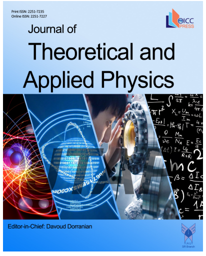

Volume 17, Issue 5, 172354 (1-6)

Journal of Theoretical and Applied Physics (JTAP)

https://dx.doi.org/10.57647/j.jtap.2023.1705.54

Electron plasma wave excitation by two copropagating super-Gaussian laser beams in collisional nanocluster plasma

Ashish Varma[1]*, S P Mishra[1], Arvind Kumar[2], Sujeet Kumar[2], Asheel Kumar[2]

[1] *Laser Plasma and Material Research Group, Department of Physics, K. N. Govt. P. G. College, Gyanpur, Bhadohi, India.*
[2] *Plasma Physics Research Group, Department of Physics, University of Allahabad, Prayagraj, India.*

*__Corresponding author__: varmaashish331@gmail.com

Received 16 May 2023; Accepted 30 Aug. 2023; Published Online 04 Oct. 2023 ORIGINAL RESEARCH

Abstract:
In this theoretical study, we investigate the electron plasma wave excitation (EPW) by two copropagating high power laser beams in collisional nanocluster plasma. The interaction of electric field profile of laser beams causes the ionization of nanocluster and very quickly it converts into the plasma plume balls. The electric field profile of each super-Gaussian laser beam imparts the oscillatory velocity to the electron associated with nanoclustered plasma. The copropagating laser beams generate the nonlinear ponderomotive force to electrons at beat wave frequency $\omega = \omega_1 - \omega_2$ and wave number $k = k_1 - k_2$. This nonlinear ponderomotive force drives the self-consisted space charge field and it might have much potential to excite the electron plasma wave in nanoclustered plasma. The expression of electron plasma wave electrostatic potential is derived in nanoplasma medium with considering the electron-ion collision effect. The effective surface plasmons resonance at the surface of nanoclustered plasma plays a crucial role for excitation process. The electron plasma wave excitation is tuned and controlled by varying the super-Gaussian index, cluster radius, density, laser beat wave frequency, laser beam width and collisional frequency. The electron plasma wave excitation might be applicable in nonlinear phenomena such as self-focusing and anomalous absorption.

Keywords: Plasma wave; Excitation; Super-Gaussian laser beam; Oscillatory velocity; Ponderomotive force; Beat wave; Cluster radius; Collisional frequency

1. Introduction

In recent few years, interaction of laser beams with plasma and nanoclustered plasma is a particular field of interest due to its applications such as heating [1], charged particle acceleration [2], current drive experiments [3], excitation of electrostatic waves [4–8] and technological aspects [9–19]. The clusters are atomic aggregation upto several hundred atoms. These are bound by weak forces. Plasma embedded with nanocluster shows peculiar and advance property that aided a new dimension to study the electron plasma wave excitation [4, 20, 21]. When an intense laser beam interacts with material then ionization process takes place and cluster plasma is formed [22]. Another mechanism of cluster formation is possible through expanding noble gases via supersonic jets flow [23]. The presence of effective surface plasmons oscillation on the surface of nanocluster affects the excitation property of plasma wave [5–8, 24].

Plasma wave is a kind of electrostatic wave [25, 26]. The nonlinear interaction of laser beam has much potential to excites [27] the electrostatic wave and heat the plasma electrons [4]. Owing to presence of effective surface plasmons frequency, the electron associated with nanocluster shows the enhanced heating rate [28]. Further, Kumar et al. [29] have studied the efficient electron heating through plasma wave aided laser beam in nanoclustered plasma. Enormous heating is achieved by intense short pulse laser via different size cluster [30]. Enhanced stimulated Raman scattering phenomena [31] can be obtained by laser interaction with cluster plasma. In nanoclustered plasma, an analytic the-

