha}}\nabla^2\sqrt{n_\alpha}\right) - \frac{2\mu_B}{m\hbar}\vec{S}_\alpha.(\nabla\vec{B}), \tag{3}$$

$$\frac{\partial\vec{S}_\alpha}{\partial t} = \frac{2\mu_B}{\hbar}(\vec{B}\times\vec{S}_\alpha), \tag{4}$$

and the equation of continuity,

$$\frac{\partial\vec{n}_\alpha}{\partial t} + \vec{\nabla}.\left(\vec{n}_\alpha\vec{v}_\alpha\right) = 0 \tag{5}$$

where, $\vec{n}_\alpha$ and $\vec{v}_\alpha$ is the electron species' particle density and velocity, and α indicates the electrons' up (↑) and down (↓) spin. The equation of motion now includes the spin moment effect [49–50]. Equation (3)'s first component on the RHS is the Lorentz force, while the second component signifies the force caused by Fermi electron pressure ($P_F = mv_F^2 n^3/3n_0^3$).The quantum Bohm potential is the third component and the force resulting from the spin magnetic moment of plasma electrons under the influence of a magnetic field, where $\mu_B = e\hbar/2mc$ the Bohr magneton is located is the last term; therefore, it is excluded from the study that uses the QHD model [50–54]. Within the slightly relativistic limit, equation (3) is true. Higher perturbation orders have been found to significantly increase the relativistic effect [55]. In the limit, the classical equations are obtained [53]. For the source current, the wave equation is

$$\left(\nabla^2 - \frac{1}{c^2}\frac{\partial^2}{\partial t^2}\right)\vec{E} = \frac{4\pi}{c^2}\frac{\partial\vec{J}_\alpha}{\partial t} \tag{6}$$

Where, $\vec{J}_\alpha = \left(\vec{J}_{c\alpha} + \vec{J}_{M\alpha}\right)$ with $\vec{J}_{c\alpha}$ being the conventional current and $\vec{J}_{M\alpha}$ being the magnetization current density. The electron quiver velocities are obtained by simultaneously solving equations (3) - (5)

$$v_{\alpha x}^{(1)} = v_{\alpha x1}E_0 e^{i(kz-\omega t)} + c.c, \tag{7a}$$

$$v_{\alpha y}^{(1)} = v_{\alpha y1} E_0 e^{i(kz-\omega t)} + c.c. \quad (7b)$$

$$v_{\alpha z}^{(1)} = v_{\alpha z1} E_0 e^{i(kz-\omega t)} + c.c \quad (7c)$$

where,

$$v_{\alpha x1} = \frac{1}{\left(\omega_c^2 - \omega^2\right)}\left[\frac{ie(\omega_c + \omega)}{m} + \frac{kQ_\alpha\left(i\omega_c n_{\alpha y1} - \omega n_{\alpha x1}\right)}{n_{\alpha 0}} + \frac{2i\mu_B S_{\alpha 0} k(\omega - \omega_c)}{m\hbar}\right],$$

$$v_{\alpha y1} = \frac{1}{\left(\omega_c^2 - \omega^2\right)}\left[\frac{-e(\omega_c + \omega)}{m} + \frac{kQ_\alpha\left(i\omega_c n_{\alpha x1} - \omega n_{\alpha y1}\right)}{n_{\alpha 0}} - \frac{2\mu_B k S_{\alpha 0}(\omega + \omega_c)}{m\hbar}\right],$$

$$v_{\alpha z1} = \frac{kQ_\alpha n_{\alpha z1}}{n_{\alpha 0}\omega}.$$

$Q_\alpha = \left[v_F^2 + \frac{\hbar^2 k^2}{4m^2}\right]$, and cyclotron frequency $\omega_c = \frac{eb}{mc}$.

