

**PLASMA WAVE AIDED TWO PHOTON DECAY OF A LASER BEAM IN PLASMA****S. P. MISHRA<sup>1</sup>**

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**ABSTRACT**

In this study, we look at how a laser beam with a varying intensity, shaped like a Gaussian, can break down into two electromagnetic waves with specific frequencies and wave numbers. This breakdown can happen if there is a ripple in the plasma density that creates a Langmuir wave. The Langmuir wave helps match up the wave numbers of the laser and the resulting electromagnetic waves, making the breakdown possible. Without this ripple, the breakdown would not occur. The wave numbers and frequencies involved must meet certain conditions to allow the breakdown. These conditions are that the wave number of the Langmuir wave is the difference between the wave number of the laser and the two electromagnetic waves, and the frequency of the Langmuir wave is the difference between the laser frequency and the two electromagnetic wave frequencies. The ripple in the plasma density causes this matching. The breakdown of the laser into the two electromagnetic waves happens when the plasma density is less than one fourth of the critical density. The resulting electromagnetic waves travel at an angle relative to the laser beam. The rate at which the decay happens depends on the density ripple and how much the laser beam's intensity varies. The highest rate of decay occurs right in the middle of the laser beam's path. The graphs show that as the frequency of the laser beam increases and the angle of the decay waves changes, the rate of decay decreases.

**KEYWORDS:** Parametric Decay, Amplitude Modulated Gaussian Laser, Ripple Density, Langmuir Wave, Nonlinear Current Density, Phase Matching

Nonlinear interaction of electromagnetic radiation (laser beam) with plasmas is a subject of notable field of interest due to its vast field applications such as charged particle acceleration (Kumar and Tripathi 2010a), soft X-ray generation (Kumar and Tripathi 2010b). The parametric instability is one of the most fascinating nonlinear process occurring in plasma. Owing to possess of various scientific and technological applications, parametric instabilities (Kumar and Tripathi 2010b; Kumar and Tripathi 2007; Dorfman *et al.* 2016; Baek *et al.* 2013) in plasmas have attracted a lot of interest in recent years. The parametric decay instability of laser into two Langmuir waves have been investigated by Liu and Rosenbluth (Liu and Rosenbluth 1976) at critical density of an inhomogeneous plasma. They investigated certain linear aspects of two plasmon decay process in an inhomogeneous plasma. Salimullah (Salimullah 1988) theoretically investigated the various possible parametric instabilities of laser beat waves in a magnetized plasma. Jain *et al.* (Jain *et al.* 1988) theoretically investigated the decay instability of a high amplitude Langmuir wave in a plasma slab. The experimental evidences of parametric instability have been reported by several groups (Yadlowsky and Goldan 1974). Stimulated Raman scattering is the one of nonlinear process (Phillion *et al.* 1982; Bénisti and Gremillet 2007; Kirkwood *et al.* 2007). Such a decay could be possible in the presence of a density ripple in the plasma where the unbalanced momentum is transferred by the density ripple between the pump electromagnetic wave and the decay electromagnetic wave photons (Sati and Tripathi 2012a; Kumar *et al.* 2014). But it is

technically hard to create a density ripple of a suitable wave number. Lin *et al.* (2006) have found great success in creating density ripple of quasi phase matching by programmable fabrication of longitudinal spatial structures in a hydrogen gas jet through machining with the help of liquid crystal spatial light modulator.

Parametric instabilities in plasmas played dominant role in a wide range of applications such as laser driven charged particle acceleration (Rajeev *et al.* 2013), nonlinear optics (Dubois and Goldman 1972), radio frequency (RF) inertial confinement fusion (ICF) (Betti and Hurricane 2016; Atzeni *et al.* 2005), current drive experiments (CDEs) (Cesario *et al.* 2006) and plasma heating (Grek and Porkolab 1973; porkolab *et al.* 1977). The parametric decay of electromagnetic waves in a plasma channel may be taken into consideration to prevent decay waves from escaping the propagation region (Sati and Tripathi 2012b).

