American Journal of Applied Sciences 5 (8): 1034-1040, 2008
ISSN 1546-9239

General Properties of $\frac{3}{2}\omega_0$ and $2\omega_0$ Harmonics Emission from Laser Driven Plasmas

A.S.A. Dib and A.H. Belbachir
Department of Physics, Laboratory of Analysis and Application of Radiation (LAAR),
University of Sciences and Technology of Oran, BP 1505,
EL-M'Naouer, Oran 31000, Algeria

Abstract: Using a simple model based on the conversion of electron plasma waves into electromagnetic waves through a process of parametric interaction of four waves, the general properties of the $\frac{3}{2}\omega_0$ emission and the $2\omega_0$ emission generated by the interaction of a Gaussian laser pulse with homogeneous plasma are studied. Some known characteristics of these emissions are reproduced within this model and compared to some experimental works. In particular, the two-wing structure of the emitted spectrum, the double-beam structure, the angular distribution and the conversion efficiency are obtained. Moreover, it is found that, the intensity of the backward beam is almost double of that of the forward beam in both emissions, while this later is narrower in the case of the $\frac{3}{2}\omega_0$ emission.

Key words: Plasma waves interaction, harmonics generation in plasmas, $\frac{3}{2}\omega_0$ and $2\omega_0$ emissions

INTRODUCTION

Harmonic generation through the interaction of high power lasers with plasmas has been the subject of many experimental and theoretical studies[1-12] beginning with the work by Burnett *at al*.[1] in the late 1970's, using CO_2 laser. During the last recent years, this area of research has become more active for at least two reasons. The first one is the affordability of high intensity lasers based on the chirp pulse amplification. The second one is the fact that the different harmonic generation processes convert, with a promising efficiency, the laser light from the visible and infrared into an UV spectrum, which has some attractive characteristics suitable for many research and technological applications such as investigating surface dynamics with time-resolved techniques which is capable of monitoring ultra-fast dynamical changes of surface properties[13], imaging experiments of molecular orbital in chemistry and biology[14] and diagnostics in fast ignition of laser fusion targets through the $\frac{3}{2}\omega_0$ emission measurement. This kind of light emissions occur when an intense laser pulse is focused into a gas[8-10] or solid[11,12] through different processes. The $\frac{3}{2}\omega_0$ emission and the $2\omega_0$ emission processes are attributed to the development of the parametric instabilities in the region of the quarter critical density $\frac{1}{4}n_c$ of the plasma and near the critical density region, respectively [15-20]. While the emission of higher order harmonics or the so-called High Harmonic Generation (HHG) is according to Quéré *et al*.[11], du to two different processes.

The first one is the process known as the oscillating mirrors (OM)[19,20] in which the intense laser field drives a relativistic oscillation of plasma surface, which causes a periodic phase modulation of the reflected light and, hence, the emission of harmonics of the laser frequency. The second one is the process called by Quéré *et al*.[11] the coherent wake emission (CWE), in which this emission can be driven by the electron plasma waves generated around the critical density by the ponderomotive force of a laser pulse.

In this study, we present a model for the emissions of $\frac{3}{2}\omega_0$ and $2\omega_0$ modes based on the conversion of electron plasma waves into electromagnetic waves

Corresponding Author: A.S.A. Dib, Department of Physics, Laboratory of Analysis and Application of Radiation (LAAR), University of Sciences and Technology of Oran, BP 1505, EL-M'Naouer, Oran 31000, Algeria

through a process of parametric interaction of four waves.

THEORETICAL MODEL

Our study is based on a two-fluid model of plasma coupled with Maxwell equations. We start with the following equations:

Continuity equation:

$$\frac{\partial n_\alpha}{\partial t} + \vec{\nabla}\left(n_\alpha \vec{v}_\alpha\right) = 0 \quad (1)$$

Momentum equation:

$$n_\alpha \frac{\partial \vec{v}_\alpha}{\partial t} + n_\alpha \vec{v}_\alpha \vec{\nabla} \vec{v}_\alpha = \frac{n_\alpha q_\alpha}{m_\alpha}\left(\vec{E} + \frac{\vec{v}_\alpha \times \vec{B}}{c}\right) - \frac{\vec{\nabla} P_\alpha}{m_\alpha} - \sum_\beta n_\alpha \nu_{\alpha\beta}\left(\vec{v}_\alpha - \vec{v}_\beta\right) \quad (2)$$

