Suppressing self-focusing effect in high peak power Nd:YAG picosecond laser amplifier systems

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Abstract: The output average power of all-solid-state picosecond amplifier suffered from self-focusing effect existed in the gain crystals. Through introducing the compensation element-gallium arsenide (GaAs) plate, the damage due to self-focusing effect has been avoided and the suppressing mechanism has been studied through theoretical analysis and experimental research for high peak power Nd:YAG crystal picosecond amplifier systems. The nonlinear refractive index coefficient of GaAs was obtained by calculation, and the relationship between the thickness of GaAs plate and the length of Nd:YAG rod under the optimal effect of suppressing self-focusing was given by numerical simulations. Under the condition that the center wavelength of the incident picosecond laser beam is 1 064 nm, the repetition frequency is 1 kHz, and the peak power density is about 12 GW/cm^2, experiments on the effect of GaAs plates with different thicknesses (200 μm and 550 μm) to reduce the self-focusing damage in Nd:YAG rod have been completed. With optimization of thickness of the GaAs plate, the compensation method demonstrates high efficiency under high peak power picosecond pulses condition especially for Nd:YAG amplifier.

Key words: self-focusing effect; nonlinear refractive index coefficient; optical damage; B-integral

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抑制高峰值功率皮秒激光放大系统 Nd:YAG 中的自聚焦效应

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摘 要: 全固态皮秒放大器的平均输出功率易受到增益晶体中自聚焦效应的影响。通过引入补偿元件—砷化镓(GaAs)片可以避免自聚焦效应造成的损伤,关于砷化镓的抑制机理对高峰值功率 Nd:YAG 晶体皮秒放大器系统的进行理论分析和实验研究。以公式计算得到了 GaAs 材料的非线性折射率系数,并由数值模拟给出了在抑制自聚焦的最佳效果下 GaAs 片厚度与 Nd:YAG 棒长度的关系。在入射皮秒激光束中心波长为 1 064 nm、重复频率为 1 kHz、峰值功率密度为 12 GW/cm^2 的条件下,进行了不同厚度(200 μm 和 550 μm)GaAs 片对抑制 Nd:YAG 棒自聚焦损伤的实验研究。通过优化 GaAs 片的厚度,该补偿方法在高峰值功率皮秒脉冲条件下,特别是对于 Nd:YAG 放大器显示出较高的效率。

关键词: 自聚焦效应; 非线性折射率系数; 光学损伤; B 积分

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0 Introduction

All-solid-state high average power lasers with ultra-short pulse output are applied to both commercial and scientific field such as micro-machining, communications engineering, laser ranging, biology sciences, etc[1-6] for its high pulse energy and high peak power. With the rapid development of laser applications, the requirement for output average power and beam quality is also increasing. However, the maximum output average power is limited by the damage of the gain medium which is produced by self-focusing effect. Ordinarily, the intensity of laser beam which is transmitted by the gradual amplification can reach the range of a few GW/cm^2 in high peak power picosecond amplifier systems. At this moment, self-focusing effect in the gain medium can not be neglected, because it will cause the laser power density in some positions increase rapidly, even the irreversible damage of the gain medium can also be produced in serious cases. Therefore, the further improvement of output power and beam quality is severely restricted.

In 1964, Hercher[7] found a long filament made up of small bubbles in BK-7 glass. Since then, scientists have gradually realized the damage of self-focusing in the gain medium. In order to protect the gain medium from the damage, some researches have been done on suppressing the self-focusing effect in recent years. A typical method to avoid the self-focusing process is using spatial filter to filter out the fastest growing spatial frequency [8]. Ferre et al.[9] applied spatial filter to beam shaping process to control the near-field profile and the self-focusing phenomenon was avoided. But it requires high vacuum auxiliary equipment and is not conducive to the structural assembly of the laser. Damian et al.[10] applied circular polarized light to the chirped pulse amplification (CPA) system of optical fiber to improve the self-focusing threshold. Because the nonlinear refractive index of circular polarized light is lower than linear polarized light. Centurion et al.[11] found that layered Kerr media consisting of glass and air can play a role in suppressing the self-focusing effect of pulsed laser. The self-defocusing behavior in the air gap counteracted the nonlinear small-scale self-focusing phenomenon in the glass medium. In addition, Rasskazov et al.[12] used binary phase shaping (BPS) combined with 4f system to mitigate self-focusing effect in fused silica. However, the prerequisite of using BPS is to obtain a stable intensity distribution of incident light in the laser system. Once the intensity distribution changes, the BPS needs to be re-customized, so using BPS has its own limitations.

