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Laser second harmonic generation in a rippled density plasma in the presence of azimuthal magnetic field

U. VERMA AND A.K. SHARMA
Center for Energy Studies, Indian Institute of Technology Delhi, New Delhi, India
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Abstract

The strong azimuthal magnetic fields, observed in many laser plasma experiments, are shown to be a potential source of second harmonic generation. The laser imparts oscillatory velocity to electrons and exerts a longitudinal pondromotive force on them. This force in conjunction with the azimuthal magnetic field and density ripple produces a second harmonic current with significant transverse component. The latter produces resonant second harmonic radiation.

Keywords: Azimuthal magnetic field; Laser; Ripple density; Second harmonic generation

1. INTRODUCTION

Harmonic generation continues to be a fascinating field of research due to its various applications. Second harmonic generation (SHG) (Gupta *et al.*, 2007; Sharma & Sharma, 2009; Abdelli *et al.*, 1992; Liu & Tripathi, 1996; Giulietti, *et al.*, 1988; Upadhyay & Tripathi, 2005; Hafeez *et al.*, 2008; Ozaki *et al.*, 2007, 2008; Liu *et al.*, 1993; Huillier & Balcou, 1993) has become one of the most investigated and discussed nonlinear optical process since 1961, when Franken *et al.* (1961) experimentally discovered SHG. The primary reason to investigate SHG has consistently been the achievement of efficient frequency doubling, the emphasis has been on phase-matched interaction between the fundamental and second harmonic beam. Phase matching is a condition that essentially requires conversion of linear momentum that also facilitates energy flow from the pump to the second harmonic signal. Experiments on electron and ion acceleration in a laser pulse field using sources of super intense radiation require high time contrast of femtosecond pulses. An efficient way to enhance the contrast is a nonlinear optical process of SHG. Second harmonic generation signals have well-defined polarizations, and thus SHG polarization anisotropy can be used to determine the orientation of proteins in tissues. It can be used in studying buried interfaces, as most surface science techniques cannot access such structures. SHG can provide information of the electric field at an interface. It allows the penetration of the laser power into the overdense region and provides a valuable diagnostics (Merdji *et al.*, 2000; Verma *et al.*, 2009; Panwar *et al.*, 2009; Prasad *et al.*, 2009) of various plasma processes (Dromey *et al.*, 2009; Hafeez *et al.*, 2008). It also provides information about linear mode conversion of the laser into a plasma wave near the critical layer. It has been observed that the uniform plasmas cannot produce even harmonics neither by a plane nor by a circularly polarized electromagnetic wave. In most laser interactions with homogeneous plasma, odd harmonics are generated (Mori *et al.*, 1993; Zeng *et al.*, 1996). Even harmonics can be produced in the presence of density gradient at an angle to the direction of the wave propagation (Esaray *et al.*, 1993; Malka *et al.*, 1997).

The current investigations are dealing with the study of pulsed SHG under condition of phase and group velocity mismatch, and low conversion efficiencies and pump intensities, in negative index materials called artificially engineered meta-materials (Ramakrishna, 2005; Wang *et al.*, 2009). Ultraviolet and X-ray SHG (Chen *et al.*, 1995) in semiconductors have been reported, which shows that the subject is of interest for the purpose of realizing coherent sources. Centini *et al.* (2008) shown theoretically and experimentally the inhibition of linear absorption for phase and group velocity mismatch second and third harmonic generation in strongly absorbing materials, GaAs, in particular, at frequency above the absorption edge. Schifano *et al.* (1994) experimentally investigated the properties of the second harmonic emission and tested the effectiveness of this emission as a diagnostics for plasma inhomogenities induced by filamentation. Mironov *et al.* (2009) recently