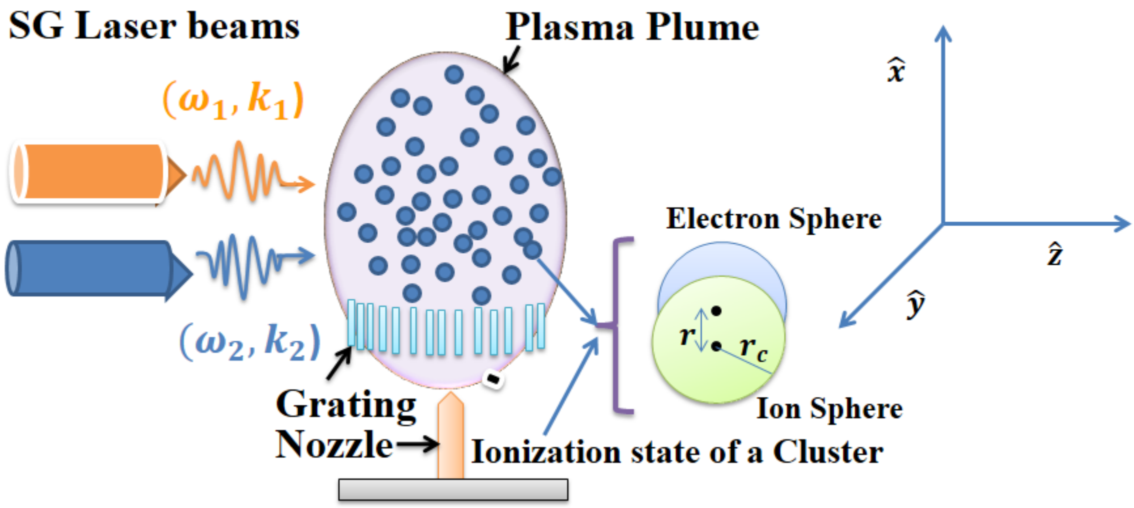

Figure 1. Schematic diagram of plasma wave excitation in a collisional nanocluster plasma.

ory of third harmonic generation is proposed by Tiwari and Tripathi [32]. Terahertz radiation generation is much more enhanced by the interaction of ultra short pulse laser beam in argon gas cluster [33]. Recent research reveal that electrostatic wave aided laser beam have significant potential for achieving the absorption [34, 35]. Lower hybrid waves [36] and electron Bernstein waves [37, 38] can be excited in plasma with static magnetic field via laser beat wave interaction.
The aim of present theoretical study is to investigate the electron plasma wave excitation by two copropagating high power SG laser beams in plasma embedded with nanocluster. The schematic diagram of electron plasma wave excitation theory is shown in Fig. 1. Initially two laser beams nonlinearly interact with nanoclustered plasma and produced plasma plume ball. The plasma wave excitation is controlled by various factors such as super-Gaussian index, collisional frequency, laser beams width parameter, and clustered radius. The coupling of two laser beam in nanocluster plasma is given in Sec. 2. In Sec. 3, dispersion relation of nanoclustered plasma and potential profile of electron plasma wave in nanocluster is derived. Sec. 4 provides the results and discussion. Finally, summary and conclusion of our proposed theory is given in Sec. 5.

2. Nonlinear coupling

Here, we consider that nanoclusters are embedded in plasma. The radius and density of cluster can be taken as r_c and n_c respectively. The two copropagating super-Gaussian laser beams with wave numbers k_1 and k_2, frequencies ω_1 and ω_2 nonlinearly interact with nanoclustered plasma. The super-Gaussian laser beam is propagating along z-direction and polarized along y-direction. The electric and magnetic field profile of each super-Gaussian (SG) laser can be taken as

$$\mathbf{E}_j = E_0 \exp[-(\frac{y}{W_0})^p] e^{-i(\omega_j t - k_j z)} \hat{y} \tag{1}$$

$$\mathbf{B}_j = \frac{\mathbf{k}_j \times \mathbf{E}_j}{\omega_j} \tag{2}$$

where w_0 is the beam width parameter of laser, p (for $p > 2$) is the super Gaussian mode index, $j = 1, 2$ is for each laser representation, m is the electro mass, e is the electron charge, and ω_p is the electron plasma frequency. The ions are immobile owing to have large mass as compared to electron mass and during the interaction of laser beam with plasma embedded with nanocluster and only electrons are responded to the laser beams in nanoclustered plasma.
We can write the equation of motion of electron in nanoclustered plasma as