In this paper, we propose a method to avoid the damage due to self-focusing effect in high peak power Nd:YAG crystal picosecond amplifier system by inserting gallium arsenide (GaAs) plate. Based on theoretical analysis, the suppressing mechanism of GaAs is introduced, and the nonlinear refractive index coefficient of gallium arsenide are calculated by formula. In terms of the nonlinear Schrödinger wave equation (NLSE), numerical simulations are performed to give the phenomenon of self-focusing in Nd:YAG and the suppressing effect of GaAs. And the relationship between the thickness of GaAs plate and the length of Nd:YAG rod under optimal compensation is obtained. Experiments on using GaAs plates with different thicknesses to suppress self-focusing produced by Nd:YAG are completed. By analyzing and discussing the results, we verify that GaAs can play an effective role in restraining the self-focusing effect in a high peak power Nd:YAG picosecond amplifier system.

1 Theory simulation

1.1 Self-action of the beam

When the high power laser beam is transmitted in the gain medium, the electric polarization and the intensity of opto-electronic field in the medium can no longer be expressed in a simple linear relation, it is given by:

$$P(r,\ t)=\chi^{(1)}\cdot E+\chi^{(2)}:EE+\chi^{(3)}\vdots EEE+\cdots \quad (1)$$

Where $P\ (r,\ t)$ is the electric polarization, E is the opto-electrionic field intensity, χ is the nonlinear susceptibility of the medium. Nd:YAG belongs to isotropic medium which with second-order nonlinear susceptibility value of zero. Accordingly, the third-order nonlinear susceptibility tensor $\chi^{(3)}$ becomes the lowest order and the most prominent nonlinear item. When nonlinear polarization is present, only considering the third-order nonlinear item, the refractive index n can be expressed as:

$$n=n_0+\delta n\approx n_0+\frac{2\pi\chi^{(3)}}{n_0}=n_0+\gamma I \quad (2)$$

Where n_0 is the linear refractive index, γ is the nonlinear refractive index coefficient, I is the intensity of laser beam, γI represents the nonlinear refractive index part. In the case of $\gamma_{\mathrm{Nd:YAG}}>0$, the refractive index of Nd:YAG increases with the intensity of increases. When Gaussian beam is incident, the intensity is stronger in the central region of the beam, the refractive index is larger and the speed of light is slower. With the propagation of the high peak power laser beam in Nd:YAG rod, the wavefront of the beam will be bent, the edge of the beam will protrude forward and the center will fall behind, ultimately will form a concave wavefront. As is well known, the propagation direction of the light is perpendicular to the wavefront. Consequently, the laser beam converges toward the center, eventually forming a self-focusing phenomenon. Similarly, GaAs has a negative nonlinear refractive index coefficient ($\gamma I<0$), so it has self-defocusing function.

When self-focusing or self-defocusing occurs in the crystal, the crystal rod can be approximately equivalent to a lens. Self-defocusing, for example, it can be seen as a negative lens, as shown in Fig.1. The light in the medium is approximated to a straight line, according to the equal optical path between the edge and center of light, the equation is obtained as follows:

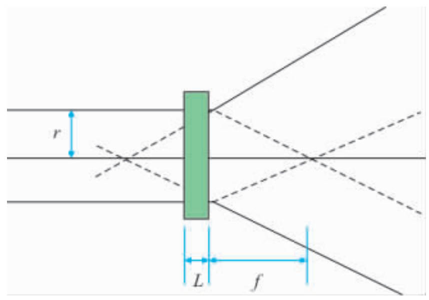

Fig.1 Equivalent focal length of self-defocusing

$$n_cL+f=n_eL+\sqrt{r^2+f^2} \quad (3)$$

Solving Eq.(3), it is obtained:

$$f=\frac{r^2-L^2(n_e-n_c)^2}{2L(n_e-n_c)} \quad (4)$$

Where f is the focal length of the equivalent lens and its positive and negative values respectively represent the effects of self-focusing and self-defocusing, r is the radius of the incident light spot. Due to the intensity values of the edge and center of Gaussian light are different, the refractive index is also divided into n_e, n_c (n_e is the refractive index of the edge light, n_c is the refractive index of the center light). In the case of the incident light intensity of 5.3 GW/cm^2, the divergence angle of the beam after it passing through GaAs is measured and the equivalent focal length can be calculated. Combined with the Eqs.(2) and (4), it is obtained as $\gamma_{\mathrm{GaAs}}=-3.47\times 10^{-13}$ cm^2/W.

1.2 Suppressing mechanism of GaAs

As a criterion of the severity of self-focusing in the nonlinear physics process, the B-integral is used to characterize the nonlinear phase delay [13] of the beam, it is defined as[14]:

$$B(x, y)=\frac{2\pi}{\lambda}\int_0^L \gamma I(x, y, z)\mathrm{d}z \qquad (5)$$

Where λ is the wavelength, I is the intensity of the incident beam, γ is the nonlinear refractive index coefficient, and L is the length of the medium. When the intensity of incident light is determined, γ and L affect the value of the B-integral. The higher the B-integral value, the greater the possibility of self-focusing. In order to reduce the B-integral value of Nd:YAG of high power laser pulses, GaAs plate with its negative refractive index coefficient is inserted into the optical path. At this time, the B-integral of the system can be expressed as the sum of the B-integral passing through both GaAs plate and Nd:YAG rod:

$$B_{sum}(x, y)=B_{GaAs}(x, y)+B_{Nd:YAG}(x, y) \qquad (6)$$

Where $\gamma_{GaAs}(x, y)<0$, $\gamma_{Nd:YAG}>0$, here the B-integral value will be reduced and thereby avoiding the occurrence of self-focusing. According to Eqs.(5) and (6), when the length of Nd:YAG rod is determined, there must be an optimum thickness d of GaAs plate corresponding to it for achieving the optimal effect of suppressing self-focusing (i.e., B_{sum} has the minimum value). Let $B_{sum}(x, y)=0$, and the relationship between the length L of Nd:YAG rod and the thickness d of GaAs plate is obtained, as show in Fig.2. The simulation parameters are as follows: $\gamma_{Nd:YAG}=6.9\times10^{-16}\mathrm{cm^2/W}$[15], $\gamma_{GaAs}=-3.47\times10^{-13}\mathrm{cm^2/W}$, $I_0=1.3\times10^{10}\mathrm{W/cm^2}$, $\omega_0=1.5$ mm, λ=1 064 nm.

Figure 3 shows that the B-integral comparative analysis graph between the situations with and without compensation of GaAs plate (d=200 μm).

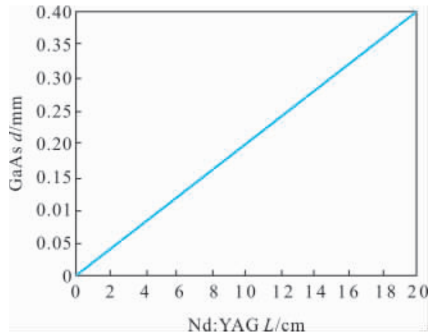

Fig.2 Length relationship of GaAs plate and Nd:YAG rod

In Fig.3, curve a gives the B-integral curve without GaAs compensation, and the B-integral value of Nd:YAG with the length of 10 cm is approximately 5.4. Curve b gives the result of using GaAs plate (d=200 μm) to compensate B-integral of Nd:YAG, obviously, there is a big gap of B-integral before and after compensation of GaAs plate in Fig.3. After compensation, the total B-integral value is reduced to only 0.01, hence the B-integral of the beam is effectively counteracted.