Similarly, the first order electron densities can be obtained by substituting the quiver velocities in continuity equation,

$$n_{\alpha x}^{(1)} = n_{\alpha x1} E_0 e^{i(kz-\omega t)} + c.c, \quad (8a)$$

$$n_{\alpha y}^{(1)} = n_{\alpha y1} E_0 e^{i(kz-\omega t)} + c.c. \quad (8b)$$

where,

$$n_{\alpha x1} = \frac{kn_{\alpha 0}}{\omega\left\{\left(\omega_c^2 - \omega^2\right) + k^2 Q_\alpha\right\}}\left[\frac{ie(\omega + \omega_c)}{m} + \frac{ikn_{\alpha y1} Q_\alpha \omega_c}{n_{\alpha 0}} + \frac{2i\mu_B S_{\alpha 0} k(\omega - \omega_c)}{m\hbar}\right],$$

$$n_{\alpha y1} = \frac{kn_{\alpha 0}}{\omega\left\{\left(\omega_c^2 - \omega^2\right) + k^2 Q_\alpha\right\}}\left[\frac{-e(\omega_c + \omega)}{m} + \frac{ikQ_\alpha \omega_c n_{\alpha x1}}{n_{\alpha 0}} - \frac{2\mu_B k S_{\alpha 0}(\omega - \omega_c)}{m\hbar}\right],$$

Oscillating current is produced by electron spin motion and density perturbations brought on by oscillatory velocities. The spin current ($\vec{J}_\alpha$) resulting from magnetization and the conventional source current added together make up the current density, which can be expressed as [56]

$$\vec{J}_{\alpha m} = \vec{\nabla} \times \left(\vec{M}_\uparrow + \vec{M}_\downarrow\right) = -\frac{2\mu_B}{\hbar}\left(n_\uparrow - n_\downarrow\right)\vec{\nabla} \times \vec{S}_\uparrow, \quad (9)$$

Where $S_\uparrow = -S_\downarrow$ and the magnetization due to spin can be written as $M = 2n\mu_B S/\hbar$. The electron current densities are calculated with the help of equations (7a), (7b) and (7c)

$$J_{\alpha x}^{(1)} = J_{\alpha x1} E_0 e^{i(kz-\omega t)} + c.c \quad (10a)$$

$$J_{\alpha y}^{(1)} = J_{\alpha y1} E_0 e^{i(kz-\omega t)} + c.c \quad (10b)$$

$$J_{\alpha z}^{(1)} = J_{\alpha z1} E_0 e^{i(kz-\omega t)} + c.c \quad (10c)$$

where,

$$J_{\alpha x1} = -n_{\alpha 0} e v_{\alpha x1} - \frac{2i\mu_B n_{\alpha 0} k(n_\uparrow - n_\downarrow)}{n_{\alpha 0}} S_{\alpha x1},$$

$$J_{\alpha y1} = -n_{\alpha 0} e v_{\alpha y1} + \frac{2i\mu_B n_{\alpha 0}(n_\uparrow - n_\downarrow)}{n_{\alpha 0}} S_{\alpha y1},$$

$J_{\alpha z1} = -n_{\alpha 0} e v_{\alpha z1}$. $\eta' = \frac{\Delta n}{n_{\alpha 0}}$ is spin polarization and $\Delta n = (n_\uparrow - n_\downarrow)$ is the difference of spin-up and spin-down concentration of electrons caused by external magnetic field.

An essential feature of quantum degenerate plasma is spin. It is important because it introduces the plasma to the external magnetic field, and its effect may be measured using spin angular momentum to determine the perturbed spin magnetic moment for the plasma electron. Under the influence of the applied magnetic field, the electrons gain a spin angular moment whose effect can be estimated by calculating the spin magnetic moments,

$$S_{\alpha x}^{(1)} = S_{\alpha x1} E_0 e^{i(kz-\omega t)} + c.c, \quad (11a)$$

$$S_{\alpha y}^{(1)} = S_{\alpha y1} E_0 e^{i(kz-\omega t)} + c.c. \quad (11b)$$

Where,

$$S_{\alpha x1} = \frac{-2i\mu_B S_{\alpha 0}}{\hbar\left\{\frac{4\mu_B^2 b^2}{\hbar^2 - \omega^2}\right\}}\left[\frac{2b\mu_B}{\hbar} + \omega\right],$$

$$S_{\alpha y1} = \frac{2\mu_B S_{\alpha 0}}{\hbar\left\{\frac{4\mu_B^2 b^2}{\hbar^2} - \omega^2\right\}}\left[\frac{2\mu_B b}{\hbar} + \omega\right].$$