Wave equation:

$$\Delta \vec{E} - \frac{\partial^2 \vec{E}}{c^2 \partial t^2} = 4\pi q_\alpha \vec{\nabla} n_\alpha + \frac{4\pi}{c^2}\sum_\beta q_\alpha \frac{\partial\left(n_\alpha \vec{v}_\alpha\right)}{\partial t} \quad (3)$$

Poisson equation:

$$\vec{\nabla}.\vec{E} = 4\pi \sum_\alpha q_\alpha n_\alpha \quad (4)$$

Where $n_\alpha(t,r)$, $v_\alpha(t,r)$ and q_α are respectively, the plasma density, the plasma fluid velocity and the electrical charge of the plasma specie α (electron or ion). E and B are the total electric field and the total magnetic induction and $\vec{\nabla} P_\alpha(t,\vec{r})$ is the pressure-gradient force.

We assume that the 3/2 ω_0 wave (k_3, $\omega_3 = 3/2\ \omega_0$) emission is resulting from the combination of the laser wave (k_0,ω_0) with a Plasmon wave (k_1,ω_1) which itself is resulting from a two-Plasmon decay ((k_0,ω_0)→(k_1,ω_1), (k_2,ω_2)). Similarly, the $2\omega_0$ wave ($k_3,\omega_3 = 2\omega_0$) is assumed to be resulting from the combination of the laser wave (k_0,ω_0) with a Plasmon (k_1,ω_1) wave which itself is resulting from an Ion-Plasmon decay.

Therefore, in both cases, we have to deal with a resonant interaction of four waves. In order to obtain the coupled equations describing this four-wave process we decompose the fluid variables into wave's components. In particular, the electric field, the plasma density and its fluid velocity can be written as follows:

$$\vec{E} = \vec{E}_0 + \vec{E}_1 + \vec{E}_2 + \vec{E}_3 \quad (5)$$

$$n_\alpha(t,\vec{r}) = n_0 + \frac{1}{2}\left(\delta n_{\alpha 1}(t) e^{i\left(\omega_1 t - \vec{k}_1.\vec{r}\right)} + \delta n_{\alpha 2}(t) e^{i\left(\omega_2 t - \vec{k}_2.\vec{r}\right)} + c.c\right) \quad (6)$$

$$\vec{v}_\alpha(t,\vec{r}) = \frac{q_\alpha}{2m_\alpha}\left(\frac{\vec{e}_0 E_0(t)}{\omega_0} e^{i\left(\omega_0 t - \vec{k}_0.\vec{r}\right)} + \frac{\vec{e}_1 E_1(t)}{\omega_1} e^{i\left(\omega_1 t - \vec{k}_1.\vec{r}\right)} + \frac{\vec{e}_2 E_2(t)}{\omega_2} e^{i\left(\omega_2 t - \vec{k}_2.\vec{r}\right)} + \frac{\vec{e}_3 E_3(t)}{\omega_3} e^{i\left(\omega_3 t - \vec{k}_3.\vec{r}\right)} + c.c\right) \quad (7)$$

Here $\vec{k}_i$ and $\vec{e}_i$ denote respectively, the wave vectors and the polarization vectors of the interacting waves. Using the expressions of equations 5, 6 and 7 in equations 1, 2 and 4 and assuming the following resonance conditions;

$$\vec{k}_0 = \vec{k}_1 + \vec{k}_2,\ \omega_0 = \omega_1 + \omega_2 \quad (8)$$

$$\vec{k}_3 = \vec{k}_0 + \vec{k}_1,\ \omega_3 = \omega_0 + \omega_1 \quad (9)$$

One can obtain the following coupled equations describing the process of generation of the $\frac{3}{2}\omega_0$ and the $2\omega_0$ harmonics in plasma.