$$\frac{d\mathbf{v}_j}{dt} + \nu \mathbf{v}_j + \frac{\omega_{pe}^2}{3} \mathbf{r}_j = -\frac{e}{m} \mathbf{E}_j \tag{3}$$

where $\mathbf{v}_j$, $\mathbf{r}_j$, and ν are the oscillatory velocity of electron, displacement, and electron-ion collisional frequency respectively. The term $\omega_{pe}/\sqrt{3}$ is the effective surface plasmon frequency and arisen in spherical nanoplasma medium.
By using Eqs. (2)-(3), we can obtain the expression of electron displacement and oscillatory velocity as

$$\mathbf{r}_j = \frac{e\mathbf{E}_j}{m(\omega_j^2 - \frac{\omega_{pe}^2}{3} + i\nu\omega_j)} \tag{4}$$

$$\mathbf{v}_j = -\frac{ie\omega_j \mathbf{E}_j}{m(\omega_j^2 - \frac{\omega_{pe}^2}{3} + i\nu\omega_j)}. \tag{5}$$

The two copropagating super-Gaussian laser beams in the nanoclusters cause a nonlinear ponderomotive force to the cluster electrons at the beat frequency $\omega = \omega_1 - \omega_2$ and beat wave number $k = k_1 - k_2$. The expression of nonlinear ponderomotive potential can be derived by using the following formula

$$\phi_p = -\left(\frac{m}{2e}\right) \mathbf{v}_1 . \mathbf{v}_2, \quad \text{and} \quad \mathbf{F}_p = e\nabla\phi_p, \tag{6a}$$

The oscillatory velocity produced by each laser beam can be obtained from Eq. (5). Thus, putting these values in Eq. (6a), we can easily find the expression of nonlinear

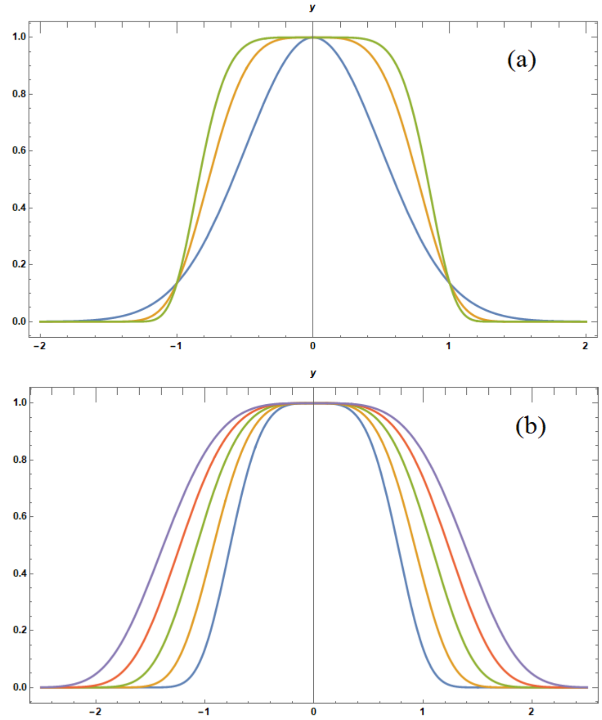

Figure 2. (a) Variation of normalized potential amplitude profile with normalized beam propagation distance for different values of super-Gaussian index of laser beams p. (b) Variation of normalized potential amplitude with normalized beam propagation distance for different values of laser beam width.

ponderomotive potential only for the plasma electrons as

$$\phi_p = -\frac{eE_0 \exp\left[-2\left(\frac{y}{W_0}\right)^p\right] e^{-i(\omega t - kz)}}{2m\omega_1\omega_2}, \tag{6b}$$