Address correspondence and reprint requests to: U. Verma, Center for Energy Studies, Indian Institute of Technology Delhi, New Delhi-110016, India. E-mail: updeshv@gmail.com

observed the effect of instantaneous cubic nonlinearity on SHG of femtosecond laser pulses. They have also analyzed the possibility of improving generation efficiency and shortening pulse duration. He observed 60% energy conversion efficiency and showed that the additional correction of spectral phase at the SH significantly reduces pulse duration. Shen (1989) has shown that SHG is a versatile tool for studies of many kinds of surfaces and interfaces. Ultrashort laser pulses can be used to monitor surface dynamics and reaction with sub-picoseconds time resolution. Krushelnik *et al.* (1995) observed second harmonic shifted by the plasma frequency giving information about the stimulated Raman process. Liu *et al.* (1993) have observed harmonic generation using a 1 ps, 1 μm, variable intensity laser in hydrogen gas jet plasma produced by tunnel ionization. Parashar & Sharma (1998) have studied SHG by an obliquely incident laser on a vacuum-plasma interface and rippled metal surface. Dahiya *et al.* (2007) presented particle-in-cell (PIC) simulations of phase matched second and third harmonic in ripple density plasmas. Yadav *et al.* (2008) have investigated stimulated Compton scattering (SCS) and stimulated Brillion scattering (SBS) of second harmonic signals. Salih *et al.* (2003) have studied SHG in self-created magnetized plasmas. The harmonic amplitude shows resonant enhancement as ω_c tends to ω. Kaur and Sharma (2009) and Kura *et al.* (2009) have shown in a collisional magnetoplasma the self-defocusing of the laser causes reduction in the efficiency of second harmonic generation. Recently Verma and Sharma (2009) developed a paraxial theory of third harmonic generation by a finite spot size laser in a tunnel ionizing gas.

In this paper, we study the generation of second harmonic in the presence of magnetic field. Physical mechanism of generation of second harmonic is as follows: laser propagating through the plasma imparts oscillatory velocity on electrons and exerts a pondromotive force on them. This pondromotive force produces nonlinear oscillatory velocity at 2ω and then produces nonlinear current at 2ω frequency, hence second harmonic current is produced. In Section 2, we have calculated the linear and nonlinear current densities, and in Section 3 amplitude of second harmonic generation is calculated. Finally, in Section 4, we discuss the results.

2. CALCULATION OF LINEAR AND NONLINEAR CURRENT DENSITIES

Consider a laser produced plasma with rippled density $n_0 = n_0^0 + n_q$, $n_q = n_{0q}\, e^{iqz}$, and sheared magnetic field,

$$\vec{B}_s = -\hat{y}\, B_0 \frac{x}{x_0}. \quad (1)$$

The magnetic field resembles azimuthal magnetic field in the slab model. A laser propagates through the plasma with electric field

$$\vec{E}_L = \hat{x}\, A_0 e^{-x^2/x_0^2} e^{-i(\omega t - kz)}. \quad (2)$$

It imparts oscillatory velocity to electrons,

$$\vec{v}_\omega = \frac{e\vec{E}_L}{mi\omega},$$

where -*e* is the electronic charge, *m* is the mass of electron, and ω is the frequency of the laser, and we have assumed $\omega \gg eB_0/m$. The laser also exerts a second harmonic ponderomotive force on electrons

$$\vec{F}_{P,2\omega} = e\nabla\phi_P,$$

where

$$\phi_{P,2\omega} = \frac{eE_L^2}{2\,m\omega^2}. \quad (3)$$

The electron response to $\vec{F}_{P,2\omega}$ is governed by

$$m\frac{\partial \vec{v}_{2\omega}^{NL}}{\partial t} = -\vec{F}_{P,2\omega} - e\vec{v}_{2\omega}^{NL} \times \vec{B}_s.$$

Replacing ∇ by ik and $\partial/\partial t$ by $-i\omega$, we get

$$\vec{v}_{2\omega}^{NL} = \frac{e^2kE_L^2}{2\,m^2\omega^3}\frac{1}{1-\left(\frac{\omega_c}{2\omega}\right)^2}\hat{z} + \frac{\omega_c}{2i\omega}\frac{e^2kE_L^2}{2\,m^2\omega^3}\frac{1}{1-\left(\frac{\omega_c}{2\omega}\right)^2}\hat{x}. \quad (4)$$

The nonlinear second harmonic current density at (2ω, $2k+q$) can be written as

$$\vec{J}_{2\omega}^{NL} = -\frac{1}{2}n_q e\vec{v}_{2\omega}^{NL}. \quad (5)$$

One may note that the transverse component of second harmonic current density, $J_{2\omega\, x}^{NL}$, scales as ω_c, i.e., it is proportional to *x*, hence is zero on laser axis.

