Journal of Applied Sciences and Nanotechnology

Journal homepage: jasn.uotechnology.edu.iq

# Stimulated Raman Scattering of Q-Gaussian Laser Beam in an Unmagnetized Plasma

**[1]Ahmed S. Ahmed*, [1]Hyder A. Salih, [1]Khaleel I. Hassoon, [2]Sukhdeep Kaur**

*[1]Department of Applied Sciences, University of Technology – Iraq*
*[2]Guru Nanak Dev University Amritsar – India*

A R T I C L E I N F O

***Article history:***
Received: July, 21, 2023
Accepted: October, 14, 2023
Available online: December, 10, 2023

***Keywords***:
Stimulated Raman scattering,
Q-Gaussian laser beam,
Self-focusing,
Plasma frequency,
Beamwidth

***Corresponding Author:***
Ahmed S. Ahmed
as.20.53@grad.uotechnology.edu.iq

A B S T R A C T

This study describes the relativistic q-Gaussian laser beam's stimulated Raman scattering (SRS) in an unmagnetized plasma. Moreover, the influence of the pump laser's relativistic self-focusing on the SRS process has been investigated. Using variational theory, we derived analytical solutions to the coupled nonlinear wave equations describing the pump, EPW, and scattered waves. The resulting equations were numerically solved to see the impacts of laser and plasma characteristics on the dynamics of the pump beam and its influence on the power of scattered waves. The power of the scattered wave was observed to be significantly altered via the self-focusing action of the pump beam, where when the effect of self-focus increases, it leads to an increase in the effect of stimulated Raman scattering. The stimulated Raman scattering yield is investigated based on the intensity of the laser beam and plasma. The main finding is that as q increases, the SRS yield rises, and as the intensity of the laser beam and plasma density increase, the SRS yield also increases. The scattering of the self-focused beam occurs at a greater distance than the beam of the pump due to the relatively diminished level of scattered power. The value of the integrated reflection increases with the increase of q and the growth rate.

https://doi.org/10.53293/jasn.2023.7035.1230, Department of Applied Sciences, University of Technology - Iraq.


## 1. Introduction

The scattering electromagnetic waves phenomenon from the Eigenmodes of plasma has been well-recognized for several years [1, 2]. The plasma's intrinsic vibrational modes, electron plasma waves, and ion plasma waves may be amplified if a powerful laser beam propagates through the plasma [3-5].

A significant instabilities class includes an extensive amplitude light wave coupling into a scattered light wave plus either the plasma wave electron (the Raman instability) or an acoustic wave of ion (the Brillouin instability) [6]. The stimulation of Raman forward scattering (SRFS) is a significant nonlinear phenomenon in the laser-plasma accelerator framework. Its function is to initiate a relativistic plasma wave that facilitates the acceleration of electrons to energies in the multi-MeV range [7, 8]. The phenomenon above holds significance in the context of the fast igniter fusion methodology. Raman instability can generate hot electrons due to the propagation of an ultra-intense laser pulse in the underdense region of expanding fusion target plasma. The plasma wave ($\omega_p$) is driven by the ponderomotive force between the pump ($\omega_0$) and its Stokes/anti-Stokes sidebands ($\omega_0 \pm \omega_p$) in this particular process. The plasma wave's density fluctuation interacts with the pump, generating nonlinear currents that drive the sidebands upwards [9, 10]. Natural modes in a collisionless plasma are Landau damped due to the absence of a pump wave (laser beam). The electron and ion waves in plasma are stimulated and can cause plasma instabilities if the pump wave power exceeds the damping threshold. The SRS is enhanced if one of the excited modes has a high frequency [11]. Lately, there has been much concern in investigating the nonlinear influence of the laser radiation scattering phenomenon at elevated powers, as they're pertinent to laser-driven fusion. An elevated energy laser photon may decline into a plasma and photon or a phonon and photon, corresponding to SRS and SBS. Interaction of this ultra-intense laser pulse with plasmas has been a topic of investigational as well as theoretical study concern owing to its prospective uses in the rapid ignition in the scheme of Inertial Confinement Fusion (ICF), the acceleration of the particle, laser-induced plasma spectroscopy and fresh sources of radiation [12, 13]. SRS and SBS are considered the ICF's most important parametric decay instabilities. Three waves interact during SRS, one causing forward-scattering (FSRS) and the other producing backward-scattering (BSRS) [14]. Reducing the effects of SRS in the laser-induced plasma is crucial to the success of the laser fusion process. The laser light wave (the pump) decays into two other waves, the scattered light wave (SLW) and the electron plasma wave (EPW), making SRS a three-wave parametric instability [15]. Numerous approaches have been suggested for suppressing the SRS, like presenting a polarization rotation or a laser bandwidth and laser smoothing method (polarization smoothing, smoothing via spectral spreading, and produced spatial incoherence) [16]. The study conducted by Salih *et al*. [17] examined the SRS in non-magnetized plasma, specifically concerning the relativistic laser beams. The pump laser's self-focusing and the relativistic electron mass's nonlinearity affected the SRS process, which was investigated in this study. Incorporating the nonlinear coupling between the scattered laser beam and the pump laser was observed to have an effect. Hasoon et al. investigated the transverse static magnetic field impact upon the SRFS of a laser in plasma [18]. An upper hybrid wave and (2) focused Stokes/Anti-Stokes sidebands were excited by the x-mode. As a result, the electrons driving the upper hybrid wave experience a ponderomotive force from the laser and the sideband. Sharma P.[19] studied how relativistic nonlinearity affected the SRS of a laser beam travelling through a collisionless plasma at zero intensity in a centre hollow Gaussian beam. Building the equations employed the theory of fluid, which evolved with Maxwell's equations and the partial differential equation. Singh A. *et al*. [20] used the moment theory to study the SRS of Gaussian laser beam in Relativistic Plasma. They discovered the reduction in the reflectivity of SRS with an increment in the pump wave intensity. In this communication, Walia K. *et al*. [21] probe the SRS of a high-power beam in Thermal Quantum Plasma. There's a pump beam interaction with the EPW, which causes the backscattered beam creation. Gupta N. *et al*. [22] theoretically explored the SRS phenomenon of elliptical q-Gaussian laser beams interacting nonlinearly with the underdense plasmas. A variational theory-informed, semi-analytical solution to a system of coupled nonlinear wave equations for three waves (EPW, pump, and scattered). The pump beam's self-focusing effect was essential to the scattered waves' strength. The q-Gaussian beam is characterized by a parameter q, distinguishing it from a standard Gaussian beam. When q becomes infinitely large, the q-Gaussian mode converges to a regular Gaussian beam [23]. According to observations by Gupta *et al*. [24], the pump beam has a self-focusing effect that significantly impacts the scattered wave's power. Our research shows that the yield of SRS grows with increasing q, laser beam intensity, and plasma density. Most previous research papers were devoted to studying the Gaussian mode, and recently, there were only two studies in the q-Gaussian modes. These studies considered the ponderomotive force and the power of the scattering wave and its effect due to self-focusing, and they did not study the relativistic and the impact of plasma density on self-focusing of the laser beam and plasma density. This paper studied the relativistic self-focusing of the q-Gaussian beam on Raman scattering.