Now in the similar way, we can obtain the expression of nonlinear ponderomotive potential for the clustered electron as

$$\phi_p^c = -\frac{\omega_1\omega_2 eE_0 \exp\left[-2\left(\frac{y}{W_0}\right)^p\right] e^{-i(\omega t - kz)}}{2m(\omega_1 - \frac{\omega_{pe}^2}{3} + iv\omega_1)(\omega_2^2 - \frac{\omega_{pe}^2}{3} + iv\omega_2)} \tag{6c}$$

3. Plasma wave excitation

Let us assume that ponderomotive force have much potential to excite a space charge wave (electrostatic wave). Also, plasma wave might be driven by this space charge wave of potential $\phi = \phi_0 e^{-i(\omega t - \mathbf{k.r})}$.
The electron density perturbation only for the plasma electrons can be written as

$$n_e = \frac{k^2}{4\pi e}\chi_{ep}(\phi + \phi_p) \tag{7}$$

In the presence of nanoplasma, the electron density perturbation due to plasma as well as clustered electrons can be written as

$$n_e^c = \frac{k^2}{4\pi e}(\chi_{ep} + \chi_{ec})(\phi + \phi_p^c), \tag{8}$$

The susceptibility of plasma electrons χ_{ep} and the susceptibility of nanoclustered electron χ_{ec} is written as

$$\chi_{ep} = -\frac{\omega_p^2}{\omega^2}, \tag{9a}$$

$$\chi_{ec} = -\frac{4}{3}\pi r_c^3 n_c \frac{\omega_{pe}^2\left(\omega^2 - \frac{\omega_{pe}^2}{3}\right)^2}{\left(\omega^2 - \frac{\omega_{pe}^2}{3}\right)^2 + v^2\omega^2} - i\frac{4}{3}\pi r_c^3 n_c \frac{\omega_{pe}^2 v\omega}{\left(\omega^2 - \frac{\omega_{pe}^2}{3}\right)^2 + v^2\omega^2} \tag{9b}$$

Using Eq. 8, one can write the Poisson's equation as

$$\nabla^2\phi = 4\pi e(n_e^c) \tag{10}$$

Further, using Eqs. (8)-(10), one can write the dispersion relation as following

$$\varepsilon\phi = -(\chi_{ep} + \chi_{ec})\phi_p^c \tag{11}$$

where ε is given as

$$\varepsilon = 1 + \chi_{ep} + \chi_{ec} \tag{12}$$

For analytic results, we have to normalize the Eq. 11 in the form of normalized potential amplitude of electron plasma wave [7].

4. Results and discussion

We have theoretically studied the electron plasma wave excitation by beating of two high power copropagating SG laser beams in plasma embedded with nanocluster. Electron plasma wave can be excited by copropagation of two super-Gaussian laser beams with beat wave frequency $\omega = \omega_1 + \omega_2$ and wave number $k = k_1 - k_2$. Since ions are massive as compared to electrons. Hence, ions motion can be neglected as compared with mass of electrons. Hence, during the interaction of SG laser beam with plasma embedded with nanocluster, only electron associated with nanocluster is responsible for excursion and oscillatory velocity.

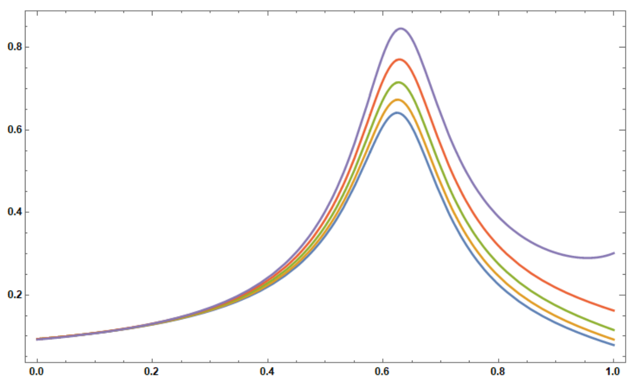

Figure 3. Variation of normalized potential amplitude profile with normalized beat frequency for different values of normalized plasmons frequency.