The linear response of electrons to the self-consistent second harmonic field $\vec{E}_{2\omega}$ is governed by

$$\frac{d\vec{v}_{2\omega}^L}{dt} + \vec{v}_{2\omega}^L \times \vec{\omega}_c = -\frac{e}{m}\vec{E}_{2\omega}. \quad (6)$$

Taking

$$\vec{E}_{2\omega} = \vec{A}_{2\omega}\, e^{-i(2\omega t - k_2 z)},\ \vec{\omega}_c = -\hat{y}\,\omega_{c0}\frac{x}{x_0}, \quad (7)$$

one obtains

$$v_{2x}^L = \frac{eE_{2\omega\,x}}{2im\omega} + \frac{eE_{2\omega\,z}}{2im\omega}\frac{\omega_c}{2i\omega},\ v_{2y}^L = \frac{eE_{2\omega\,y}}{2im\omega},$$
$$v_{2z}^L = \frac{eE_{2\omega\,z}}{2im\omega} - \frac{eE_{2\omega\,x}}{2im\omega}\frac{\omega_c}{2i\omega}, \quad (8)$$

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where we have assumed $(\omega_c/2\omega)^2 \ll 1$. The linear current density at 2ω can be written as

$$\vec{J}^L_{2\omega} = -n_0 e \vec{v}^L_{2\omega} = \underline{\underline{\sigma_2}}.\vec{E}_{2\omega}, \quad (9)$$

$$\sigma_{2zz} = \sigma_{2yy} = \sigma_{2xx} = -\frac{n_0 e^2}{2im\omega},$$
$$\sigma_{2xz} = -\sigma_{2zx} = -\frac{n_0 e^2}{2im\omega}\frac{\omega_c}{2i\omega},$$
$$\sigma_{2zy} = \sigma_{2xxy} = \sigma_{2yz} = 0.$$

3. SECOND HARMONIC GENERATION

The wave equation governing $\vec{E}_{2\omega}$ is

$$\nabla^2 \vec{E}_{2\omega} - \nabla(\nabla.\vec{E}_{2\omega}) + \frac{4\omega^2}{c^2}\underline{\underline{\varepsilon_2}}.\vec{E}_{2\omega} = -\frac{2i\omega}{c^2\varepsilon_0}\vec{J}^{NL}_{2\omega}, \quad (10)$$

where

$$\underline{\underline{\varepsilon_2}} = \underline{\underline{I}} + \frac{i}{2\omega\varepsilon_0}\underline{\underline{\sigma_2}}, \; \varepsilon_{2xx} = \varepsilon_{2yy} = \varepsilon_{2zz} = 1 - \frac{\omega_p^2}{4\omega^2},$$
$$\varepsilon_{2xz} = -\varepsilon_{2zx} = i\frac{\omega_p^2}{4\omega^2}\frac{\omega_c}{2\omega},$$
$$\varepsilon_{2xy} = \varepsilon_{2yx} = \varepsilon_{2yz} = \varepsilon_{2zy} = 0.$$

Since $\vec{E}_{2\omega}$ has fast variation along $\hat{z}$ and slow in $\hat{x}$, i.e. $\partial/\partial x \ll \partial/\partial z$, we get from the z component of Eq. (10)

$$E_{2\omega z} = -\frac{i}{2\omega\varepsilon_0}\frac{\vec{J}^{NL}_{2\omega}}{\varepsilon_{2xx}} + \frac{\varepsilon_{2xz}}{\varepsilon_{2xx}}E_{2\omega x} + \frac{c^2}{4\omega^2}\frac{1}{\varepsilon_{2xx}}\frac{\partial^2}{\partial z\partial x}E_{2\omega x}. \quad (11)$$