## 2. Relativistic Self-focusing

Let us contemplate a laser beam characterized by a frequency. $\omega_0$ and wave no. $k_0$, which undergoes propagation in a medium of unmagnetized plasma alongside the z-axis. The linear polarization of electromagnetic waves, specifically the laser beam, is denoted as $\overrightarrow{E_0} = \hat{y}E_0$, where $E_0$ represents the wave's electric field. The beam's intensity distribution along the wavefront at a distance of $z = 0$ is expressed in Eq. (1) [25]:

$$\mathbf{E_0E_0^*} = \mathbf{A_{00}^2}\left[\mathbf{1} + \frac{\mathbf{r^2}}{\mathbf{q{r_0}^2}}\right]^{-\mathbf{q}} \tag{1}$$

The equation mentioned above involves using a cylindrical coordinate system, where $E_0$ is the axial amplitude, r denotes the radial coordinate, $r_0$ is the original width of the beam, and $E_0$ signifies the axial amplitude. Therefore, the plasma dielectric constant can be expressed in Eq. (2) [26]:

$$\boldsymbol{\varepsilon} = \mathbf{1} - \frac{\omega_p^2}{\gamma\omega_0^2} \tag{2}$$

where $\boldsymbol{\omega_p}$ denotes the plasma frequency, defined as $\omega_p(=4\pi n_e e^2/m)^{1/2}$, $E_0$ is represented by $k_0 = (\omega_0/c)\varepsilon_0^{1/2}$. The $n_e$ Denotes the electron plasma density, while m and e represent the electronic mass and charge, respectively. The relativistic factor, denoted by γ, is expressed in Eq. (3) [26]:

$$\boldsymbol{\gamma} \approx \left[\mathbf{1} + \frac{e^2E_0E_0^*}{m_0^2\omega_0^2c^2}\right]^{\mathbf{1/2}} \tag{3}$$

The wave equation is the governing equation for the pump laser beam's electric field in the plasma and is expressed in Eq. (4) [17]:

$$\nabla^2\vec{E}_0 - \nabla\left(\nabla\cdot\vec{E}_0\right) + \frac{\omega_0^2}{C^2}\varepsilon_0\cdot\vec{E}_0 = 0 \tag{4}$$