In the present theoretical investigation, we study the decay of a high power amplitude modulated Gaussian laser beam assisted plasma wave into two electromagnetic waves in rippled density plasma. The large amplitude of amplitude modulated Gaussian (AMG) laser beam imparts an oscillatory velocity  $v_{\omega_0, k_0}$  to the plasma electrons. The pump laser wave excites a pair of low frequency electromagnetic wave  $(\omega_1, k_1)$  and a sideband electromagnetic wave  $(\omega_2, k_2)$  in the presence of Langmuir wave  $(\omega_r, k_r)$ , where the phase matching conditions are taken as  $\omega_r = \omega_0 - \omega_1 - \omega_2$ ,  $\vec{k}_r = \vec{k}_0 - \vec{k}_1 - \vec{k}_2$ . The amplitude modulated Gaussian laser beam

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beats with the sideband electromagnetic wave and exerts a nonlinear ponderomotive force on the plasma electrons at frequency  $\omega_0 - \omega_2$  and wave vector  $\vec{k}_0 - \vec{k}_2$  providing oscillatory velocity  $v_{\omega_0 - \omega_2, \vec{k}_0 - \vec{k}_2}$  to the plasma electrons. The oscillatory velocity beats with the ripple density perturbation  $n_{\omega_r, k_r}$  related with the Langmuir wave and produce a nonlinear current density  $J_{\omega_1, k_1}$  which driving the low frequency electromagnetic wave ( $\omega_1, k_1$ ). The low frequency electromagnetic wave couples with the amplitude modulated Gaussian laser beam and produce oscillatory velocity  $v_{\omega_0 - \omega_1, \vec{k}_0 - \vec{k}_1}$ , which further on beating with the Langmuir wave ripple density perturbation gives rise to a nonlinear current  $J_{\omega_2, k_2}$  and driving the sideband electromagnetic wave. Consequently, due to this feedback mechanism, both the decay waves grow at the expense of the pump electromagnetic wave. The schematic diagram of three wave coupling process in the presence of ripple density plasma and the scheme for the direction of the waves coupling in the process is shown in Fig. 1 and Fig. 2 respectively. Quantum mechanically, a pump electromagnetic wave having photon of energy and momentum ( $\hbar\omega_0, \hbar k_0$ ) decays into two photons of energy and momentum ( $\hbar\omega_1, \hbar k_1$ ) and ( $\hbar\omega_2, \hbar k_2$ ) sharing unbalanced energy as well as momentum with the plasma wave. We analyze the effect of pump wave frequency, decay wave frequency and laser beam transverse distance on the growth rate for different values of modulation index as well as the angle  $\theta_r$  ( $\theta_r$  is the angle between  $k_0$  and  $k_r$ ). In section 2, we have analytically derived the expressions of growth rate of decay wave. In section 3, the results and discussions of our findings are explained via graphically. Finally, the summary and conclusions are given in section 4.

**Theoretical Investigation (Growth Rate)**

The laser field profile of an amplitude modulated Gaussian laser beam of frequency  $\omega_0$  and laser wave vector  $\vec{k}_0$  propagating in the z-direction and polarized along the x-direction in hot, unmagnetized, homogeneous and collisionless plasma can be written as,

$$\vec{E}_0 = \hat{x}A_0 \left[ 1 + \mu \cos\Omega \left( t - \frac{z}{c} \right) \right] e^{-i(\omega_0 t - k_0 z)} e^{-x^2/2r_0^2}, \quad (1)$$

$$\vec{B}_0 = \left( \frac{\vec{k}_0 \times \vec{E}_0}{\omega_0} \right),$$

$$k_0 = \frac{\omega_0}{c} \sqrt{1 - \frac{\omega_p^2}{\omega_0^2}}, \quad \omega_p = \sqrt{\frac{n_0^0 e^2}{m \epsilon_0}},$$

Where  $A_0$ ,  $\Omega$ ,  $\mu$  and  $r_0$  are the initial electric field amplitude of laser beam, modulation frequency, modulation index, initial pulse width of the amplitude-

modulated Gaussian laser respectively,  $\omega_p$  is the plasma frequency,  $m$  and  $e$  are the rest mass and electronic charge of the electron and  $\epsilon_0$  is the electrical permittivity of free space.