Using this value in the x component of Eq. (10) we get

$$\frac{\partial^2}{\partial z^2}E_{2\omega x} + \frac{\partial^2}{\partial x^2}E_{2\omega z} + \frac{4\omega^2}{c^2}\left(\frac{\varepsilon_{2xx}^2 + \varepsilon_{2xz}^2}{\varepsilon_{2xx}^2}\right)E_{2\omega x} = -\frac{2i\omega}{c^2\varepsilon_0}J^{NL}_{2\omega x} - \frac{4\omega^2}{c^2}\frac{\varepsilon_{2xz}}{2i\omega\varepsilon_0\varepsilon_{2xx}}J^{NL}_{2\omega z} + \frac{\partial^2}{\partial z\partial x}\left(\frac{J^{NL}_{2\omega z}}{2i\omega\varepsilon_0\varepsilon_{2xx}}\right). \quad (12)$$

Using the values of $\underline{\underline{\varepsilon_2}}$ from above we may write

$$\frac{\varepsilon_{2xx}^2 + \varepsilon_{2xz}^2}{\varepsilon_{2xx}^2} = \varepsilon_{00} - \varepsilon_2\frac{x^2}{x_0^2}, \quad (13)$$

where $\omega_p^2 = (n_0 e^2/m\varepsilon_0)$, $\omega_{c0} = eB_0/m$, $\varepsilon_{00} = 1 - (\omega_p^2/4\omega^2)$, and $\varepsilon_2 = (\omega_{c0}^2/4\omega^2)(\omega_p^2/\,(4\omega^2 - \omega_p^2))$. Then Eq. (12) can be written as

$$\frac{\partial^2}{\partial z^2}E_{2\omega x} + \frac{\partial^2}{\partial x^2}E_{2\omega z} + \frac{4\omega^2}{c^2}\left(\varepsilon_{00} - \varepsilon_2\frac{x^2}{x_0^2}\right)E_{2\omega x} = R, \quad (14)$$

where

$$R = -\frac{2i\omega}{c^2\varepsilon_0}J^{NL}_{2\omega x} - \frac{4\omega^2}{c^2}\frac{\varepsilon_{2xz}}{2i\omega\varepsilon_0\varepsilon_{2xx}}J^{NL}_{2\omega z} + \frac{\partial^2}{\partial z\partial x}\left(\frac{J^{NL}_{2\omega z}}{2i\omega\varepsilon_0\varepsilon_{2xx}}\right). \quad (15)$$

Writing

$$E_{2\omega x} = A_2(x)e^{-i(2\omega t - k_2 z)} \text{ and } R = R_0(x)e^{-i(2\omega t - k_2 z)}, \quad (16)$$

where $k_2 = 2k + q$, Eq. (14) can be written as

$$2ik_2\frac{\partial A_2}{\partial z} + \frac{\partial^2}{\partial x^2}A_2 + \left[\left(\frac{4\omega^2}{c^2}\varepsilon_{00} - k_2^2\right) - \frac{4\omega^2}{c^2}\varepsilon_2\frac{x^2}{x_0^2}\right]A_2 = R_0. \quad (17)$$

The phase matching condition for resonant second harmonic generation is

$$2k + q = \frac{2\omega}{c}\left(1 - \omega_p^2/4\omega^2\right)^{1/2}.$$

If right-hand-side of Eq. (17) is ignored, it resembles the Harmonic oscillator equation,

$$\frac{\partial^2 A_2}{\partial \xi^2} + (\lambda_n - \xi^2)A_2 = 0, \quad (18)$$

with $\xi = x/a$, $\lambda_n = \left(\frac{4\omega^2}{c^2}\varepsilon_{00} - k_2^2\right)a^2 = 2n + 1$ and $a^2 = (c/2\omega)(x_0/\sqrt{\varepsilon_2})$. The above equation has bounded solutions. The first two Eigen modes with corresponding eigen values are

$$A_{21}(\xi) = e^{-\xi^2/2}, \text{ for } n = 0,\ \lambda_n = 1,$$

$$A_{22}(\xi) = \xi e^{-\xi^2/2}, \text{ for } n = 1,\ \lambda_n = 3. \quad (19)$$