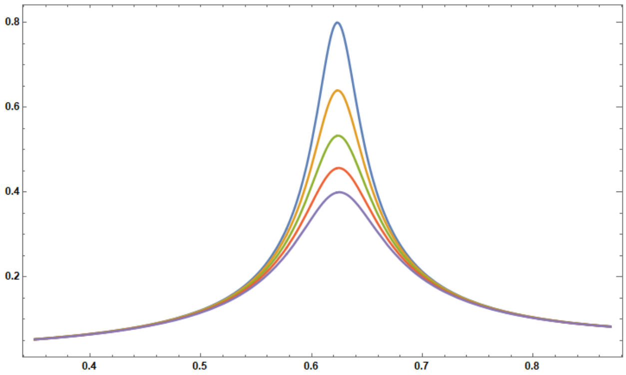

Figure 4. Variation of normalized potential amplitude with normalized beat frequency for different values of collisional frequency.

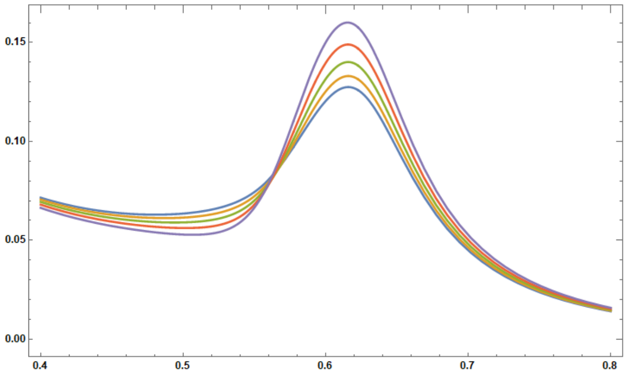

Figure 5. Variation of normalized potential amplitude with normalized beat frequency for different values of cluster radius.

The nonlinear ponderomotive force has much potential to excite the large amplitude electron plasma wave in plasma embedded with nanocluster.

Fig. 2(a) shows the variation of normalized potential amplitude profile of electron plasma wave as a function of normalized transverse distance propagation of SG laser beam from y-axis for different value of laser beam super-Gaussian index p. The potential profile of electron plasma wave is appeared purely Gaussian for index $p = 2$ and for the super-Gaussian index $p = 4, 6$ the profile is appeared like flattened shape. The super-Gaussian laser beam responses larger time as compared with purely Gaussian laser beam. Therefore, we can say that large response time promises more generation of electrons and thus leads to much more electron plasma wave excitation. Fig. 2(b) shows the variation of normalized potential amplitude profile of plasma wave as a function of normalized transverse distance of laser beat wave from y-axis for different value of nanocluster radius. We can also see that with increasing the nanocluster radius, the amplitude of normalized potential profile of electron plasma wave is increased. The increased nanocluster radius promises for large interacting area and thus causes to impartation of large oscillatory to the electron associated with nanoclustered plasma. This leads to enhanced excitation of electron plasma wave with increase in nanocluster size.

The variation of normalized potential amplitude profile of plasma waves as a function of normalized laser beat wave frequency for different value of normalized plasmons frequency is shown in Fig. 3. It shows that maximum peak profile is attained at $\omega \sim 0.62\omega_{pe}$. At this particular point, electron plasma wave is excited much more as compared with other values. Also, we can see that on increasing the electron plasmons frequency, the electron plasma wave amplitude of potential is increased.

In Fig. 4, the variation of normalized potential amplitude profile of electron plasma waves as a function of normalized laser beat wave frequency for different value of normalized electron-ion collisional frequency has been plotted. In this medium of nanoclustered plasma, the collision is occurred between the electron and ion. We can see that on increasing the collisional frequency, the peak profile of excited electron plasma wave is decreased. The spatial inhomogeneity of nanoclustered plasma density and nonlinearity are decreased with the presence of collisional frequency. Therefore, one can say that collision effect causes the destruction effect on excitation of electron plasma wave.

