

Study on stimulated rotational Raman scattering effects on high power ICF Super–Gaussian laser propagating through air

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When high power laser propagating through tens to hundreds of meters air path in ICF experiment, once beyond stimulated rotational Raman scattering (SRRS) threshold, the high power laser beam would be subject to loss of energy and a decrease in beam quality, even causing the optical components to be destroyed. In this paper we studied how SRRS process effects high power super-Gaussian laser, and made corresponding analysis of the lasers' intensity distribution in near field. We settled the numerical simultaneous equations by finite element method of MATLAB. Finally the rule of SRRS effects on high power super –Gaussian laser's beam intensity distribution in near field through air was obtained.

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1. Introduction

All energy comes from nucleus fusion of the sun .For people have grasped the technology of uncontrollable nucleus fusion, namely hydrogen bomb, then how to control nucleus fusion has become an important task. There are two methods to realize controllable nucleus fusion, one is magnetic confinement fusion, the other is inertial confinement fusion (ICF) which was first suggested by Lebedev and N.G.Basov from former Soviet Union in 1960s [1].

The strict requirements to ICF's high power laser drive [2] are(1) enough ensemble output capability to assure high temperature and high density conditions; (2)good beam quality to insure target practice experiment, to satisfy the basic requirements of high energy conversion efficiency of the triple- harmonic, running stability and safety; and (3)strengthen beam and pulse control to assure the black cavity radiation field can be strong enough in indirect driving of the physical experiment and to satisfy the drive running stability. These requirements suggest that the even quality of beams in the near field is important for running the laser drive. In the ICF laser drive, the power of the beam is far higher than the self focusing critical power and usually is 10 times that of the latter one. In this case the beam's uneven quality in near field leads to small size self focusing easily which divides the beam into silk, then makes partial of the beam destroy optics components. From above we know the beam's even quality in the near field determines the destruction

threshold of optics components, and furthermore it restricts the working load (or light energy), running stability and safety [3] of the ICF drive.

However tens to hundreds of high power laser beams are required to propagate with equal optical distance at the terminal of the high power ICF device and the beam quality must be even. Finally the space assignment of the high power laser is that tens of beams have to propagate through a long air path of tens to hundreds of meters. In this procession, high power ICF lasers interact with molecules in air (mainly nitrogen gas molecule) producing SRRS effects oriented in the direction of pump laser's propagation. Once reaching the SRRS threshold , (1)the energy of laser is reduced;(2)the quality of laser beam is worse sometimes not reaching the fusion target;(3)the laser after propagation would be a fundamental frequency beam to be converted to triple- harmonic, so the quality of the laser significantly effects the efficiency of triple- harmonic conversion;(4)it might destroy the optics components [4,5]. So the systemical harmful effects of the SRRS process are necessary to study.

From the 1970s, the main trend of solid laser was the American's high power solid laser technology, represented by the NOVA laser drive made by LLNL laboratory in 1984, the Omega laser drive made by LLE in 1995 and the NIF laser drive now. The SRRS four dimension physical equations (Maxwell-Bloch-Langevin equations) were also be suggested by Y.Lin,T.J.Kessler and J.J.Armstrong from Rochester University in America. Their research was based on SRRS effects through air on the Omega device.

The simulation results fit the experiment results well and the laser wave shape of their research was Gaussian one. Till now a systemic research on super-Gaussian shape pump pulse laser through SRRS process has not been carried out, which also corresponding to the facts of ICF experiments, so the research is required urgently. Some scholars from different countries have made continuous research on SRRS modeling with different experiment parameters but most of their work unfit the facts of our ICF experiments.

We use Maxwell-Bloch-Langevin equations to describe the high power ICF super-Gaussian lasers' SRRS effects through long air path on ICF high power laser drive [6-10]. The modeling includes the laser pulse shape, medium excitation and relaxation, spontaneous and stimulated Raman scattering, the diffraction of the pump laser and the Stokes laser. The modeling synthetically describes three sub-influences transient coupling results. We computed the modeling with the finite element method of MATLAB without approximation in manipulation or process neglecting. Finally the rule of SRRS effects on high power ICF super-Gaussian lasers beam distribution in near field after propagating through long air path is obtained.