The second order perturbed electron velocities and densities can be obtained from QHD equations in the procedure similar to that adopted for first order which come out to be,

$$v_{\alpha x}^{(2)} = v_{\alpha x2} E_0^2 e^{2i(kz-\omega t)} + c.c, \quad (12a)$$

$$v_{\alpha y}^{(2)} = v_{\alpha y2} E_0^2 e^{2i(kz-\omega t)} + c.c, \quad (12b)$$

$$v_{\alpha z}^{(2)} = v_{\alpha z2} E_0^2 e^{2i(kz-\omega t)} + c.c, \quad (12c)$$

$$n_{\alpha x}^{(2)} = n_{\alpha x2} E_0^2 e^{i(kz-\omega t)} + c.c, \quad (13a)$$

$$n_{\alpha y}^{(2)} = n_{\alpha y2} E_0^2 e^{i(kz-\omega t)} + c.c, \quad (13b)$$

$$n_{\alpha z}^{(2)} = n_{\alpha z2}E_0^2 e^{i(kz-\omega t)} + c.c\cdot \tag{13c}$$

where,

$$v_{\alpha x2} = \frac{2ik\mu_B}{m\hbar\{\omega_c^2 - 4\omega^2\}}\left[\omega_c S_{\alpha y1} + 2\omega S_{\alpha x1}\right],$$

$$v_{\alpha y2} = \frac{-2\mu_B k}{m\hbar\{\omega_c^2 - 4\omega^2\}}\left[\omega_c S_{\alpha x1} + 2\omega S_{\alpha y1}\right]$$

$$v_{\alpha z2} = \frac{-ie}{2mc\omega}\left[v_{\alpha x1} + iv_{\alpha y1}\right]$$

$$n_{\alpha x2} = \frac{k}{\omega}\left[n_{\alpha 0}v_{\alpha x2} + n_{\alpha x1}v_{\alpha x1}\right],\ n_{\alpha y2} = \frac{k}{\omega}\left[n_{\alpha 0}v_{\alpha y2} + n_{\alpha y1}v_{\alpha y1}\right],$$

$$n_{\alpha z2} = \frac{k}{\omega}\left[n_{\alpha 0}v_{\alpha z2}\right]\cdot$$

The second order velocities oscillate at the second harmonic of the fundamental frequency of the polarized wave. The second order spin magnetic moment for two spin states (spin-up and spin-down) comes out to be,

$$S_{\alpha x}^{(2)} = S_{\alpha x2}E_0^2 e^{2i(kz-\omega t)} + c.c, \tag{14a}$$

$$S_{\alpha y}^{(2)} = S_{\alpha y2}E_0^2 e^{2i(kz-\omega t)} + c.c \tag{14b}$$

$$S_{\alpha z}^{(2)} = S_{\alpha z2}E_0^2 e^{2i(kz-\omega t)} + c.c\cdot \tag{14c}$$

where,

$$S_{\alpha x2} = \frac{1}{\left\{\frac{4\mu_B^2 b^2}{\hbar^2} - 4\omega^2\right\}}\left[\frac{2ibk\mu_B v_{\alpha y1}S_{\alpha y1}}{\hbar} - 2k\omega v_{\alpha x1}S_{\alpha x1}\right],$$

$$S_{\alpha y2} = \frac{1}{\left\{\frac{4\mu_B^2 b^2}{\hbar^2} - 4\omega^2\right\}}\left[\frac{2i\mu_B bkS_{\alpha x1}v_{\alpha x1}}{\hbar} - 2k\omega v_{\alpha y1}S_{\alpha y1}\right],$$

$$S_{\alpha z2} = \frac{-i\mu_B}{\hbar\omega}\left[iS_{\alpha y1} + S_{\alpha x1}\right]\cdot$$