Fig. 5 shows the graph between normalized potential amplitude of electron plasma wave as a function of laser beat wave normalized frequency for different value of nanocluster radius. As one increases the size of nanocluster, the excitation of plasma wave is increased. This occurrence due to increase in cluster radius, the effective surface region of interaction is increased and the electron associated with nanocluster plasma is increased. In this way, one can say that large effective surface area causes the excitation of large amplitude of potential profile of electron plasma wave.

Fig. 6 depicts the variation of normalized potential amplitude profile of electron plasma wave as a function of normalized laser beat wave frequency for different value of laser beam width w_0. It is noticed that by increasing the laser beam width (in μm), the peak profile of excited plasma wave is increased. Therefore, plasma wave is much more excited by increasing the laser beam width.

5. Summary and conclusion

In this present theoretical investigations, we study the plasma wave excitation by using the super-Gaussian

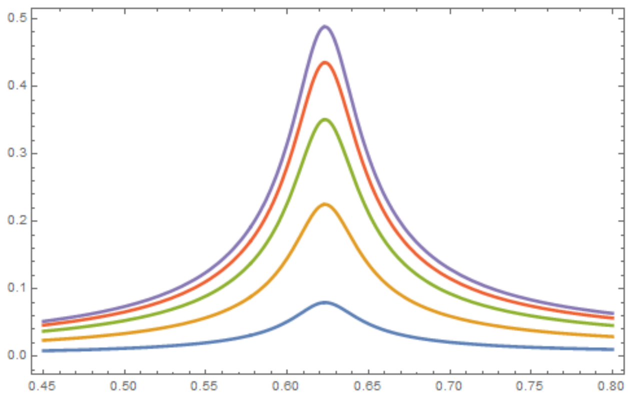

Figure 6. Variation of normalized potential amplitude with normalized beat frequency for different values of laser beam width.

laser beat wave frequency in collisional nanoclustered plasma. Our proposed theory is in good agreement with theoretical results of Kumar et al. [5] in which they have excited the electron Bernstein wave in plasma by two laser beams. Here, we see the results of excitation of electron plasma wave in nanocluster by the beating of two copropagating laser beams. Aided of electron plasma wave with high power laser beam might be promised for enhanced absorption in plasma embedded with nanocluster. The dependence of the electron plasma wave excitation on the laser beam super-Gaussian mode index, collisional frequency, laser beam width, cluster radius is presented. The spatial shape of plasma wave potential with laser beat wave frequency and propagation distance were depicted the much excitation. The effective plasmons oscillations on the surface of nanocluster plasma plays an effective role for enhancing the plasma wave excitation. Large amplitude of normalized potential profile of electron plasma wave is obtained in nanoclustered plasma as compared with only plasma medium. The maximum excitation is achieved at normalized laser beat wave frequency around $\omega \sim 0.62\omega_{pe}$. The profile of plasma wave potential scale is decreased by increasing the collisional frequency. The excitation is also increased with increases the laser beam width, super-Gaussian index, and nanocluster radius. This excited plasma wave might be applicable in nonlinear phenomena such as electron heating [29] and anomalous absorption [35].

Acknowledgement
One of the author, Dr. Ashish Varma would like thankful to Prof. VK Tripathi (IIT Delhi), Prof. M. S. Tiwari (Dr. H. S. Gaur University, Sagar) for valuable discussions and suggestion and also thankful to Prof. K. N. Uttam (Department of Physics, University of Allahabad, Prayagraj) for discussion in nanocluster. We would like to thank Dr. P. N. Dongre (Principal) of K. N. Govt. P. G. College, Gyanpur-Bhadohi for providing the research facilities.

Declarations

Ethical Approval
Not applicable

Consent to participate
Informed consent was obtained from all individual participants included in the study.

Consent for publication
The participant has consented to the submission of the case report to the journal.

Competing interests
The authors declare that they have no competing interests.

Authors' contributions
Ashish Varma and S P Mishra have done the analytical calculations and write the manuscript. Arvind Kumar has plotted the graphs. Asheel Kumar supervised the whole problem.

Funding
The authors have no funding.