2. Numerical modeling and analysis

2.1. Maxwell-Bloch-Langevin equations

SRRS four dimension physical equations are as following [6] - [12]:

$$[\nabla_{\perp}^2 + 2ik_L \frac{\partial}{\partial z}]E_L = 2\kappa_3 k_L Q E_S \quad (1)$$

$$[\nabla_{\perp}^2 + 2ik_S \frac{\partial}{\partial z}]E_S = 2\kappa_2 k_S Q^* E_L \quad (2)$$

$$\frac{\partial Q^*}{\partial t} = -\Gamma Q^* + i\kappa_1 E_L^* E_S + F^* \quad (3)$$

where E_L and E_S are pump and Stokes laser's complex amplitudes; Q is medium polarization; k_L and k_S are wave numbers of pump and Stokes laser respectively;

$\kappa_1, \kappa_2, \kappa_3$ are gain medium constants that

$$\kappa_1 = \sqrt{\frac{\Gamma c g}{8\pi^2 n \hbar \omega_s}}; \quad \kappa_2 = \kappa_3 = \left(\frac{2\pi n \hbar \omega_s}{c}\right) \cdot k_1^*; \quad F \text{ is } \Delta$$

-correlated random force represented random dephasing

due to collisions; Γ is Raman bandwidth; g is steady state Raman gain; ω_s is the frequency of Stokes laser; n is density of activated atom number; h is Planck's constant.

Equation (1) and (2) are in a moving coordinate system at the speed of light.

Both of the initial Q distribution and the Langevin term F are generated as complex Gaussian random noise sources:

$$\text{Pr ob}(Q_0(x, y, z, 0)) = \frac{1}{\pi \sigma_Q^2} \exp\left(-\frac{|Q_0(x, y, z, 0)|^2}{\sigma_Q^2}\right)$$

$$\text{Pr ob}(F(x, y, z, \tau)) = \frac{1}{\pi \sigma_F^2} \exp\left(-\frac{|F(x, y, z, \tau)|^2}{\sigma_F^2}\right)$$

$$\text{where } \sigma_Q^2 = \frac{1}{n \delta_x \delta_y \delta_z}; \quad \sigma_F^2 = \frac{2\Gamma}{n \delta_x \delta_y \delta_z \delta_\tau};$$

A —region of interaction; δ_x —finite difference step in X direction; δ_y —finite difference step in Y direction; δ_z —finite difference step in Z direction; δ_τ —finite difference step in t direction.

2.2. Near field distribution character of high power ICF super-Gaussian lasers beams after SRRS through long air path

The parameters we used in this paper are as follows; the pump pulse distribution in space is 18-step super-Gaussian, the density of Raman activated atoms n is $2.234 \times 10^{19} \text{ cm}^{-3}$, the Raman bandwidth Γ is $7.52 \times 10^9 \text{ s}^{-1}$, the steady state Raman gain g is $6.76 \times 10^{-12} \text{ cm/W}$, peak power of pump laser is 3 GW/cm^2 , the wavelength of pump laser is $3.511 \times 10^{-7} \text{ m}$, the propagation length is 50meter, the wavelength of Stokes is $3.5204 \times 10^{-7} \text{ m}$, FWHM (Full Width at Half Maximum) of the pump pulse is 1ns and the beam diameter is 2cm (square shape). Then we discussed SRRS effects on pump laser and Stokes laser's longitudinal and transverse distribution of intensity in near field of high power ICF super-Gaussian lasers.