In non-degenerate plasmas where $T >> T_F$, the concentration difference $n_\uparrow - n_\downarrow = n\tanh(\mu_B B_0/k_B T)$, but in the case of degenerate plasmas ($T << T_F$), $n_\uparrow - n_\downarrow = 3n\mu_B B_0/2k_B T_F$, with T_F being the Fermi temperature. The Second order magnetization current density,

$$J_{m\alpha x}^{(2)} = J_{m\alpha x2}E_0^2 e^{2i(kz-\omega t)} + c.c \tag{15a}$$

$$J_{m\alpha y}^{(2)} = J_{m\alpha y2}E_0^2 e^{2i(kz-\omega t))} + c.c \tag{15b}$$

where,

$$J_{m\alpha x2} = \frac{4i\mu_B k}{\hbar}\left[\frac{n_{\alpha 0}(n_\uparrow - n_\downarrow)}{n_{\alpha 0}}S_{\alpha y1} + n_{\alpha 0}S_{\alpha x2}\right],$$

$$J_{m\alpha y2} = \frac{-4i\mu_B k}{\hbar}\left[\frac{n_{\alpha 0}(n_\uparrow - n_\downarrow)}{n_{\alpha 0}}S_{\alpha x1} + n_{\alpha 0}S_{\alpha y2}\right]\cdot$$

The first order velocities, particle density and spin angular momentum teat together to produce second order nonlinear current at second harmonic radiation generation at $(2\omega, 2k)$ as,

$$J_{NL}^{(2)} = (J_{\alpha m2} + J_{\alpha c2})E_0^2 e^{2i(kz-\omega t)} + c.c \tag{16}$$

where,

$$J_{m\alpha 2} = \frac{-4ik\mu_B}{\hbar}\left[n_{\alpha 0}S_{\alpha x2} + n_{\alpha x2}S_{\alpha 0} + n_{\alpha x1}S_{\alpha x1} + n_{\alpha 0}S_{\alpha y2} + S_{\alpha 0}n_{\alpha y2} + n_{\alpha y1}S_{\alpha y1} + n_{\alpha 0}S_{\alpha z2} + S_{\alpha 0}n_{\alpha z2} + S_{\alpha z1}n_{\alpha z1}\right]$$

and

$$J_{\alpha c2} = -e.\left[n_{\alpha 0}v_{\alpha x2} + n_{\alpha x1}v_{\alpha x1} + n_{\alpha 0}v_{\alpha y2} + n_{\alpha y1}v_{\alpha y1} + n_{\alpha 0}v_{\alpha z2} + n_{\alpha z1}v_{\alpha z1}\right].$$

Further, there is a self-consistent second harmonic field $\vec{E}^{(2)} = E_2 e^{i(k_2 z - 2\omega t)}c.c$, that gives effect to the linear current density as given by .

$$\vec{J}_L^{(2)} = \left(\frac{ie^2 n_{\alpha 0}E_2}{2m\omega}\right)e^{i(k_2 z - 2\omega t)} + c.c\cdot \tag{17}$$

Second Harmonic Efficiency

We now proceed to obtain the normalized amplitude for the phase mismatched case, which is obtained by substitution of the first and second order currents in the wave equation. The normalized amplitude denoted as η comes out to be

$$\eta = \left|\frac{E_2}{E_0}\right| = \left[\frac{8\pi i a_0 mc(J_{c2} + J_{m2})(\omega/\omega_p)^2}{e\left\{\frac{2im\omega(J_c(2\omega) + J_m(2\omega))}{e^2 n_{\alpha 0}} + 1\right\}}e^{i\Delta k.z}\right]^2\cdot \tag{18}$$

where, $a_0 = \left(\frac{eE_0}{mc\omega_0}\right)$, and $\Delta k = (k_2 - 2k)$ represents the phase difference between the generated second harmonic and the fundamental frequency.

$$J_c(2\omega) = -en_{\alpha 0}\left[v_{\alpha x1} + v_{\alpha y1} + v_{\alpha z1}\right](2\omega),$$

$$J_m(2\omega) = \frac{-2ik\mu_B}{\hbar}\left[n_{\alpha 0}S_{\alpha x1} + n_{\alpha x1}S_{\alpha 0} + n_{\alpha 0}S_{\alpha y1} + n_{\alpha y1}S_{\alpha 0} + n_{\alpha 0}S_{\alpha z1} + S_{\alpha 0}n_{\alpha z1}\right]$$