Availability of data and material
The data that supports the findings of this study are available within this article.

Code availability
Not applicable.

References

[1] M. Ali Asgarian and M. Abbasi. "Excitation of half-integer up-shifted decay channel and quasi-mode in plasma edge for high power electron Bernstein wave heating scenario". *AIP Advances*, **8**:045119, 2018.

[2] A. Kumar, B. K. Pandey, and V. K. Tripathi. "Charged particle acceleration by electron Bernstein wave in a plasma channel". *Laser and Particle Beams*, **28**:409, 2010.

[3] V. A. Turikova and A. M. Umnova. "Parametric interaction of high-power laser radiation with plasma in a strong magnetic field". *Plasma Physics Reports volume*, **46**:859, 2020.

[4] A. Varma and A. Kumar. "Electron Bernstein wave excitation and heating by nonlinear interactions of Laguerre and Hermite Gaussian laser beams in a magnetized plasma". *Optik*, **228**:166212, 2021.

[5] A. Kumar, A. Kumar, and A. Varma. ", Excitation of electron Bernstein waves by beating of two cosh-Gaussian laser beams in a collisional plasma". *Laser Physics*, **31**:106001, 2021.

[6] A. Varma and A. Kumar. "Electron Bernstein wave aided beat wave of Hermite-cosh-Gaussian laser beam absorption in a collisional nanocluster plasma". *Optik*, **245**:167702, 2021.

[7] A. Varma and A. Kumar. "Electron Bernstein wave excitation by beating of two copropagating super-Gaussian laser beam in a collisional nanocluster plasma". *Optik*, **240**:166872, 2021.

[8] A. Varma, A. Kumar, and A Kumar. "Nonlocal Theory of Excitation of Electron Bernstein Waves by a Relativistic Electron Beam in Plasma with Loss-Cone Distribution of Electron". *Brazilian Journal of Physics*, **51**:661, 2021.

[9] L. Malik and A. Escarguel. "Role of the temporal profile of femtosecond lasers of two different colours in holography". *EPL*, **124**:64002, 2018.

[10] L. Malik and A. Escarguel. "Uncovering the remarkable contribution of lasers peak intensity region in holography". *Laser Physics Letters*, **18**:086003, 2021.

[11] H. K. Malik. *Laser-Matter Interaction for Radiation and Energy*. CRC press, 2021.

[12] L. Devi and H. K. Malik. "Resonant third harmonic generation of super-Gaussian laser beam in a rippled density plasma". *Journal of Theoretical and Applied Physics*, **12**:265, 2018.

[13] L. Devi and H. K. Malik. "Self-focusing and defocusing phenomena of super-Gaussian laser beams in plasmas carrying density gradient". *Journal of Optics*, **25**:035401, 2023.

[14] T. Punia, D. Sharma, and H. K. Malik. "THz radiation generation through graphite nanoparticles having two different shapes and orientations of Basal planes". *IEEE Transactions on Plasma Science*, **50**:1087, 2022.

[15] H. K. Malik. "Terahertz radiation generation by lasers with remarkable efficiency in electron–positron plasma". *Physics Letters A*, **379**:2826, 2015.

[16] L. Malik. "Dark Hollow lasers may be better candidates for holography". *Optics and Laser Technology*, **132**:106485, 2020.

[17] H. K. Malik and S. Punia. "Dark hollow beams originating terahertz radiation in corrugated plasma under magnetic field". *Physics of Plasmas*, **26**:063102, 2019.

[18] H. K. Malik. "Generalized treatment of skew-cosh-Gaussian lasers for bifocal terahertz radiation ". *Physics Letters A*, **384**:126304, 2020.

[19] H. K. Malik. "Analytical calculations of wake field generated by microwave pulses in a plasma filled waveguide for electron acceleration". *Journal of Applied Physics*, **104**:053308, 2008.

[20] S. Sarkar, R. Gopal, M. Kundu, K. Gope, M. Anand, and M. Krishnamurthy. "Measurement of asymmetric electron cloud in cluster nano-plasma". *Physics of Plasmas*, **26**:070703, 2019.