$$\left(\frac{\partial}{\partial t} + \Gamma_2\right)\delta n_{\alpha 2}(t) = \mu_2 E_0(t)\delta n^*_{\alpha 1}(t) \quad (10)$$

$$\left(\frac{\partial}{\partial t} + \Gamma_1\right)\delta n^*_{\alpha 1}(t) = \mu_1 E^*_0(t)\delta n^*_{\alpha 2}(t) + \mu'_1 E^*_3(t) E_0(t) \quad (11)$$

$$\left(\frac{\partial}{\partial t} + \Gamma_3\right)E^*_3(t) = \mu_3 E^*_0(t)\delta n^*_{\alpha 1}(t) \quad (12)$$

Table1: Coupling coefficients of interacting waves

Coefficients	$3/2\omega_0$ emission	$2\omega_0$ emission
μ_2	$-\dfrac{ik_1e(\vec{e}_0.\vec{e}_1)(\omega_0-\omega_1(1+\frac{k_2^2}{k_1^2}))}{2m\omega_2\omega_0}$	$-\dfrac{imeZk_2^3(\vec{e}_0.\vec{e}_2)\omega_1}{2Mm\omega_2\omega_0k_1^2}$
μ_1	$\dfrac{ik_1e(\vec{e}_0.\vec{e}_1)(\omega_0-\omega_2(1+\frac{k_1^2}{k_2^2}))}{2m\omega_1\omega_0}$	$\dfrac{iZek_2e(\vec{e}_0.\vec{e}_1)(\omega_0-\omega_2(1+\frac{k_1^2}{k_2^2}))}{2m\omega_1\omega_0}$
$\mu_1^{'}$	$\dfrac{in_0e^2k_1^2(\vec{e}_0.\vec{e}_3)}{2m^2\omega_1\omega_3\omega_0}$	$\dfrac{in_0Ze^2k_1^2(\vec{e}_0.\vec{e}_3)}{2m^2\omega_1\omega_3\omega_0}$
μ_3	$\dfrac{i\omega_{pe}^2(\vec{e}_0.\vec{e}_3)}{2n_0\omega_0}$	$\dfrac{iZ\omega_{pe}^2(\vec{e}_0.\vec{e}_3)}{2n_0\omega_0}$
Γ_1	$\dfrac{\nu_{ei}}{2}$	$\dfrac{k_1^2\lambda_{De}^2\nu_{ei}}{2}$
Γ_2	$\dfrac{\nu_{ei}}{2}$	$\dfrac{\nu_{ei}}{2}$
Γ_3	$\dfrac{\omega_{pe}^2\nu_{ei}}{2\omega_3^2}$	$\dfrac{\omega_{pe}^2\nu_{ei}}{2\omega_3^2}$

Where the collision frequency is given by $\nu_{ei}=\left(\dfrac{\pi}{2T_e}\right)^{\frac{3}{2}}\dfrac{n_0e^2}{\sqrt{m_e}}\ln(12\pi n_0\lambda_{De}^3)$

Where $E_0(t)$ is the slowly varying complex amplitudes of the laser wave electric field. $\delta n_1(t)$ and $\delta n_2(t)$ are the slowly varying plasma densities corresponding to the two excited electrostatic plasma waves, which describe the two Plasmon decay in the case of the $\frac{3}{2}\omega_0$ emission or, the Ion-Electron decay in the case of the $2\omega_0$ emission. $E_3(t)$ is the slowly varying complex amplitudes of the electric field of the considered harmonic($\frac{3}{2}\omega_0$ or $2\omega_0$).

Γ_1, Γ_2 and Γ_3 are the damping constants of the plasma waves, μ_1, $\mu_1^{'}$, μ_2 and μ_3 are the coupling constants (Table 1). θ_1 and θ_2 are the directions of propagation of the resulting daughter waves (k_1,ω_1), (k_2, ω_2) of the pump wave decay, while θ_3 is the propagation direction of the resulting harmonic (k_3, ω_3). The z-axis is chosen in the direction of propagation of the laser wave.

This model is valid for the description of the linear stage of the interaction of an intense laser beam with plasma. It can also be extended to include the $\frac{3}{2}\omega_0$ emission related to the combination of the Plasmon of the Stimulated Raman Scattering (SRS) with the laser wave and, the $2\omega_0$ emission, related to the laser scattering off the electromagnetic scattered wave of the Stimulated Brillouin Scattering (SBS).