The symbol $\boldsymbol{\varepsilon_0}$ Represents the permittivity of free space. When an electric field is expressed in Eq. (5) [6]:

$$\vec{E}_0 = \vec{A}_0\exp\{i(\omega_0 t - k_0 z)\} \tag{5}$$

The amplitude field of the laser beam is denoted by $\vec{A}_0$. Assuming further the variation of $\vec{A}_0$ in Eq(6):

$$\vec{A}_0 = \vec{A}_{20}\exp\{-ik_0S_0(x,y,z)\} \tag{6}$$

The functions $A_{00}$ and $S_0$ are defined as natural functions of space and giving by Eq. (7) and (8):

$$A_{20}^2(r,z) = \frac{A_{00}^2}{f^2(z)}\left[1 + \frac{r^2}{qr_0^2f^2(z)}\right]^{-q} \tag{7}$$

$$S_0 = \frac{1}{2}r^2\frac{1}{f_0}\frac{df_0}{dz} + \Phi_0(z) \tag{8}$$

The variables $f$ , $\Phi_0(z)$ and $r_0$represent the beam width, nonlinear dielectric function and spot size parameter, respectively. The equation for the beamwidth parameter $f$ of the fundamental wave can be derived using the methodology outlined by Salih *et al*. [27, 28]:

$$\frac{d^2f}{d\xi^2} = \frac{q^2}{k^2f^3(r^2/f^2+qr_0^2)^2} + \frac{\alpha A_{00}^2\omega_p^2}{c^2f^3k^2r_0^2} \tag{9}$$

The Runge-Kutta fourth-order method, Matlab, and Mathematica program [29] have been used to numerically solve Eq. 9 for the different laser-plasma parameters since an analytical solution is not possible; the laser beam's vacuum wavelength is (λ = 1.053 μm), as well as the laser original radius is $r_0$ =10 μm for the intensity of the laser beam (($I = 10^{18}\ W/cm^2$)). The graphical representation in Fig. 1 displays the fluctuations in the laser beamwidth parameter (f) about the normalized propagation distance, denoted as (ξ), across various q-parameter values. For example, as the parameter q increases from 1 to 10, the efficacy of self-focusing intensifies, but at values greater than 10, the defocusing is obvious.

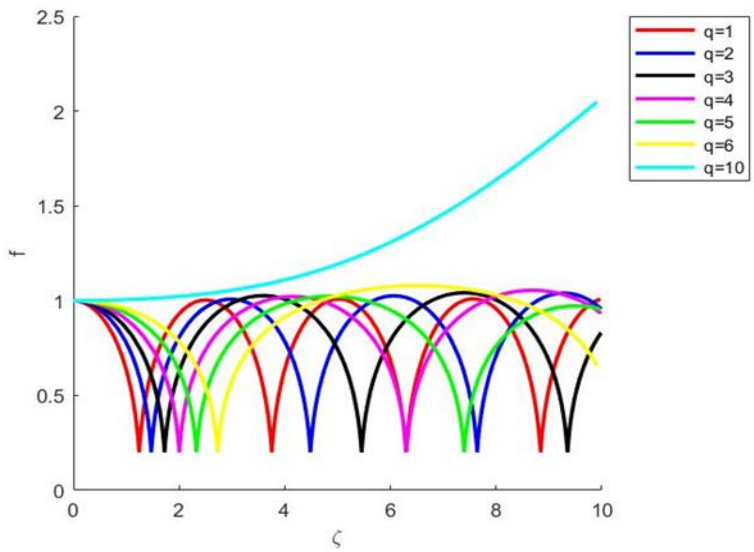


**Figure 1:** Variation of beamwidth parameter f with propagation distance ξ for parameters: $\alpha E_{00}^2 = 0.5$, $\omega_{p0}^2/\omega^2 = 0.02, and\ q = 1, 2, 3, 4, 5, 6, and 10$.

The impact of plasma density ($\omega_{p0}^2/\omega^2$ on the efficacy of self-focusing is illustrated in Fig. 2. At the elevated levels of plasma density ($\omega_{p0}^2/\omega^2$, it has been observed that focusing exhibits greater efficacy than defocusing when the plasma density increases. When the plasma density is less than 0.03, defocusing occurs.

The following relation gives the analytical solution to Eq. (10):

$$\boldsymbol{f}(\boldsymbol{\zeta}) = \sqrt{\mathbf{1} + \boldsymbol{q}^2\boldsymbol{\zeta}^2 + \boldsymbol{R}\boldsymbol{\zeta}^2} \qquad (10)$$

Where:

$$\boldsymbol{R} = \frac{\boldsymbol{\alpha A_{00}^2 \omega_p^2}}{\boldsymbol{c^2 k^2 r_0^2}} \qquad (11)$$