[21] T. Nagashima, H. Hirayama, K. Shibuya, M. Hangyo, M. Hashida, S. Tokita, and S. Sakabe. "Terahertz pulse radiation from argon clusters irradiated with intense femtosecond laser pulses". *Optics Express*, **17**:8807, 2009.

[22] U. Saalmann, C. Siedschlag, and J. M. Rost. "Mechanisms of cluster ionization in strong laser pulses". *Journal of Physics B: Atomic, Molecular and Optical Physics*, **39**:R39, 2006.

[23] O. F. Hagena and W. Obert. "Cluster formation in expanding supersonic jets: effect of pressure, temperature, nozzle size, and test gas". *The Journal of Chemical Physics*, **56**:1793, 1972.

[24] P. K. Tiwari and V. K. Tripathi. "Laser beat-wave excitation of plasma waves in a clustered gas". *Physica Scripta*, **73**:393, 2006.

[25] H. P. Laqua. "Electron Bernstein wave heating and diagnostic". *Plasma Physics and Controlled Fusion*, **49**:R1, 2007.

[26] A. K. Ram and S. D. Schultz. "Excitation, propagation, and damping of electron Bernstein waves in tokamaks". *Physics of Plasmas*, **7**:4084, 2000.

[27] A. Kumar and V. K. Tripathi. "Electron Bernstein wave excitation by counterpropagating electromagnetic waves in a plasma". *Physics of Plasmas*, **12**:102308, 2005.

[28] A. Varma and A. Kumar. "Electron Bernstein wave aided heating of collisional nanocluster plasma by nonlinear interactions of two super-Gaussian laser beams". *Laser Physics*, **32**:016001, 2022.

[29] A. Kumar, A. Kumar, S. P. Mishra, and M. S. Yadav. "Plasma wave aided heating of collisional nanocluster plasma by nonlinear interaction of two high power laser beams". *Optical and Quantum Electronics*, **54**:753, 2022.

[30] T. Taguchi, T. M. Antonsen, Jr., and H. M. Milchberg. "Resonant heating of a cluster plasma by intense laser light". *Physical Review Letters*, **92**:205003, 2004.

[31] P. K. Tiwari and V. K. Tripathi. "Stimulated Raman scattering of a laser in a plasma with clusters". *Physics of Plasmas*, **11**:1674, 2004.

[32] P. K. Tiwari and V. K. Tripathi. "Laser third-harmonic generation in clustered plasmas". *Physica Scripta*, **74**:682, 2006.

[33] K. Mori, M. Hashida, T. Nagashima, D. Li, K. Teramoto, Y. Nakamiya, S. Inoue, and S. Sakabe. "Increased energy of THz waves from a cluster plasma by optimizing laser pulse duration". *AIP Advances*, **9**:015134, 2019.

[34] A. Kumar, S. P. Mishra, A. Kumar, and A. Varma. "Electron Bernstein wave aided cosh-Gaussian laser beam absorption in plasma". *Optik*, **273**:170436, 2023.

[35] A. Varma, S. P. Mishra, A. Kumar, and A. Kumar. "Electron Bernstein wave aided Hermite cosh-Gaussian laser beam absorption in collisional plasma". *Laser Physics Letters*, **20**:076001, 2023.

[36] A. Varma and A. Kumar. "Excitation of lower hybrid wave by counterpropagating cosh Gaussian laser beams in a magnetized plasma". *Optik*, **231**:166326, 2021.

[37] A. Varma, A. Kumar, and A. Kumar. "Electron Bernstein wave aided heating of collisional nanocluster plasma by nonlinear interactions of two super-Gaussian laser beams". *Laser Physics*, **32**:016001, 2022.

[38] A. Kumara, A. Kumar, S. P. Mishra, and A. Varma. "Excitation of electron Bernstein wave by nonlinear interaction of two copropagating Hermite–Gaussian laser beams in collisional plasma with static magnetic field". *Optical and Quantum Electronics*, **55**:598, 2023.