RESULTS AND DISCUSSION

The coupled equations 10, 11 and 12 can be solved, numerically for example, for the amplitudes of the electric field of the considered harmonic $E_3(t,p)$; here p is a parameter which can be the frequency ω_i or the wave vector k_i or the emission direction θ_i of any one of the interacting plasma waves (k_1,ω_1), (k_2, ω_2) and (k_3, ω_3).

To obtain the value of any of these parameters we have solved a set of equations composed of Eq. 8, 9 and the three corresponding linear dispersion relations; $\omega^2=\omega_p^2+3v_{th}^2k^2$ for Plasmon wave, $\omega^2=c_s^2k^2$ for the Ion-acoustic wave and $\omega^2=\omega_p^2+c^2k^2$ for the electromagnetic wave. The initial conditions used for the solution of the coupled differential equations are;

$$|\delta n_{\alpha 1}(0)| = |\delta n_{\alpha 2}(0)| \approx 10^{-3} n_c$$

and

$$|\vec{E}_3(0)| = 0$$

Where n_c is the critical density of the plasma. Some characteristic properties of these harmonics can be investigated by studying their emitted intensity $I_3(t,p) = \frac{c}{\pi}|E_3(t,p)|^2$ as a function of time and the parameter p.

$\frac{3}{2}\omega_0$ and $2\omega_0$ harmonics spectrum: For instance, one may define and study the emitted energy per unit surface of the emitted harmonic mode due to one laser pulse only as a function of its wavelength λ_3 or as a function of its emission angle θ_3 through the quantity;

$$\varepsilon_3(\omega_3) = \int_0^\infty I_3(t,\omega_3)dt \qquad (13)$$

Or

$$\varepsilon_3(\theta_3) = \int_0^\infty I_3(t,\theta_3)dt \qquad (14)$$

Figure 1 shows that the spectrum of the emitted energy during one laser pulse, $\varepsilon_3(\lambda_3)$ of the resulting mode $(\mathbf{k}_3, \omega_3)$ of the combination of the laser wave $(\mathbf{k}_0, \omega_0)$ with a Plasmon wave $(\mathbf{k}_1, \omega_1)$ in the case of Two-Plasmon decay has a red shifted wing and a blue shifted wing around the value 749 nm which corresponds to the wavelength of the exact frequency $2\omega_0$.

Similarly, Fig. 2 shows a two wings structure around the value 610 nm which corresponds to the wavelength of the exact frequency $2\omega_0$, for the emitted energy $\varepsilon_3(\lambda_3)$ of the resulting mode $(\mathbf{k}_3, \omega_3)$ from the combination of the laser wave $(\mathbf{k}_0, \omega_0)$ with a Plasmon wave $(\mathbf{k}_1, \omega_1)$ of the Ion-Acoustic decay. Several experimental works[15-20] have obtained the two-wing structure of the $\frac{3}{2}\omega_0$ spectrum and discussed their possible origins. Within our model, we may simply attribute the blue shifted spectrum to the $\frac{3}{2}\omega_0$ photons resulting from the combination of a forward Plasmon with the laser photon and the red shifted spectrum to the $\frac{3}{2}\omega_0$ photons resulting from the combination of a backward Plasmon with the laser photon.

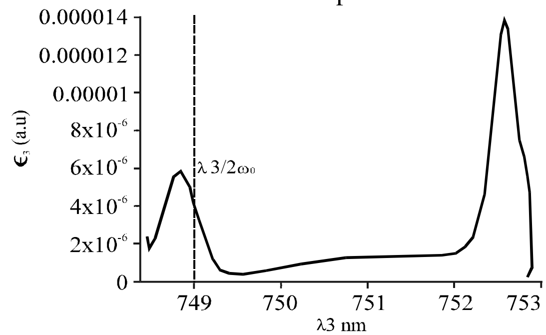

Fig. 1: The spectrum of the emitted energy per unit surfaceϵ $\varepsilon_3(\lambda_3)$ of the three half harmonic mode due to one Gaussian laser pulse for a laser intensity $I_0 = 10^{14}$ Watt cm^{-2}, plasma density $n_0 \approx 0.244\ n_c$, electron and ion temperatures Te = 1 KeV, $T_i = T_e/3$ and a laser pulse duration τ = 0.35 ps. The wavelength $\lambda = \lambda_{\frac{3\omega_0}{2}}$ = 749 nm which corresponds to the exact frequency $\frac{3}{2}\omega_0$ is in the blue shifted wing. The red shifted wing is much more important than the blue shifted wing