Since R_0 is proportional to x, the coupling of only $n = 1$ mode of the second harmonic to the pump is relevant. In the presence of right-hand-side in Eq. (17), we presume that the mode structure of $E_{2\omega}$ remains the same but amplitude acquires a z-dependence. Thus, we write

$$A_2(x, z) = F(x)G(z), \quad (20)$$

where

$$F(x) = (x/a)\,e^{-x^2/2a^2}, \quad (21)$$

substituting this in Eq. (17) multiplying the resulting equation by Fdx and integrating over x from $-\infty$ to ∞, we get

$$\frac{\partial}{\partial z}G(z) = \frac{1}{2ik_2(\Gamma_{20}/a)}\frac{I_1}{I_2},$$

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where

$$I_1 = \int_{-\infty}^{\infty} R_0 \, x \, e^{-x^2/2a^2} dx \quad \text{and } I_2 = \int_{-\infty}^{\infty} x^2 e^{-x^2/a^2} dx. \qquad (22)$$

After solving it we get

$$|G(z)| = \frac{A_0^2 a}{8ik_2\sqrt{2}a^3} \frac{\omega_{pq}^2 \, ek \, z}{2\, m\omega^3 \alpha^{3/2}} \times \left[\frac{2}{x_0^2} \frac{k_2}{\omega} \frac{1}{\left(1 - \omega_p^2/4\omega^2\right)} + \frac{\omega_{c0}}{c^2 x_0} + \frac{\omega_p^2}{4\omega^2} \frac{\omega_{c0}}{c^2 x_0} \right]. \qquad (23)$$

The normalized second harmonic amplitude can be written as

$$\left|\frac{G(z)}{A_0}\right| = \frac{a_0}{16\sqrt{2}} \left(\frac{n_{q0}}{n_0^0}\right) \left(\frac{\omega_p^2}{\omega^2}\right) \left(\frac{k}{k_2}\right) \times \left[\frac{(2\,k_2/a^2\alpha^{3/2})(\omega_p z/c)(\omega_p/\omega)}{(r_0\omega_p/c)^2(1-\omega_p^2/4\omega^2)} + \frac{(\omega_{c0}/ca^2\alpha^{3/2})}{(r_0\omega_p/c)} + \frac{(\omega_{c0}/ca^2\alpha^{3/2})(\omega_p^2/4\omega^2)(\omega_p z/c)}{(r_0\omega_p/c)} \right] \qquad (24)$$

where

$$\frac{2\,k_2}{a^2\alpha^{3/2}} = \frac{8(1-\omega_p^2/4\omega^2)^{1/2}\sqrt{\varepsilon_2}}{(r_0\omega_p/c)(\omega_p/\omega)^2[2/(r_0\omega_p/c)^2 + \sqrt{\varepsilon_2}/(\omega_p/\omega)(r_0\omega_p/c)]^{3/2}},$$

$$\frac{\omega_{c0}}{ca^2\alpha^{3/2}} = \frac{2\sqrt{\varepsilon_2}}{(r_0\omega_p/c)(\omega_p/\omega)(\omega_p/\omega_{c0})[2/(r_0\omega_p/c)^2 + \sqrt{\varepsilon_2}/(\omega_p/\omega)(r_0\omega_p/c)]^{3/2}},$$

with $\alpha = (2/x_0^2) + (1/2a^2)$ and $A_0 =$ amplitude of the laser.

We have solved Eq. (24) numerically for the following parameters: $\omega_{c0}/\omega = 0.2$, 0.4, $a_0 = 0.4$, $n_{q0}/n_0^0 = 0.3$, $\omega_p^2/\omega^2 = 0.05$, 0.1 and $\omega_p \, z/c = 1000$.

In Figure 1, we have plotted the normalized second harmonic amplitude as a function $\omega_p \, r_0/c$ for $\omega_{c0}/\omega = 0.2$, and 0.4. At small laser spot size, the ratio of second harmonic amplitude to the amplitude of the fundamental wave is low as the electromagnetic modes are strongly localized. As the laser spot size grows, the no local effects. As the laser spot size grows, the nonlocal effects become important and magnetic field effects are there. As magnetic field increases i.e., ω_{c0}/ω from 0.2 to 0.4 second harmonic generations become fast and its normalized amplitude increases from 0.09 to 0.185. This is due to the fact that as the laser goes into the plasma its spot size increases and magnetic field coupling becomes stronger and hence nonlinearity increases. Thus, more and more second harmonic generates. After some value of $\omega_p \, r_0/c$ generation of second harmonic saturates. Since as the spot size becomes larger, non-local effects become un- important and hence the amplitude of the second harmonic saturates. In Figure 2, variation in normalized second harmonic amplitude is plotted with $\omega_p \, r_0/c$ for different values of $\omega_p^2/\omega^2 = 0.05$ and 0.1. Figure 2 shows that as the electron density increases more and more, the second harmonic generates likewise. By increasing the electron density, the nonlinearity increases. As SHG is a nonlinear phenomenon, it increases more and more. As ω_p^2/ω^2 increases from $= 0.05$ to $= 0.1$ the amplitude of second harmonic increases from 0.135 to 0.195.