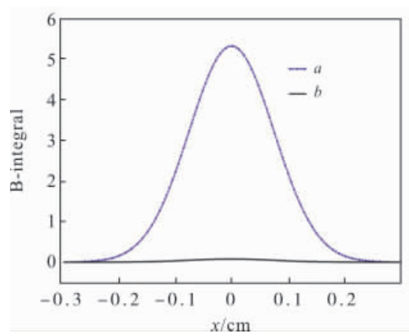

Fig.3 B-integral comparative analysis graph between the situations with and without compensation of GaAs plate

1.3 Numerical simulation

To further analyze the process of self-focusing in a high power laser system, in the paraxial approximation, we use the nonlinear Schrödinger wave equation to describe the propagation of the high power laser beam in a nonlinear medium:

$$\nabla_\perp^2 E+2ik_0\frac{\partial E}{\partial z}+2k_0^2\frac{\gamma I}{n_0}E=0 \qquad (7)$$

Where $\nabla_{\perp}^{2}+\nabla_{x}^{2}+\nabla_{y}^{2}$, k_0 is the wave number in the vacuum, the first term of the equation represents the diffraction process, the second term represents the transmission along the z axis, and the third represents the nonlinear effect. It gives the results of self-focusing effect appearing in Nd:YAG and the influence of GaAs plates with different thicknesses under the condition of neglecting the air gap between GaAs plate and Nd:YAG rod by using the split-step Fourier method to make numerical analysis based on the Eq.(7), as shown in Fig.4. The simulation parameters are as follows: $I_0=1.3\times10^{11}$ W/cm^2, $\omega_0=1.5$ mm, $\lambda=1\ 064$ nm, $\gamma_{\rm Nd:YAG}=6.9\times10^{-16}$ cm^2/W, $\gamma_{\rm GaAs}=-3.47\times10^{-13}$ cm^2/W.

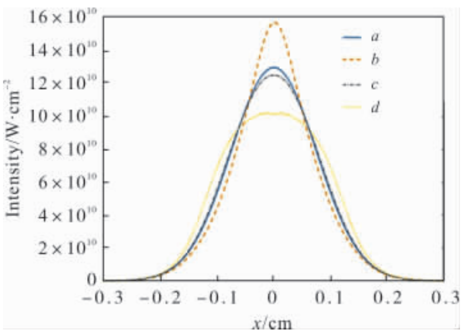

Fig.4 Calculated beam profiles

Illustrates the field distributions at position for different setups. In Fig.4, curve a indicates that Gaussian beam pass through neither Nd:YAG rod nor GaAs plate, it is the incident light. Curve b indicates that the Gaussian beam is only passing through the Nd:YAG crystal rod without GaAs plate. It is easily seen that the intensity in the center of the beam is increased from 1.3×10^{11} W/cm^2 to 1.6×10^{11} W/cm^2, which shows the Nd:YAG rod is more likely to be damaged. Curve c shows that the beam is passing through the Nd:YAG rod and the GaAs plate with the optimum thickness (d=200 μm). The intensity of the central light is close to the incident light, it indicates that the detrimental effects of self-focusing is reduced. According to the simulation results, the GaAs plate reduces the intensity in the center of the beam of curve b. Comparing with curve a, GaAs plate with the optimum thickness make the beam profile close to the incident light which indicates that it has an desired effect on suppressing self-focusing effect of Nd:YAG. From curve d in Fig.4, in the center of the beam, the intensity is lower than the initial intensity of curve a, it is the results of over-compensation. Over-compensation will cause the beam profile seriously deviate from the Gaussian distribution, and the effect is not as ideal as that of curve c.