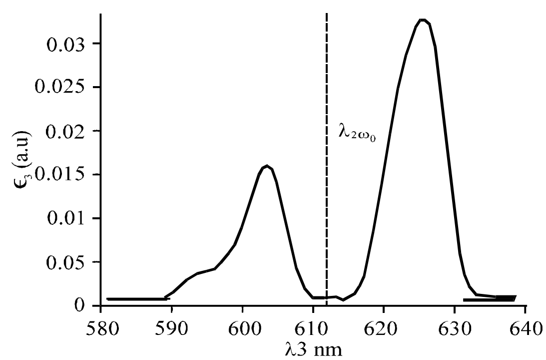

Fig. 2: The spectrum of the emitted energy per unit surface ϵ $\varepsilon_3(\lambda_3)$ of the $2\omega_0$ emission mode due to one Gaussian laser pulse for a laser intensity $I_0 = 10^{14}$ Watt cm^{-2}, plasma density $n_0 \approx 0.98\ n_c$, electron and ion temperatures Te = 1 KeV, $T_i = T_e/3$ and a laser pulse duration τ = 1.2 ps. The central wavelength $\lambda = \lambda_{2\omega_0}$ = 610 nm corresponds to the exact frequency $2\omega_0$. The red shifted wing is more important than the blue shifted wing

Temporal evolution and angular distribution: The intensity of emitted harmonic $I_3(t,\theta_3)$ can be studied as function of the time *t* and the emission angle θ_3.

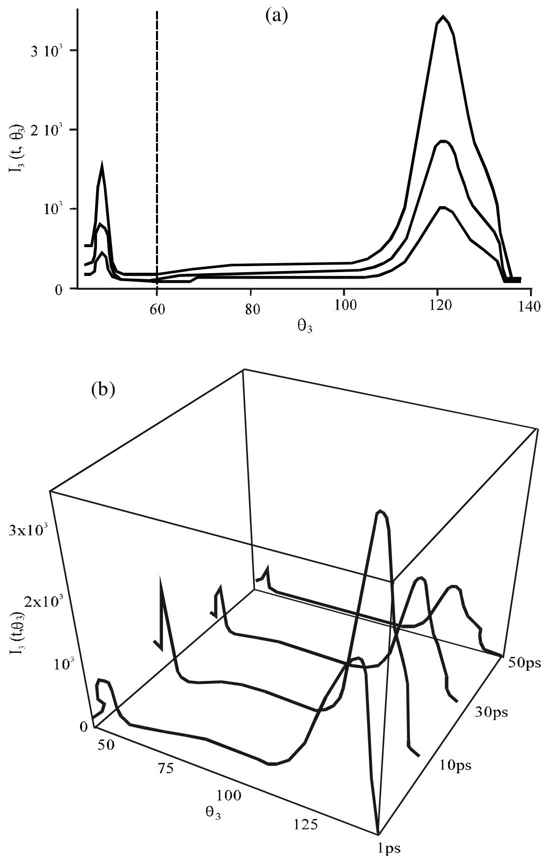

Fig. 3: Temporal evolution and angular distribution of the $\frac{3}{2}\omega_0$ emission due to one Gaussian laser pulse for a laser intensity $I_0 = 10^{14}$ Watt cm^{-2}, plasma density $n_0 \approx 0.244\ n_c$, electron and ion temperatures Te = 1 KeV, $T_i = T_e/3$ and laserpulse duration $\tau = 0.35$ ps

Figures 3a and 3b show the time evolution and the angular distribution of the intensity of the $\frac{3}{2}\omega_0$ emission. As it can be seen from the angular distribution, the emitted intensity is concentrated around two directions. The first one has an angle of about 45° and the second one has an angle of about 125°. The intensity of the light beam emitted in the 125° direction is almost double of that of the light beam emitted in the direction of 45°, while this later is narrower. This result is globally in agreement with some experimental results[12,16,17,19,20], which in particular have demonstrated the existence of the two-beam structure for the $\frac{3}{2}\omega_0$ emission.