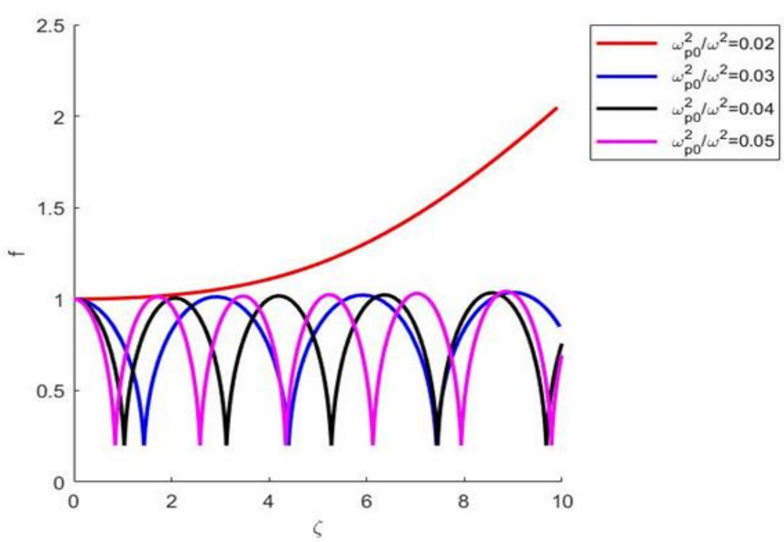


**Figure 2:** Variation of beamwidth parameters f with propagation distance ξ for parameters: $E_{00}^2 = 0.5$, $\omega_{p0}^2/\omega^2 = 0.02, 0.03, 0.04, 0.05, and\ q = 10$.

**3. Stimulated Raman Scattering**

Electron plasma waves have frequencies $\omega$ and wave numbers $k$, and when they interact with a powerful laser beam, they produce SRS waves with frequencies. $\omega_s$ and wave numbers $k_s$, where $\omega_s = \omega - \omega_0$ and $k_s = k - k_0$. The nonlinear coupling between the SRBS wave and the pump wave reduces the strength of the pump wave. The wave equations for the dispersed laser beam and the depleted laser beam with frequencies $\omega_d$ and wave numbers $k_d$ are expressed in Eq. (12) and (13):

$$\nabla^2\vec{E}_d + \frac{\omega_d^2}{c^2}\left(1 - \frac{\omega_p^2}{\gamma\omega_d^2}\right)\vec{E}_d + \frac{ie^2\omega_p^2 k|\vec{E}_s\vec{E}_s^*|\vec{E}_d}{16\Gamma_e m_0^2\gamma^3 c^2\omega_d\omega_s^2} = 0 \quad (12)$$

$$\nabla^2\vec{E}_s + \frac{\omega_s^2}{c^2}\left(1 - \frac{\omega_p^2}{\gamma\omega_s^2}\right)\vec{E}_s + \frac{ie^2\omega_p^2 k^2|\vec{E}_d\vec{E}_d^*|\vec{E}_s}{16\Gamma_e m_0^2\gamma^3 c^2\omega_s\omega_d^2} = 0 \quad (13)$$

Where:

$$\vec{E}_d = \vec{E}_{d0}\exp(i\{\omega_d t - k_d[z + S_d]\}) \quad (14)$$

$$\vec{E}_s = \vec{E}_{s0}\exp(i\{\omega_s t - k_s[z' + S_s]\}) \quad (15)$$

The symbol $\Gamma_e$Represents the damping factor arising from Landau damping, collisional damping, and other relevant factors. The remaining symbols in the equation retain their conventional meanings.

By substituting the expressions for $\vec{E}_d$ and $\vec{E}_s$ Obtained from Eq. (14) and Eq. (15) into Eq. (12) and subsequently separating the real and imaginary components, one arrives at a set of interdependent equations governing the behaviour of the depleted pump laser beam. For example, the equation for the fundamental part is as follows:

$$2\frac{\partial S_d}{\partial z} + \left(\frac{\partial S_d}{\partial r}\right)^2 = \frac{\omega_d^2\varepsilon_d}{c^2k_d^2} + \frac{1}{k_d^2E_{d0}}\left(\frac{\partial^2 E_{d0}}{\partial r^2} + \frac{1}{r}\frac{\partial E_{d0}}{\partial r}\right) \quad (16)$$

Where:

$$E_{d00}^2(r,z) = \frac{E_{d20}^2}{f_d^2(z)}\left[1 + \frac{r^2}{qr_0^2f_d^2(z)}\right]^{-q}e^{-2l_dz} \quad (17)$$

$$S_{d0} = \frac{1}{2}r^2\frac{1}{f_d}\frac{df_d}{dz} + \Phi_d(z) \quad (18)$$

$$E_{s00}^2(r,z) = \frac{E_{s20}^2}{f_s^2(z)}\left[1 + \frac{r^2}{qr_0^2f_s^2(z)}\right]^{-q}e^{-2l_sz'} \quad (19)$$

By substituting Eq. (8) and Eq. (9) into Eq. (10), one gets the following equation:

$$\frac{d^2f_d}{d\xi^2} = \frac{q^2}{k^2f_d^3(r^2/f_d^2+qr_0^2)^2} + \frac{\alpha E_{d20}^2\omega_p^2}{c^2f_d^3k^2r_0^2}e^{-2l_dz} \quad (20)$$