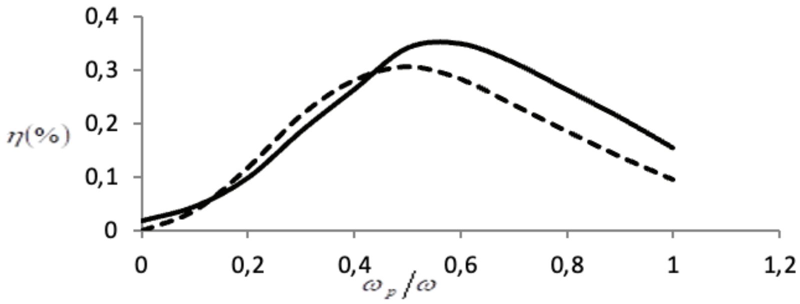

Figure. 1. Maximum conversion efficiency of second-harmonic generation η(%) as a function of normalized electron density ω_p/ω at $a_0 = 3$ and 5 (dashed and solid lines) and spin polarization 0.98.

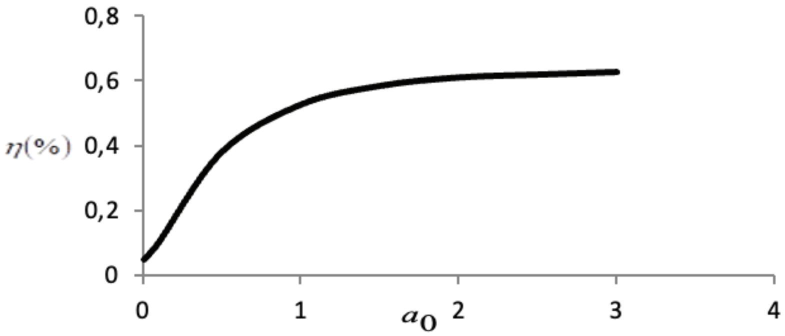

Figure 2. Maximum conversion efficiency of second-harmonic generation η(%) as a function of laser intensity a_0 at $\omega_p/\omega = 0.3$ and spin polarization 0.98.

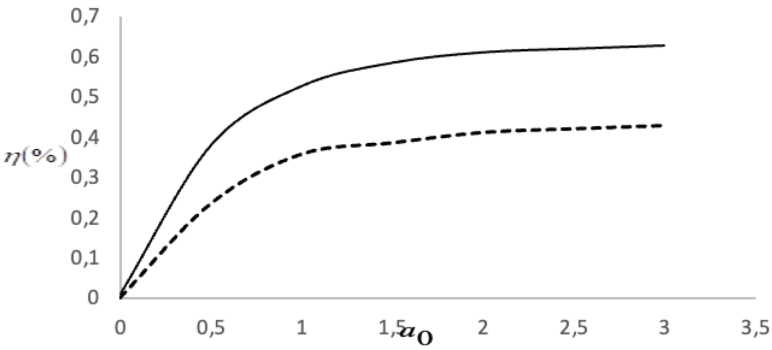

Figure 3. Variation of conversion efficiency of second harmonic with normalized laser intensity a_0 at $\omega_c/\omega = 0.3$ and $\omega_c/\omega = 0.5$ (dashed and solid lines).