Consider a plasma wave with frequency  $\omega_r$  and wave vector  $\vec{k}_r$ . The component form of wave vector can be written

$$\vec{k}_r = k_r \cos\theta_r \hat{z} + k_r \sin\theta_r \hat{x}. \quad (2)$$

The electron ripple density associated with the plasma can be written as,

$$n_0 = n_0^0 + n_{\omega_r, k_r}, \quad n_{\omega_r, k_r} = n_{\omega_r, k_r}^0 e^{-i(\omega_r t - \vec{k}_r \cdot \vec{r})}, \quad (3)$$

where  $\vec{k}_r$  lies in the x-z plane making an angle  $\theta_r$  with z-axis and  $n_0^0$  is the equilibrium electron density and  $n_{\omega_r, k_r}$  is the ripple electron density.

The linearly polarized amplitude-modulated Gaussian laser propagates through the plasma and it imparts an oscillatory velocity to electrons of the plasma,

$$\vec{v}_0 = \hat{x} \frac{e}{mi\omega_0} A_0 \left[ 1 + \mu \cos\Omega \left( t - \frac{z}{c} \right) \right] e^{-i(\omega_0 t - k_0 z)} e^{-x^2/2r_0^2} \quad (4)$$

and excites a pair of electromagnetic waves.

$$\vec{E}_1 = \vec{A}_1 e^{-i(\omega_1 t - \vec{k}_1 \cdot \vec{r})}, \quad \vec{B}_1 = \left( \frac{\vec{k}_1 \times \vec{E}_1}{\omega_1} \right) \quad (5)$$

$$\vec{E}_2 = \vec{A}_2 e^{-i(\omega_2 t - \vec{k}_2 \cdot \vec{r})}, \quad \vec{B}_2 = \left( \frac{\vec{k}_2 \times \vec{E}_2}{\omega_2} \right) \quad (6)$$

The growth rate can be expressed as

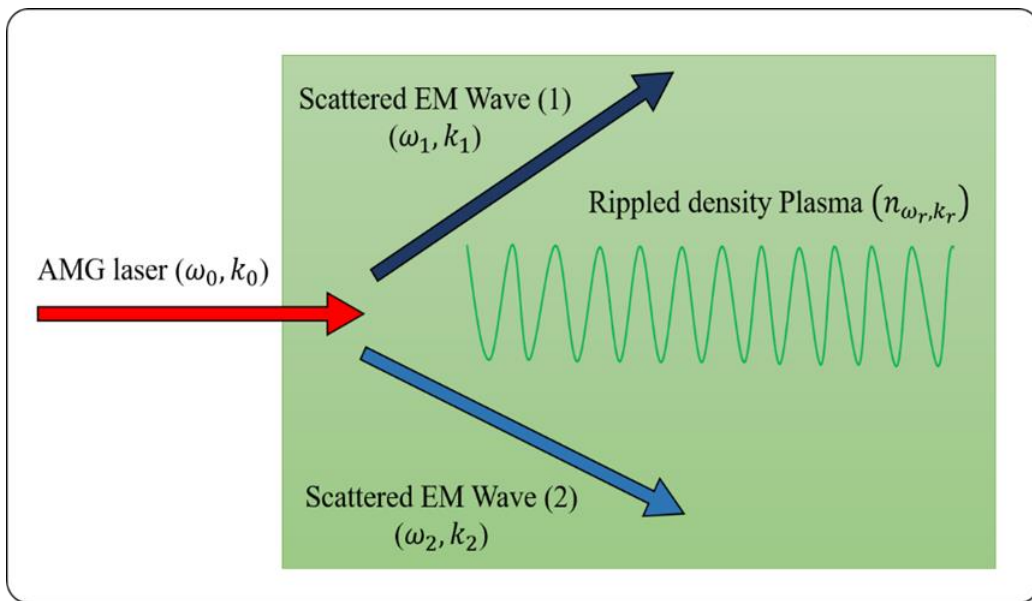
$$\frac{\Gamma}{\omega_p} = \Gamma_0 \sqrt{\frac{\left[ \omega_1 - \left( \frac{c^2}{\omega_1 \epsilon_{\omega_1}} \right) \left( \frac{k_{1x}}{k_{rx}} \right) (\vec{k}_1 \cdot \vec{k}_r) \right] \left[ \omega_2 - \left( \frac{c^2}{\omega_2 \epsilon_{\omega_2}} \right) \left( \frac{k_{2x}}{k_{rx}} \right) (\vec{k}_2 \cdot \vec{k}_r) \right]}{\epsilon_{\omega_r + \omega_2} \epsilon_{\omega_r + \omega_1} (\omega_r + \omega_2)(\omega_r + \omega_1)}}} \quad (7)$$

The growth rate obtained in this investigation is dependent on the density  $n_{\omega_r, k_r}^0$ . We performed numerical calculations to estimate the growth rate and theoretically studied the effects of various plasma parameters on it.