Additionally, the variation of $E_{s0}$ is presumed to be:

$$E_{s0} = E_{s00}exp\{-ik_sS_s\} \quad (21)$$

In a similar way to get Eq. (21) and assuming that:

$$\boldsymbol{S_{s0}} = \frac{1}{2}\boldsymbol{r^2}\frac{1}{\mathrm{g}}\frac{dg}{dz} + \boldsymbol{\Phi_s(z')} \quad (22)$$

By separating into the fundamental part and imaginary part, one gets the fundamental part as:

$$2\frac{\partial S_s}{\partial z'} + \left(\frac{\partial S_s}{\partial r}\right)^2 = \frac{\omega_s^2 \varepsilon_s}{c^2 k_s^2} + \frac{1}{k_s^2 E_{s0}}\left(\frac{\partial^2 E_{s0}}{\partial r^2} + \frac{1}{r}\frac{\partial E_{s0}}{\partial r}\right) \quad (23)$$

Substituting Eq. (19), Eq. (21), and Eq. (22) into Eq. (23) and equating the coefficients of the variable $\boldsymbol{r^2}$ on the two equation sides, one gets the subsequent Eq. (24):

$$\frac{\mathrm{d}^2 g}{\mathrm{d}\xi'^2} = \frac{q^2}{k^2 f_s^3 (r^2/f_s^2 + q r_0^2)^2} + \frac{\alpha E_{s20}^2 \omega_p^2}{c^2 f_s^3 k^2 r_0^2} e^{-2 l_s z'} \quad (24)$$

$l_s$ Is the power of scatter wave, where [18]:

$$\boldsymbol{l_s} = \frac{-e^2 \omega_p^2 k^2 |E_{d0}|_{r=0}^2}{32 m_0^2 \gamma_0^3 \Gamma_e c \omega_s^2 \omega_d^2 \varepsilon_s^{\frac{1}{2}}} \quad (25)$$

$E_{d0}$ is a complex function where,

$$\boldsymbol{E_{d0}} = \boldsymbol{E_{d00}}\, \boldsymbol{exp}\{-\boldsymbol{i k_d S_d}\}. \quad (26)$$

Substituting Eq. (26) into Eq. (25) gives:

$$\boldsymbol{l_s} = -\boldsymbol{G_{\mathrm{srs}}}\, \frac{\alpha_d' E_{d0}^2}{f_0^2 \gamma_0^3} e^{-2 g_s z} \quad (27)$$

$G_{\mathrm{srs}}$ is the growth rate of stimulated Raman scattering, where [17]:

$$\boldsymbol{G_{\mathrm{srs}}} = \frac{\omega_p^2 k^2 c}{32 \Gamma_e \omega_s \varepsilon_s^{1/2}} \quad (28)$$

And, $z' = L - z$ is the interaction length. A seed beam intensity of $2\times10^{-5}$ times the ultimate pump intensity has been selected. The findings are in graphical format, as depicted in Fig. 3 and 4. Fig. 3 illustrates the changes in the beamwidth parameter of the scattered wave g as a function of the normalized propagation distance ξ for varying plasma densities $\omega_{p0}^2/\omega^2$ (0.02, 0.03, 0.04, and 0.05). The results indicate that a rise in plasma density is associated with a decrease in the scatter wave's beamwidth parameter, as evidenced by Fig. 3. This phenomenon is because the self-focusing of the laser beam is directly proportional to the plasma density.

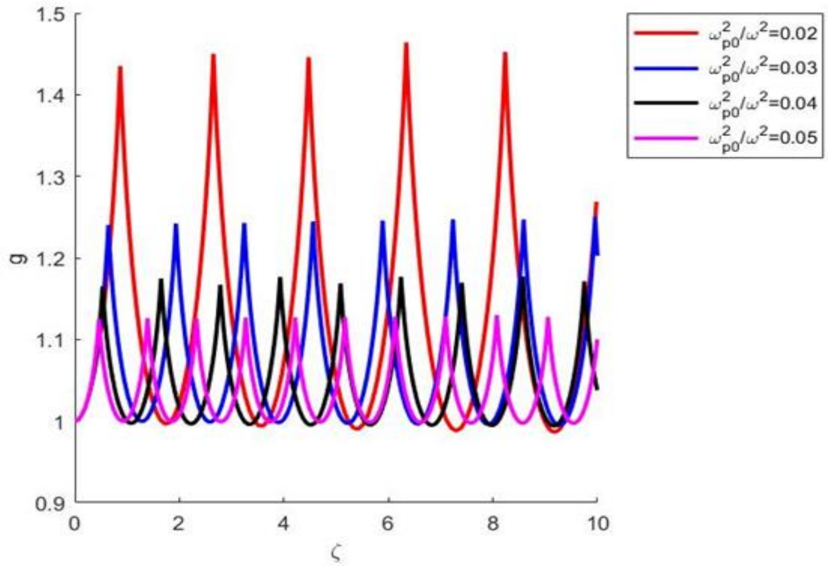


**Figure 3:** Variation of stimulated Raman scattering pump beam backscattered laser beamwidth parameters g with propagation distance ξ for parameters: 〖$\alpha A_{00}^2 = 0.5, \omega_{p0}^2/\omega^2 = 0.02,0.03,0.04,0.05, and\ q = 10$.