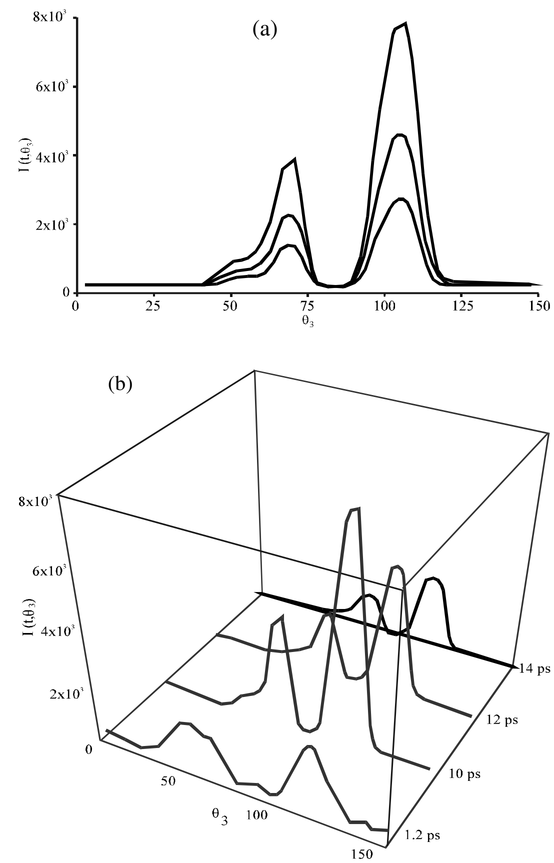

Fig. 4: Temporal evolution and angular distribution of the $2\omega_0$ emission due to one Gaussian laser pulse for a laser intensity $I_0 = 10^{14}$ Watt cm^{-2}, plasma density $n_0 \approx 0.98\ n_c$, electron and ion temperatures Te = 1 KeV, $T_i = T_e/3$ and laser pulse duration $\tau = 01.2$ ps

References[12,20] have reported an angle of about 65°-70° for the forward beam and an angle of about 110°-120° for the backward beam, while reference[17] has obtained the maximum forward at 37° and the backward maximum at 153°, with respect to the laser incidence. They also have found that the angular distribution is also subject to the variation of the experimental parameters such as pulse-prepulse time delay and plasma scale length.

Similarly, Fig. 4a and b show the time evolution and the angular distribution of the $2\omega_0$ emission intensity. As it can be seen from these figures, this emission is concentrated around two principal directions. The first one is 75° with respect to the laser incidence and the second one is 115° with respect to the laser incidence. The emission intensity around the 75° is almost double of that around the 115°.

The backward beam emission around 115° has been reported by several experimental works, however, to the best of our knowledge, the forward beam emission has not been reported before. However, reference[21] pointed out that the disappearance of the double-beam structure for $2\omega_0$ emission is a consequence of spatial effects. We have found that the intensity of both, the $\frac{3}{2}\omega_0$ emission and the $2\omega_0$ emission increases with the laser intensity in the range of 10^{11}-10^{15} watt cm^{-2}, but their angular distribution does not change. This is may be because of our simple model which cannot take into account the spatial effects and of the plasma.

Conversion efficiency of $\frac{3}{2}\omega_0$ and $2\omega_0$ harmonics generation: In order to study the conversion efficiency of a laser pulse into $\frac{3}{2}\omega_0$ and $2\omega_0$ emissions, one may define this efficiency Є as the total energy of the generated harmonic mode, emitted in all directions, due to one laser pulse only, divided by the total energy of the laser pulse.