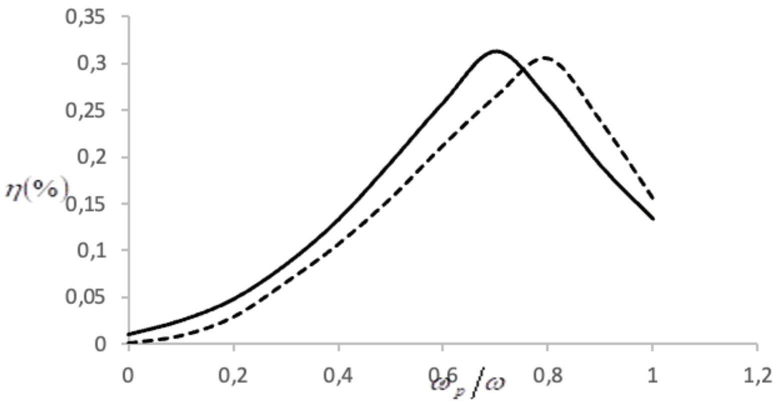

Figure. 4. Variation of conversion efficiency η(%) as a function of ω_p/ω, (i) solid line in the presence of spin effects and (ii) dashed line in absence of spin effects.

The conversion efficiency η(%) variation with normalized plasma electron density for a different values of laser field strengths ($a_0 = 3$) for dotted line and $a_0 = 5$ for solid line) is shown in Figure 1. The figure shows how harmonic radiation increases until saturation considering a constant laser beam and an increase in plasma density. The saturation value of plasma density depends on the applied laser field and is more for the weaker laser field.

The second harmonic conversion efficiency variation for a normalized plasma density has been shown with laser pulse strength in Figure 2. The efficiency increases for lower values of intensity, however conversion efficiency saturates at large value of the intensity of laser pulse.

Figure 3, the harmonic conversion efficiency varies with laser intensity for different magnetic field strength values ($\omega_c/\omega = 0.3$ for solid line and $\omega_c/\omega = 0.5$ for dashed line). The graph shows that when the laser intensity and magnetic field grow, correspondingly increases the conversion efficiency of formation of second harmonic radiation. Strong nonlinear current generation is the cause of the second harmonic conversion efficiency increasing with fundamental laser intensity. For high values of, the efficiency begins to saturate.

Figure 4 has been showed for parameters $\omega_c/\omega = 0.3$, $a_0 = 0.2$ and $n_0 = 10^{30}\ m^{-3}$ in order to compare the conversion efficiency of second harmonic due to presence as well as absence of spin in quantum plasma. The dashed line shows a situation where spin effects are not present and the upper solid line shows an increase in conversion efficiency if spin effects are present. The fact that spin effects play an important part in modifying the efficiency of the second harmonic of a circular pulse, it is seen from the figure that the presence of spin effects in magentoplasma represents for the about 3% increase in second harmonic conversion efficiency.

COCNLUSION

A study of SHG in homogenous high-density magnetized quantum plasma resulting from circularly polarized wave propagation is presented. The longitudinal direction is in which the static magnetic field is applied for magnetization. The recently established QHD model has been employed to develop the interaction mechanism. The quantum Bohm potential, the influence of spin density projection's evolution and the Fermi statistical pressure have all been investigated. The perturbative expansion of QHD equations resulted in the quiver and second order velocities, electron densities and spin angular momenta. The sum of the conventional current and the current derived from the spin magnetic moment is the nonlinear current density. The self-consistent field generates the linear current. The variations in particle concentrations can be observed through the spin density projection along the z-axis. The direction of the spin density projection on the external magnetic field is not an independent variable. It appears as a difference between the concentrations of two different electron spin states. For the phase mismatched situation, the SHG efficiency has been established. It is found that the SHG increases with plasma density and magnetic field up to the appropriate saturation values. Harmonic development disappears when saturation is obtained. Saturation of the plasma density occurs rapidly with stronger magnetic fields. The interesting finding is that high-density degenerate plasma shows enhanced SHG at lower levels of the external magnetic field intensity. The current research of second harmonic will be helpful in producing microelectronic devices, processing high-quality plasma and generating dc current for toroidal fusion devices.

AUTHORSHIP CONTRIBUTIONS

Authors equally contributed to this work.

DATA AVAILABILITY STATEMENT

The authors confirm that the data that supports the findings of this study are available within the article. Raw data that support the finding of this study are available from the corresponding author, upon reasonable request.

CONFLICT OF INTEREST

The author declared no potential conflicts of interest with respect to the research, authorship, and/or publication of this article.

ETHICS

There are no ethical issues with the publication of this manuscript.

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