Fig. 4 manifests the scattered wave's beamwidth parameter fluctuation about the normalized propagation distance ξ, with the values of q (1, 2, 3, 4, 5, 6, and 10). This phenomenon can be attributed to the high sensitivity of the scatter wave and the degree of self-focusing exhibited by the laser beam.

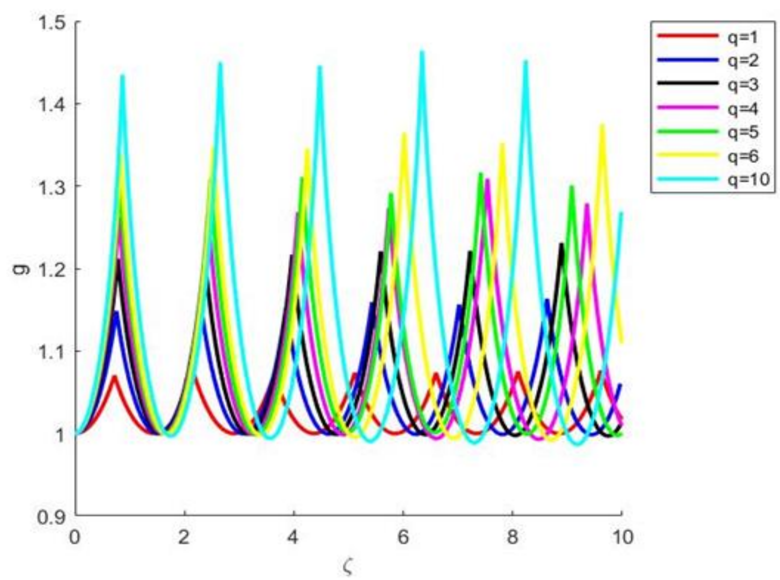


**Figure 4:** Variation of stimulated Raman scattering pump beam backscattered laser beamwidth parameters g with propagation distance ξ for parameters: $\alpha A_{00}^2 = 0.5, \omega_{p0}^2/\omega^2 = 0.02, and\ q = 1, 2, 3, 4, 5,6\ and\ 10$.

The SRS yield is influenced by the peak intensity of the pump laser beam, as depicted in Fig. 5. This effect can be attributed to the laser beam's increased self-focusing at higher intensities. This figure shows that an increase in the laser beam's intensity and plasma density results in a corresponding increase in the SRS yield. At higher intensities, the laser beam exhibits greater self-focusing, which can be credited to increased SRS yield.

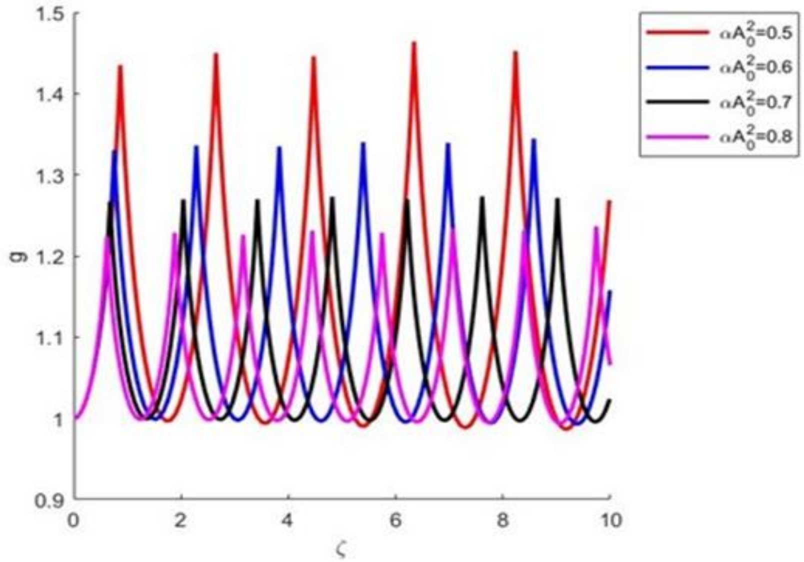


**Figure 5:** Variation of stimulated Raman scattering pump beam backscattered laser beamwidth parameters g with propagation distance ξ for parameters: $\alpha A_{00}^2 = 0.5,0.6,0.7,0.8$, $\omega_{p0}^2/\omega^2 = 0.02$, and $q = 10$.

The integrated reflectivity R is defined as the scattering power $P_s$ divided by the pump power $P_0$ and given by Eq. (29):

$$\boldsymbol{R_{z=0}} = \frac{E_{s20}^2}{A_{00}^2}\frac{r_{s0}}{r_0}e^{-l_s z'} \quad (29)$$

Fig. 6 shows the relationship between the integrated reflection and the growth rate in the SRS, where the value of the reflectivity increases with the increase in the value of q and also with the increase in the value of the growth rate for the SRS since the value of the growth rate depends on the parameter of the bandwidth of the pump wave and the scattering wave for these cases.