From equation 14, one may define the conversion efficiency as;

$$\in = \frac{\int_0^{\pi} \varepsilon_3(\theta_3)\,d\theta_3}{\int_0^{\infty} I_0(t)\,dt} = \frac{\int_0^{\pi} d\theta_3 \int_0^{\infty} I_3(t,\theta_3)\,dt}{\int_0^{\infty} I_0(t)\,dt} \qquad (15)$$

In this study, where we have assumed homogeneous plasma, we have found that, the conversion efficiency as given by equation 15 is approximately 6×10^{-4} for the $2\omega_0$ emission. Tarasevitch *et al*.[12] have experimentally obtained conversion efficiency of the order of 10^{-4} for the $\frac{3}{2}\omega_0$ emission.

CONCLUSION

In this article, we have used a two-fluid plasma model to study the general properties of the $\frac{3}{2}\omega_0$ emission and the $2\omega_0$ emission generated by the interaction of a Gaussian laser pulse with homogeneous plasma. The model of these emissions is based on the conversion of electron plasma waves into electromagnetic waves through a process of parametric interaction of four waves. This model has permitted to obtain many interesting results and properties concerning these emissions. The two-wing structure of these emissions was demonstrated by studying the intensity of the emitted mode as a function of its wavelength. The double-beam structure of these emissions is obtained with a forward beam around the 45° angle and a backward beam around the 125° angle for the $\frac{3}{2}\omega_0$ emission. Similarly, for the $2\omega_0$ emission the forward beam is obtained around the 75° angle and the backward beam is obtained around the 115° angle. Moreover, the intensity of the backward beam is almost double of that of the forward beam in both emissions, while this later is narrower in the case of the $\frac{3}{2}\omega_0$ emission. In addition, for the $2\omega_0$ emission, our result shows clearly the existence of the forward beam which is less intense than the backward beam. The backward beam of the $2\omega_0$ emission has been reported by several experimental works, but, to the best of our knowledge, its forward beam has not been measured or reported before. Its disappearance in the measured spectrum is may be caused by the spatial effects, as reference[20] has pointed out. Conversion efficiency of the order of 6×10^{-4} was obtained for the $2\omega_0$ emission.

ACKNOWLEDGMENT

The Algerian Ministry of Higher Education and Scientific Research supported this work through a CNEPRU project N° D3102/02/05.

REFERENCES

1. Burnett, N.H., H.A.Baldis, M.C. Richardson, G.D.Enright, 1977. Self-Steepening of the Density Profile of a CO_2 Laser-Produced Plasma. Applied Phys. Lett., 31: 172.
2. Khalfaoui, A.H., S. Abdelli, T. Kerdja and D. Ghobrini, 1993. Filamentation Effects and Second-Harmonic Spectra in Laser-Produced Plasmas. Phys. Rev., E 48 N°2, p: 133.
3. Vonder Linder, D., T. Engers, G. Jenke, D. von der Linde, P. Agostini, G. Grillon, E. Nibbering, A. Mysyrowicz and A. Antonetti, 1995. Generation of High-Order Harmonics from Solid Surfaces by Intense Femtosecond Laser Pulses. Phys. Rev. A 52, R25.