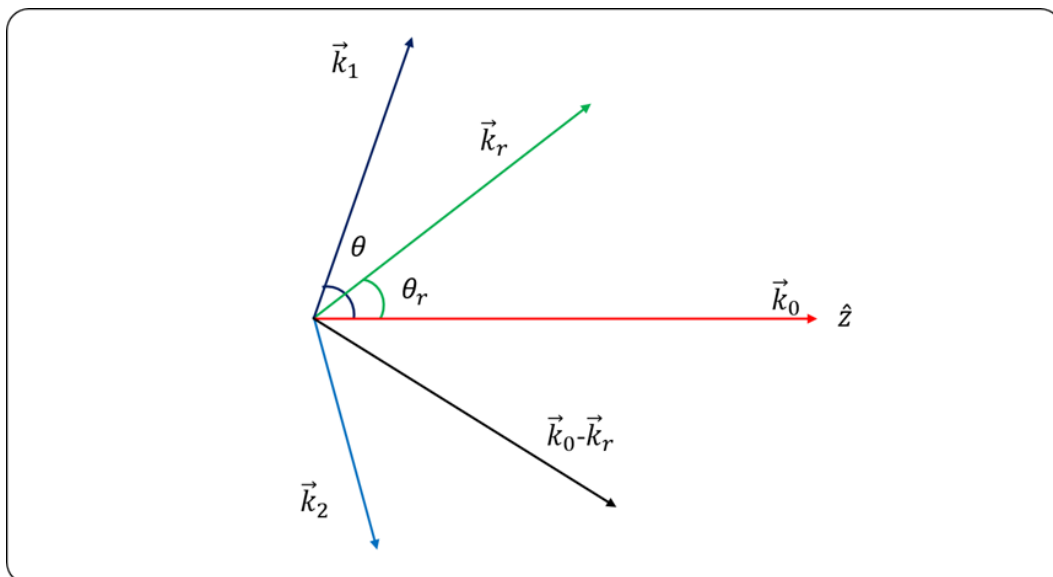
**RESULTS AND DISCUSSION**

The decay of amplitude modulated Gaussian pump wave in the presence of Langmuir wave (plasma wave) is analytically studied in ripple density plasma. The amplitude modulated Gaussian laser beam has much potential to couple with two electromagnetic waves in association with plasma wave. The effect of pump wave frequency, decay wave frequency and laser beam transverse propagation distance for different values of modulation index as well as  $\theta_r$  have been studied. The decay waves propagate at finite angles with respect to the amplitude modulated Gaussian laser beam. The growth rate has been found to be directly proportional to the plasma density. In Fig. 3, the variation of growth rate

with respect to the normalized transverse propagation distance of laser beam has been plotted for different values of modulation index  $\mu = 0.2, 0.4, 0.6, 0.8$ . The growth rate attains its peak value at the centre ( $x = z = 0$ ) of laser beam. At this value of transverse beam propagation distance, the laser beam imparts the large oscillatory velocity to the electrons of rippled density plasma and results the generation of large amount nonlinear current density. This promises the large amplitude of growth rate obtained at the centre of laser beam transverse propagation distance. It is found that as one increases the modulation index of the amplitude modulated Gaussian laser, the growth rate of decay wave is increased.