(1) Super-Gaussian laser 's character

Flat-Gaussian and super-Gaussian beams' field distributing [7]: in the system of rectangular coordinates, the 2-dimension flat-Gaussian beam's field distributing $E(x,0)$ at $z=0$ is

$$E(x,0) = A_0 \exp\left[-\frac{(N_{FGB}+1)x^2}{\omega_0^2}\right] \sum_{k=0}^{N_{FGB}} \frac{1}{k!} \left[\frac{(N_{FGB}+1)x^2}{\omega_0^2}\right]^k \quad (4)$$

Where N_{FGB} is the step number of Flat-Gaussian beam ($N_{FGB}=0, 1, \dots$), ω_0 is the waist width of beam. $A_0=E(0,0)$ is the amplitude of the field center, when $x=\omega_0$ the equation (4) is as follows

$$\frac{E(\omega_0,0)}{E(0,0)} = \exp[-(N_{FGB}+1)] \sum_{k=0}^{N_{FGB}} \frac{(N_{FGB}+1)^k}{k!} \quad (5)$$

From equation (5) could we know that to Flat-Gaussian beam, the waist width of beam at $z=0$ could be defined as the abscissa value of field amplitude which

is $\exp[-(N_{FGB}+1)] \sum_{k=0}^{N_{FGB}} \frac{(N_{FGB}+1)^k}{k!}$ times of the amplitude at center (0,0). (Equivalently, beam intensity is $\exp[-2(N_{FGB}+1)] \left[\sum_{k=0}^{N_{FGB}} \frac{(N_{FGB}+1)^k}{k!}\right]^2$ times of center beam intensity.)

The remarkable point is that $\frac{E(\omega_0,0)}{E(0,0)}$ increases

with the increasing of N_{FGB} . but when N_{FGB} is big

enough, $\frac{E(\omega_0,0)}{E(0,0)}$ changes slow with the changing of

N_{FGB} .

The two-dimension super-Gaussian beam's field distribution at $z=0$ is

$$E(x,0) = A_0 \exp\left[-\left(\frac{x}{\omega_0}\right)^{N_{SGB}}\right] \quad (6)$$

Where N_{SGB} is the step number of super-Gaussian beam ($N_{SGB} \geq 2$), ω_0 is the waist width of beam.

$A_0=E(0,0)$ is the amplitude of the field center (0,0), when $x=\omega_0$ the equation (6) is as follows

$$\frac{E(\omega_0,0)}{E(0,0)} = e^{-1} \quad (7)$$

The equation (7) shows that unlike Flat-Gaussian beam, ω_0 could be defined as the abscissa value of field amplitude at e^{-1} of the center amplitude (when the beam intensity is e^{-2} of the center beam intensity), it has nothing to do with the step number N_{SGB} of the super-Gaussian beam.

(2) ICF super-Gaussian laser and Stokes laser's longitudinal distribution of intensity in near field after SRRS through long air path

We use four-dimension numerical modeling of SRRS effects focusing on beam distribution in near field under ICF conditions. The initial wave shape of high power super-Gaussian laser is showed as Fig. 1. SRRS effects on the laser could be ignored until beyond the SRRS threshold.

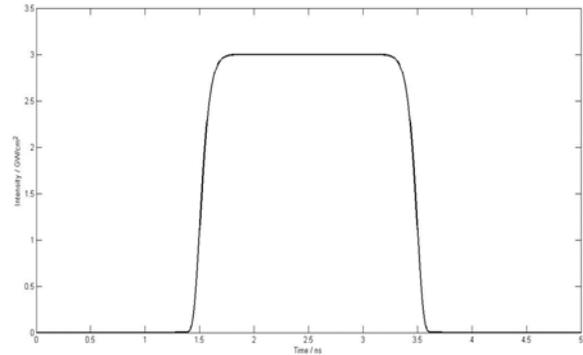


Fig. 1. Super-Gaussian pump laser 's intensity distribution in time field.

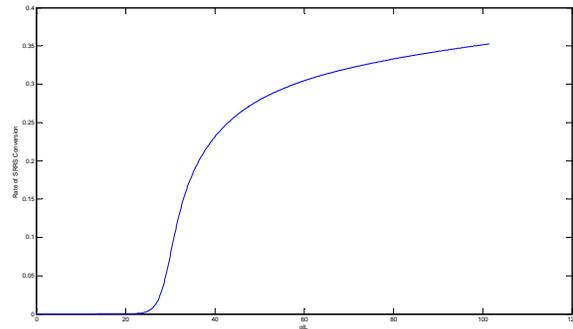


Fig. 2. The super-Gaussian beam 's rate of SRRS conversion after 50meter propagation in air.