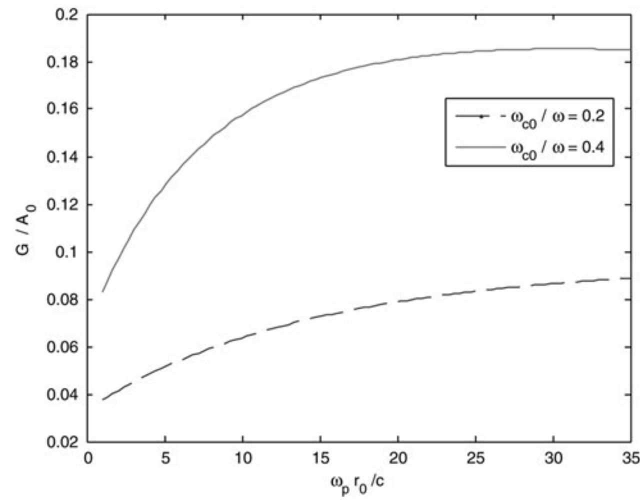

Fig. 1. Variation in normalized second harmonic amplitude with $\omega_p \, r_0/c$ for $\omega_{c0}/\omega = 0.2$ and 0.4. The other parameters are: $a_0 = 0.4$, $n_{q0}/n_0^0 = 0.3$, $\omega_p^2/\omega^2 = 0.1$ and $\omega_p \, z/c = 1000$.

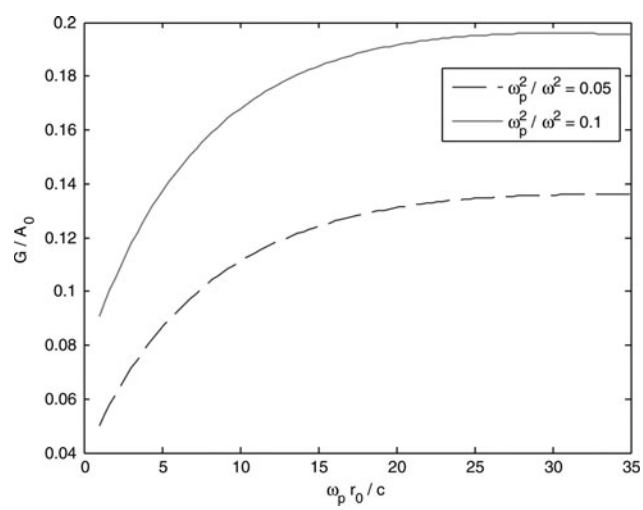

Fig. 2. Variation in normalized second harmonic amplitude with $\omega_p \, r_0/c$ for $\omega_p^2/\omega^2 = 0.05$ and 0.1. The other parameters are: $a_0 = 0.4$, $n_{q0}/n_0^0 = 0.3$, $\omega_{c0}/\omega = 0.4$ and $\omega_p \, z/c = 1000$.

4. DISCUSSION

Second harmonic signals are very useful in reading DVD's as they can read a four times smaller area than the fundamental signal of the laser. We find that as magnetic field increases,

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generation of second harmonic becomes faster. This happens due to the strong coupling between magnetic field and laser field. Here ripple density provides phase matching between fundamental and second harmonic beam. Phase matching is a condition that essentially requires conversion of linear momentum that also facilitates energy flow from the pump to the second harmonic signal. Hence, more and more second harmonic generates. Electron density also plays important role since as electron density increases for particular value of magnetic field nonlinearity increases and hence second harmonic generation increases.

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