2 Experiment

To demonstrate the suppressing effect of the GaAs plate on the self-focusing effect, an experimental setup was established. Moreover, the experimental setup has been simplified as shown in Fig.5, the source used in the experiment is an all-solid-state picosecond laser, the center wavelength of the incident picosecond laser beam is 1 064 nm, the repetition frequency is 1 kHz, and the peak power density was about 12 GW/cm^2. The optical beam expansion system was used to increase the diameter of the laser beam incident on the GaAs plate to protect the thin piece from high peak power laser-induced damage. At this moment, the peak power density incident on the GaAs plate reached about 5.3 GW/cm^2. The optical beam shrink system is placed behind the GaAs plate in order to make the nonlinear effect of Nd:YAG crystal rod become more obvious and

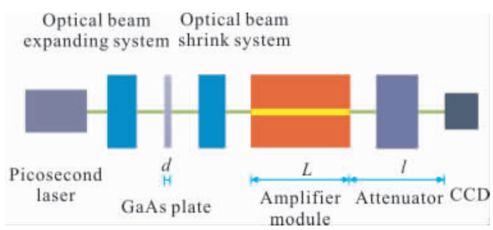

Fig.5 Experimental setup. L: length of the Nd:YAG rod in amplifier module; d: thickness of the GaAs plate; l: distance from the Nd:YAG rod to the CCD camera

convenient for experimental observation. And the peak power density of the beam passing through the optical beam shrink system is 12.7 GW/cm^2. In the experiment, the Nd:YAG crystal rod with a diameter of 4 mm and a length of 10 cm was positioned in amplifier module. The laser pulses were recorded by a 1 600 pixel×1 200 pixel CCD camera located 26 cm distance (l=26 cm) after the amplifier module. The intensity before every time entering the CCD camera is controlled to remain approximately the same by adjusting the attenuator placed in front of the CCD. It is to ensure that the observations of several experiments are accurate and reliable. GaAs plates with thicknesses of 200 μm and 550 μm were prepared for different experimental observations. And GaAs plates were coated with dou ble -sided anti - reflective(AR) coatings at a wavelength of 1 064 nm to reduce the optical power loss. Fig.6 shows the transmittance curve of the GaAs plate measured by the UV -2300 spectro -photometer, and the transmittance at a wavelength of 1 064 nm can reach more than 95%.

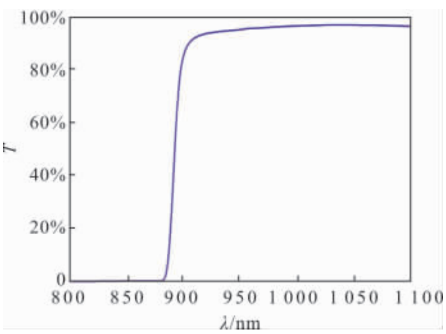

Fig.6 Plot of transmittance curve of the GaAs plate

3 Results and discussions

The intensity distributions of laser spots were measured by the OPHIR company M2 -200 s, as shown in Fig.7. And the specific parameters can be seen in the upper right corner of the picture: the total values represent the relative values of the total intensity after attenuation, the peak values represent the relative values of the peak intensity of the laser spot. Under the condition that the total values have essentially the same values, the variation of peak values in different experimental results were compared and analyzed.

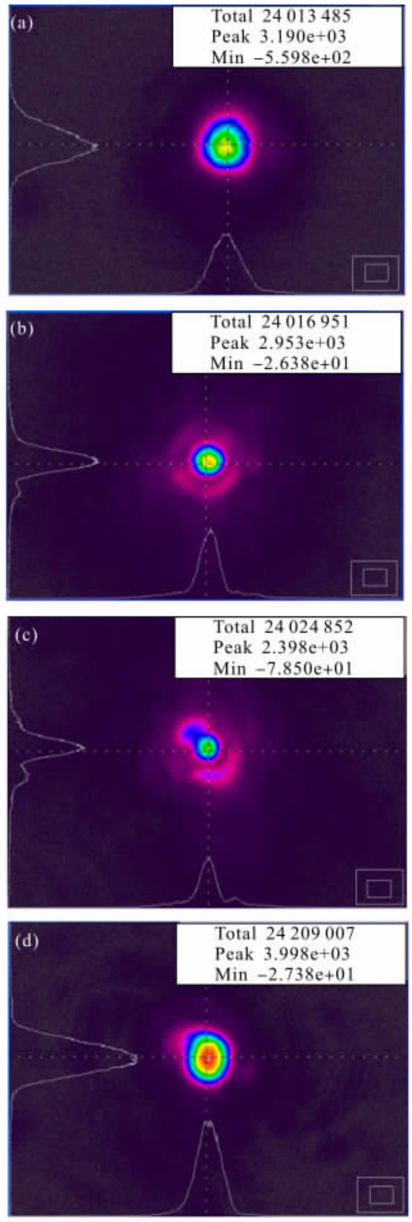

Fig.7 Images of laser spots are recorded by the CCD camera (I=12.7 GW/cm^2)