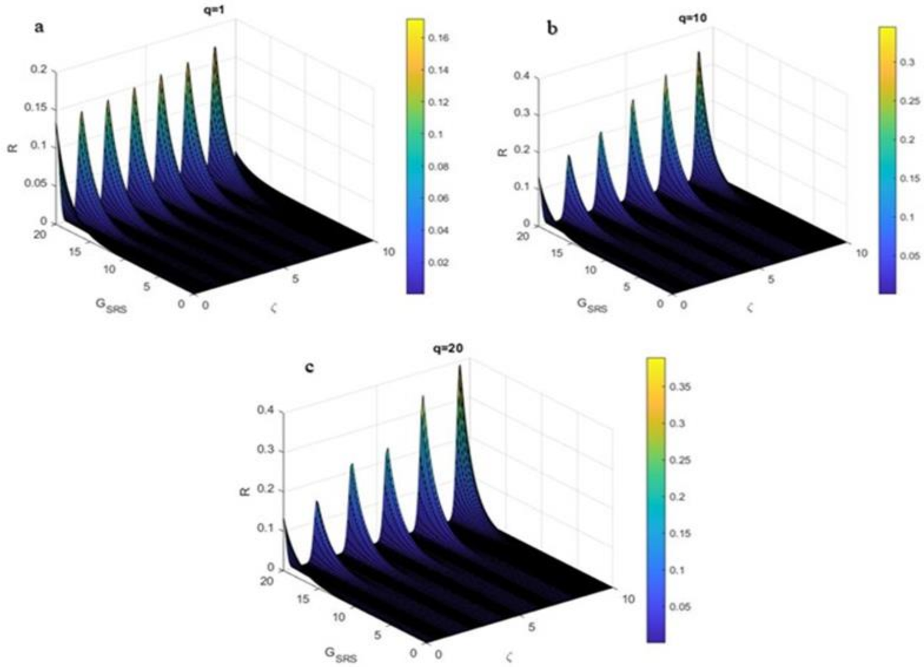


**Figure 6:** Evolution of integrated reflectivity with growth rate for a) q=1, b) q=10 and c) q=20 for parameter $\alpha A_{00}^2 = 0.5$, $\omega_{p0}^2/\omega^2 = 0.02$.

## 4. Conclusions

In summary, the present study has examined the occurrence of SRS when a q-Gaussian laser beam propagates through an unmagnetized plasma. It can be inferred that the scattered beam's relativistic self-focusing decreases substantially as the laser beam's amplitude structure approaches the optimal Gaussian profile. Also, the self-focusing of the q-Gaussian laser beam portrays a decreasing trend, while its nonlinear absorption demonstrates an increasing trend as q is increased. Additionally, the scattering of the self-focused beam occurs at a greater distance than the beam of the pump due to the relatively diminished level of scattered power. As q increases, the SRS yield increases, and as the intensity of the laser beam and plasma density increase, the SRS yield also increases. Also, the value of the integrated reflection is affected by increasing the value of q, as its value increases with the increase of q and the growth rate.

## Conflict of Interest

The authors declare that they have no conflict of interest.

## References

[1] M. I. Stockman, "Nanoplasmonics fundamentals and surface-enhanced Raman scattering as a physical phenomenon," *Recent developments in plasmon-supported Raman spectroscopy, World Scientific (Europe)*, pp. 1-32, 2017.

[2] J. J. Hsu, *Visual and computational plasma physics*. World Scientific Publishing Company, 2014.

[3] A. Krasnok, D. Baranov, H. Li, M.-A. Miri, F. Monticone, and A. Alú, "Anomalies in light scattering," *Advances in Optics and Photonics,* vol. 11, no. 4, pp. 892-951, 2019.

[4] T. Mealy and F. Capolino, "Traveling wave tube eigenmode solution for beam-loaded slow wave structure based on particle-in-cell simulations," *IEEE Transactions on Plasma Science,* vol. 50, no. 3, pp. 635-648, 2022.

[5] H. A. Salih and S. N. Mazhir, "Relativistic Self-Focusing of Intense Laser Beam in Magnetized Plasma," *Engineering and Technology Journal*, vol. 32, no. 5 Part (B) Scientific, 2014.

[6] W. Kruer, *The physics of laser plasma interactions*. crc Press, 2019.

[7] A. Deng *et al.*, "Betatron radiation damping in laser plasma acceleration," *Laser and Particle Beams,* vol. 30, no. 2, pp. 281-289, 2012.

[8] R. Sentis, "models and simulations for the laser-plasma interaction and the three-wave coupling problem," *Discrete & Continuous Dynamical Systems-Series S,* vol. 5, no. 2, 2012.

[9] P. Kaw, "Nonlinear laser–plasma interactions," *Reviews of Modern Plasma Physics,* vol. 1, pp. 1-42, 2017.