**Figure 1: Schematic diagram of density rippled plasma wave assisted amplitude modulated Gaussian laser beam coupling with decay of electromagnetic waves.**



**Figure 2: Schematic for direction of wave vectors and pump laser coupling with decay waves.**

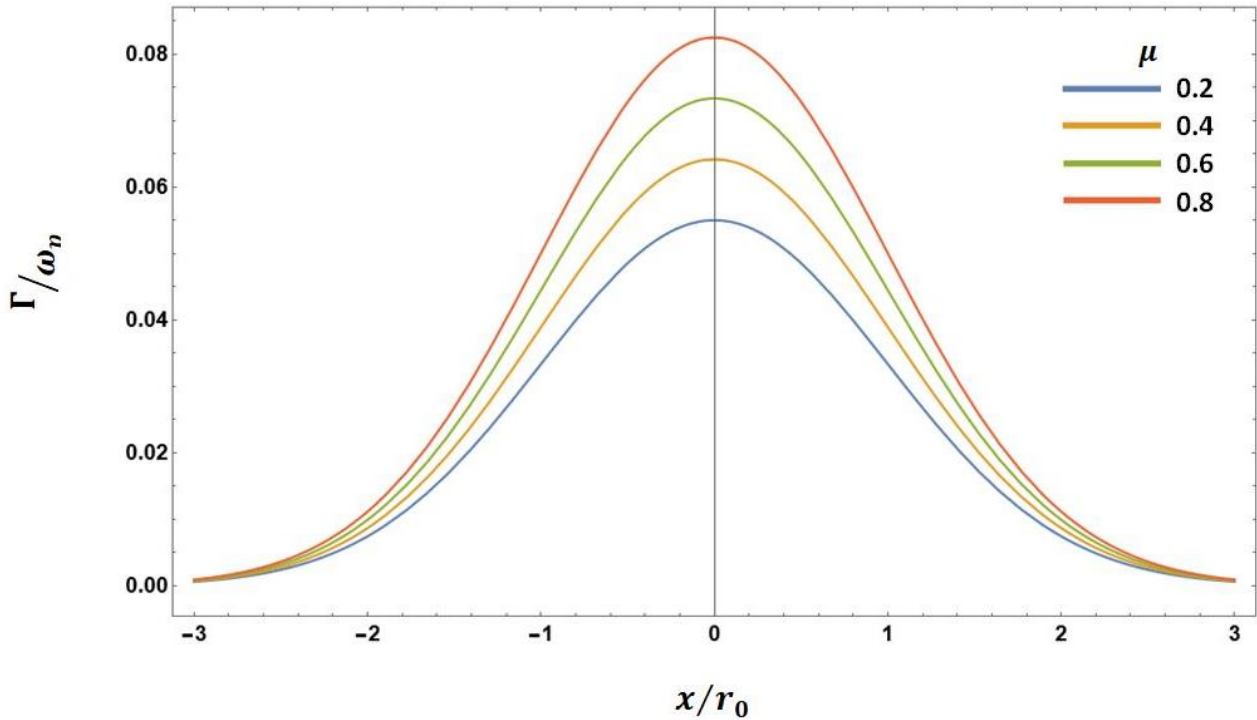


Figure 3: The variation of normalized growth rate  $\Gamma/\omega_p$  with normalized laser beam transverse propagation

distance  $x/r_0$  for different values of  $\theta_r$ . The parameters are:  $\frac{n_0^0 \omega_r k_r}{n_0^0} = 1.88$ ,  $\frac{eA\omega_0}{m\omega_p c} = 0.3$ ,  $\frac{k_r c}{\omega_p} = 1.2$ .

## SUMMARY AND CONCLUSION

We have herein theoretically analyzed the parametric decay of amplitude modulated laser wave  $(\omega_0, k_0)$  into two electromagnetic waves in the presence of Langmuir wave  $(\omega_r, k_r)$  in density rippled plasma. Previous theoretical study of laser decay into two electromagnetic waves has been studied by several research groups in plasma but in the present work, we have studied the decay of an amplitude modulated Gaussian laser beam assisted by plasma wave. The various laser parameter (modulation index  $\mu$ , pump wave frequency, laser beam transverse propagation distance from x-axis), decay wave frequency, angle between  $k_r$  and  $k_0$  much affects the growth rate of decay wave. It has been depicted from the theory that the phase matching conditions are satisfied in the presence of ripple density. In the absence of ripple density plasma, the plasmon decay takes place instead of photon decay i.e. the electromagnetic wave would decay into two plasma wave.

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