When high power super-Gaussian laser propagated 50meter in air, GIL product was 101.4 which far beyond SRRS threshold (the conversion of Stokes has passed 1%) (Fig. 2). Now we could see the growth of stokes intensity took on semi-exponential in Fig. 1, this result fit well with the conclusion of related literature from American Rochester University.

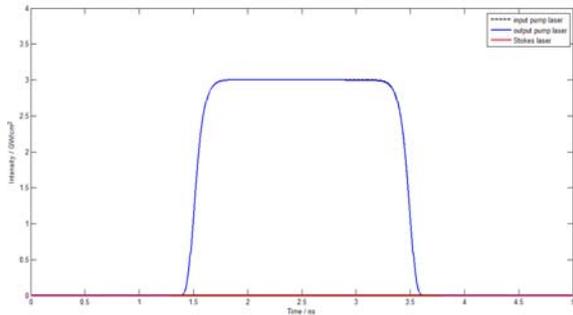


Fig. 3. Pump and Stokes light intensity distributions in time field after high power super-Gaussian laser propagating 10meter in air.

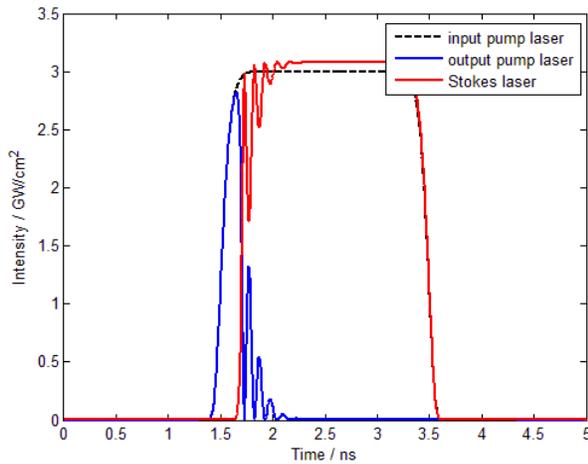


Fig. 4. Pump and Stokes light intensity distributions in time field after high power super-Gaussian laser propagating 50meter in air.

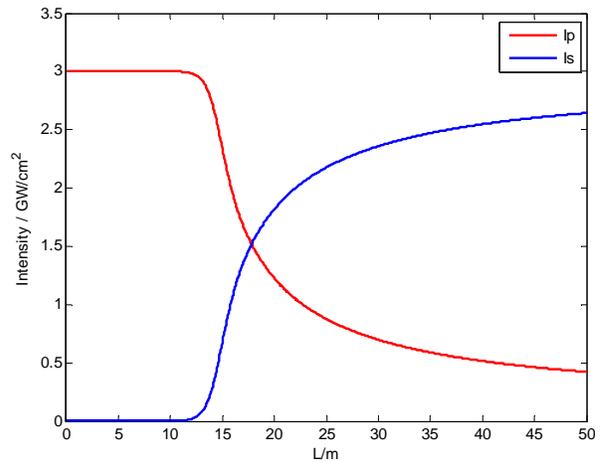


Fig. 5. Comparison between relaxation of pump laser and amplification of Stokes laser after high power super-Gaussian laser propagating 50meter in air.

Fig. 3 showed that to high power super-Gaussian laser the SRRS effect was not obviously after 10 meters propagation in air for it had not arrived to the SRRS threshold.

Fig. 4 showed when the GIL product beyond SRRS threshold with Stokes pulse producing a delay of pump laser. Then Stokes would be amplified continuously throughout the SRRS process. Finally pump laser would converse to Stokes laser entirely in theory. Figure 5 compared the relaxation of pump laser and amplification of Stokes laser. Noticing that in this process not only Stokes laser intensity was amplified but also beam divergence angle was amplified in SRRS progress which might leads to such a serious consequence that output laser might miss the fusion target.