[10] G. Cristoforetti *et al.*, "Time evolution of stimulated Raman scattering and two-plasmon decay at laser intensities relevant for shock ignition in a hot plasma," *High Power Laser Science and Engineering,* vol. 7, p. e51, 2019.

[11] D. Turnbull, S. Li, A. Morozov, and S. Suckewer, "Simultaneous stimulated Raman, Brillouin, and electron-acoustic scattering reveals a potential saturation mechanism in Raman plasma amplifiers," *Physics of Plasmas,* vol. 19, no. 8, 2012.

[12] B. Gaur, P. Rawat, and G. Purohit, "Mitigation of stimulated Raman backscattering by elliptical laser beam in collisionless plasma," *Optik,* vol. 157, pp. 99-112, 2018.

[13] H. M. Fadhil, K. I. Hassoon, and H. A. Salih, "Spectroscopic and Structural Analysis of Aluminum Bulk and Nanoparticles: A Comparative Study," *Journal of Applied Sciences and Nanotechnology,* vol. 2, no. 3, 2022.

[14] Q. Feng, L. Cao, Z. Liu, C. Zheng, and X. He, "Stimulated Brillouin scattering of backward stimulated Raman scattering," *Scientific Reports,* vol. 10, no. 1, pp. 1-14, 2020.

[15] N. Gupta, S. Kumar, and S. Bhardwaj, "Stimulated Raman scattering of self-focused elliptical q-Gaussian laser beam in plasma with axial density ramp: effect of ponderomotive force," *Journal of Optics,* vol. 51, no. 4, pp. 819-833, 2022.

[16] Y. Zhao, S. Weng, M. Chen, J. Zheng, H. Zhuo, and Z. Sheng, "Stimulated Raman scattering excited by incoherent light in plasma," *Matter and Radiation at Extremes*, vol. 2, no. 4, pp. 190-196, 2017.

[17] H. Salih, S. Mahmoud, R. Sharma, and M. Rafat, "Stimulated Raman scattering of relativistic laser beam in plasmas," *Physics of plasmas*, vol. 12, no. 4, p. 042302, 2005.

[18] K. Hassoon, H. Salih, and V. Tripathi, "Stimulated Raman forward scattering of a laser in a plasma with transverse magnetic field," *Physica Scripta,* vol. 80, no. 6, p. 065501, 2009.
[19] P. Sharma, "Stimulated Raman scattering of ultra intense hollow Gaussian beam in relativistic plasma," *Laser And Particle Beams,* vol. 33, no. 3, pp. 489-498, 2015.
[20] A. Singh and K. Walia, "Stimulated Raman scattering of gaussian laser beam in relativistic plasma," *Optik-International Journal for Light and Electron Optics,* vol. 124, no. 18, pp. 3470-3475, 2013.
[21] K. Walia, Y. Tyagi, D. Tripathi, A. Alshehri, and N. Ahmad, "Stimulated Raman scattering of high power beam in thermal quantum plasma," *Optik,* vol. 195, p. 163166, 2019.
[22] N. Gupta, S. Kumar, and S. Bhardwaj, "Stimulated Raman scattering of self-focused elliptical q-Gaussian laser beam in plasma with axial density ramp: effect of ponderomotive force," *Journal of Optics,* pp. 1-15, 2022.
[23] A. S. Ahmed, H. A. Salih, and K. I. Hassoon, "Relativistic Self-Focusing of a q-Gaussian Laser Beam in Plasma by the Influence of Magnetic Field," *Brazilian Journal of Physics,* vol. 53, no. 4, p. 112, 2023.
[24] N. Gupta, S. Kumar, and S. Bhardwaj, "Stimulated Raman scattering of self focused elliptical q-Gaussian laser beam in plasma with axial temperture ramp: effect of ponderomotive force," *Journal of Electromagnetic Waves and Applications,* vol. 36, no. 6, pp. 767-786, 2022.
[25] R. Kaur, T. Singh Gill, and R. Mahajan, "Relativistic effects on evolution of a q-Gaussian laser beam in magnetoplasma: application of higher order corrections," *Physics of Plasmas,* vol. 24, no. 5, 2017.
[26] C. Liu, V. Tripathi, and B. Eliasson, *High-power laser-plasma interaction*. Cambridge University Press, 2019.
[27] H. A. Salih, K. I. Hassoon, and R. A. Khamis, "Investigating some parameters of q-Gaussian laser beam in plasma," *Physics of Plasmas,* vol. 29, no. 2, p. 023103, 2022.
[28] A. S. Ahmed, H. A. Salih, and K. I. Hassoon, "q-Gaussian laser beam for second-harmonic generation from unmagnetized plasma," *Journal of Optics,* pp. 1-8, 2023.
[29] B. Kamal and N. Al-Saidi, "Extended Chaotic Nonlinear Programming Technique Constructing with Genetic Algorithms," *Journal of Applied Sciences and Nanotechnology,* vol. 1, no. 1, pp. 15-22, 2021.