4. Norreys, P.A., M. Zepf, G.D. Tsakiris, G. Pretzler, I. Watts, D.M. Chambers, P.A. Norreys, U. Andiel, A.E. Dangor, K. Eidmann, C. Gahn, A. Machacek, J.S. Wark and K. Witte, 1998. Role of the Plasma Scale Length in the Harmonic Generation from Solid Targets. Phys. Rev., E 58, R5253.
5. Tarasevitch, A., A. Orisch, D. Von der Linder, Ph. Balcou, G. Rey, J.-P. Chambaret, U. Teubner, D. Klöpfel and W. Theobald, 2000. Generation of High-Order Spatially Coherent Harmonics from Solid Targets by Femtosecond Laser Pulses. Phys. Rev., A 62, 023816.
6. Teubner, U., G. Pretzler, Th. Schlegel, E. Eidman, E. Forster and K. Witte, 2003. Anomalies in High-Order Harmonic Generation at Relativistic Intensities. Phys. Rev., A 67, 013816.
7. Pascal Monot, Gilles Doumy, Sundrine Dobosz, Michel Perdrix, Pascal D'Oliveira, Fabion Quéré, Fabrice Réau, Philippe Martin, Patrick Audebert, Jean-Claude Gauthier and Jean-Paul Geindre, 2004. High-Order Harmonic Generation by Nonlinear Reflection of an Intense High-Contrast Laser Pulse on a Plasma. Opt. Lett., 29: 893.
8. Emily A. Gibson, Ariel Paul, Nick Wagner, Ra'anan Tobey, Sterling Backus, Ivan P. Christov, Margaret M. Murnane and Henry C. Kapteyn, 2004. High-Order Harmonic Generation up to 250 eV from Highly Ionized Argon, Phys. Rev. Lett., 92: 033001.
9. McPherson, A., G. Gibson, H. Jara, U. Johann, T.S. Luk, I.A. McIntyre, K. Boyer and C.K. Rhodes, 1987. Studies of Multi-photon Production of Vacuum Ultraviolet Radiation in the Rare Gases. J. Opt. Soc. Am., B4, 595.
10. Ferray M., *et al.* and K.C. Kulander *et al.*, 1988. Super-Intense Laser-Atom Physics. K. Rzazewski (Ed.)(Plenum, New York, 1993), J. Phys. B 21, L31, 316: 95.
11. Quéré, F., C. Thaury, P. Monot, S. Dobosz, Ph. Martin, J.-P. Geindre and P. Audebert, 2006. Coherent Wake Emission of High-Order Harmonics from Overdense. Plasmas Phys. Rev. Lett., 96: 125004.
12. Tarasevitch, A., C. Dietrich, C. Blome, K. Sokolowski-Tinten and D. Vonderlinde, 2003. 3/2 Harmonic Generation by Femtosecond Laser Pulses in Steep-Gradient Plasmas. Phys. Rev., E 68, 026410.
13. Michael Bauer, 2005. Femtosecond Ultraviolet Photoelectron Spectroscopy of Ultra-Fast Surface Processes. J. Phys. D: Appl. Phys., 38: R253-R267.
14. Vozzi, C., F. Calegari, E. Benedetti, J.-P. Caumes, G. Sansone, S. Stagira, M. Nisoli, R. Torres, E. Heesel, N. Kajumba, J.P. Marangos, C. Altucci and R. Velotta, 2004. Controlling Two-Center Interference in Molecular High Harmonic Generation. Nature (London), 432: 867.
15. Young, P.E., B.F. Lasinski, W.L. Kruer, E.A. Williams, K.G. Estabrook, E.M. Campbell, R.P. Drake and H.A. Baldis, 1988. Simultaneous Spectrally and Spatially Resolved Measurements of $3\omega_0/2$ emission from Laser-Produced Plasmas. Phys. Rev. Lett., 61: 2766.
16. Meyer, J. and Y. Zhu, 1993. Measurement of Two Plasmon Decay Instability Development in k Space of a Laser Produced Plasma and its Relation to 3/2-Harmonic Generation. Phys. Rev. Lett., 71: 2915.
17. Dubois, D.F., D.A. Russell and Harvey A. Rose, 1995. Saturation Spectra of the Two-Plasmon Decay Instability. Phys. Rev. Lett., 74: 3983.
18. Gupta, G.P., T.K. Achal, S.V. Gogawale and B.K. Sinha, 1995. Observation of Both Wings of the Backscattered $^3/_2$ Omega $_0$ Emission near Threshold Laser Intensity from Long-Scale-Length Plasma. Plasma Phys. Control, Fusion, 37: 1277.
19. Russell, D.A. and D.F. Dubois, 2001. $3/2\omega_0$ Radiation from the Laser-Driven Two-Plasmon Decay Instability in an Inhomogeneous. Plasma Phys. Rev. Lett., 86: 428.
20. Veiz, L., W. Teobald, T. Feurer, H. Schillinger, P. Gibbon and R. Sauerbrey, 2002. Three-halves Harmonic Emission from Femtosecond Laser Produced Plasmas. Phy. Plasmas, 9: 3197.
21. Veisz, L., 2003. Investigation of Parametric Instabilities in Femtosecond Laser-Produced Plasma. Ph.D. Thesis, Friedrich-Schiller-Universitat. Jena.