(3)ICF super-Gaussian laser and Stokes laser’s transversal distribution of intensity in near field after SRRS through long air path

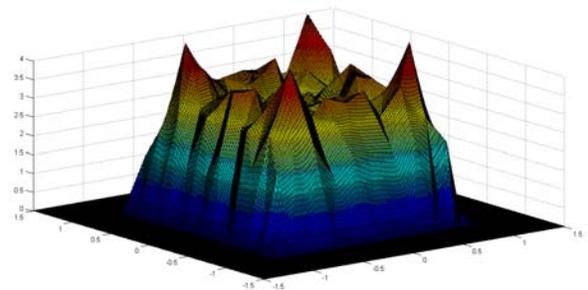


Fig. 6. Diffraction of high power super-Gaussian laser propagating after 50meter in air with 2cm beam aperture.

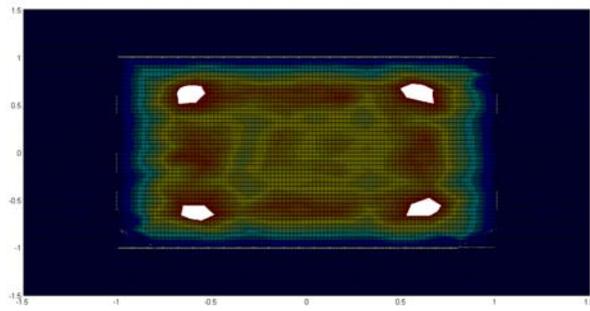


Fig. 7. High power super-Gaussian laser 's transversal intensity distribution after 50 meter propagation with 2cm beam aperture.

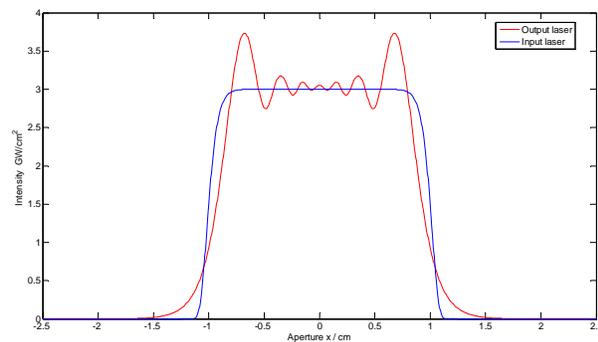


Fig. 8. High power super-Gaussian laser 's transversal intensity 2-dimension distribution after 50 meter propagation with 2cm beam aperture.

Figs. 6, 7, 8 showed after diffraction beam transversal surface became intense and the hot spot phenomenon became much sharper when exceeded SRRS threshold. The diffraction modulation expanded from borders to center along with propagation length increasing and the fastest modulation points were all on the borders (the fastest modulation increasing locations of rectangle diaphragm were four point angles). All the diffraction fringes symmetrical distributed at the center of diaphragm.

3. Conclusion

The paper emphasized on super-Gaussian shape high power pump pulse's distribution throughout the SRRS process in long air path, we used four-dimension numerical modeling of SRRS effects focusing on beam distribution in near field under ICF conditions. The rule of four-dimension numerical modeling of SRRS effects on beam distribution in near field after ICF high power super-Gaussian ultraviolet laser propagating through long air path was got that SRRS effects were not sharp until beyond SRRS threshold, then the conversion of SRRS would be in shape of semi-exponential which was similar to the American scholars 's conclusion of Gaussian ones.

Equally after the diffraction, beam transversal surface became intense and the hot spot phenomenon was much sharper when exceeded SRRS threshold. The diffraction modulation expanded from borders to center along with propagation length increasing and the fastest modulation points were all on the borders (the fastest modulation increasing locations of rectangle diaphragm were four point angles). All the diffraction fringes symmetrical distributed at the center of diaphragm.

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