Figure 7(a) shows the spot image of incident light, that is say, the beam passed through neither the GaAs plate nor the Nd:YAG rod; Figure 7(b) shows the experimental result of the beam first passing through GaAs plate with the length of

200 μm and then passing through the Nd:YAG crystal rod. Comparing the spots parameters of Fig.7(a) and (b), it is found that the peak value of spot was slightly lower than the incident light when the GaAs plate and the Nd:YAG rod work together. Combining with the results of previous simulation, the GaAs plate (d =200 μm) can restore the profile of incident light as much as possible. However, the spot profile was not completely restored, as it has not achieved full compensation. In simulation, the thickness of 200 μm is not completely accurate, precious few microns produce a little self-defocusing effect. In addition, the incident Gaussian beam profile cannot reach the ideal profile completely. It can be seen that Nd:YAG crystal rod has no self-focusing effect at this point. At the end of this experiment, Nd:YAG crystal rod was taken down and the damage point was not detected, as shown in Fig.8(a).

The experiment was repeated by replacing a 200 μm thickness GaAs plate with a 550 μm GaAs plate, as shown in Fig.7 (c). Compared with Fig.7 (b), the center peak value of the spot has dramatically decreased, which means that over-compensation of B-integral occurring. It is consistent with the results of the above mentioned theoretical simulations. In the case of over-compensation, the effect of GaAs plate is so strong that the Nd:YAG crystal rod also has no optical damage, the same as Fig.8(a).

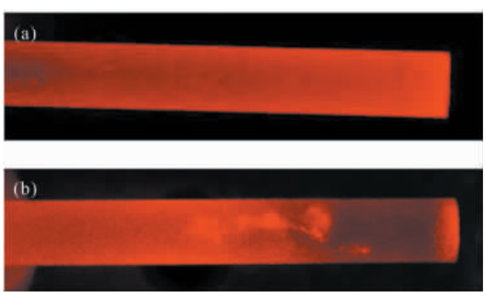

Fig.8 Comparison between damage and no damage in Nd:YAG rod

When the GaAs plate is removed, the laser beam only through Nd:YAG rod, the intensity distribution is shown in Fig.7 (d). Comparing the peak parameter values in Fig.7(a), it can be seen that the relative value of the center peak of the laser spot is very high, and the damage point in the spot distribution was observed. A series of self-focusing points appeared in the Nd:YAG crystal rod, as shown in Fig.8(b). It is proved that self-focusing effect has caused irreversible optical damage to the crystal rod.

4 Conclusion

In this paper, we showed theoretically and experimentally the effectiveness of the suppression of self-focusing effect in a high peak power Nd:YAG crystal picosecond amplifier system by inserting a GaAs plate. The nonlinear refractive index coefficient of GaAs is obtained by calculation, and the relationship between the thickness of GaAs plate and the length of Nd:YAG under optimal compensation is given by numerical simulation. The nonlinear interaction between high peak power laser and medium is simulated by using the nonlinear Schrodinger equation. Under the condition of the center wavelength of the incident picosecond laser beam is 1 064 nm, the repetition frequency is 1 kHz, experiments demonstrated that this method can effectively suppress the self-focusing in the peak power amplifier system and protect the crystal rod from damage. This method can control the loss of laser beam within 5% and easy to operate. It did not achieve full compensation in the experiment, the possible reasons were the calculation error of the nonlinear refractive index coefficient of GaAs, the slight difference of the thickness of GaAs plate and the inconsistency of the incident Gaussian beam profile with the ideal profile.

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