Linear polarization output performance of Nd:YAG laser at 946 nm considering the energy-transfer upconversion*

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A theoretical model of quasi-three-level laser system is developed, in which both the thermally induced depolarization loss and the effect of energy-transfer upconversion are taken into account. Based on the theoretical investigation of the influences of output transmission and incident pump power on thermally induced depolarization loss, the output performance of 946 nm linearly polarized Nd:YAG laser is experimentally studied. By optimizing the transmission of output coupler, a 946 nm linearly polarized continuous-wave single-transverse-mode laser with an output power of 4.2 W and an optical–optical conversion efficiency of 16.8% is obtained, and the measured beam quality factors are $M_x^2 = 1.13$ and $M_y^2 = 1.21$. The theoretical prediction is in good agreement with the experimental result.

Keywords: 946 nm laser, linear polarization, thermally induced depolarization losses, energy-transfer upconversion

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1. Introduction

The realization of 946 nm laser based on Nd:YAG has great potential applications in vapor detection, diffraction absorption radar, and 473 nm blue laser generation by frequency doubling.[1–5] Solid-state blue lasers are attractive due to their numerous applications, such as color display, high-density optical data storage, and underwater communication. In addition, Si photodiode with a quantum efficiency over 99% is available at 946 nm. The use of Nd:YAG laser at 946 nm along with Si photodiode will reduce the detection loss in the generation of squeezed light.[6]

However, it is relatively difficult to obtain an efficient 946 nm Nd:YAG laser, due to the characteristics of the quasi-three-level transition, the need for a high pump deposition density to achieve population inversion, and the extremely small stimulated emission cross section compared with those near 1064 nm and 1320 nm,[7] thereby leading to very strong thermal effects and limiting the power scaling of laser as well.[8] Several methods have been used to reduce the thermal lensing effect and improve the performance of Nd:YAG laser at 946 nm, such as using a composited laser rod,[9] efficient cooling schemes,[10,11] direct pumping and thermally boosted pumping.[12] Another factor that limits the scaling of Nd:YAG laser output is the energy-transfer upconversion (ETU) effect. This ETU effect will reduce the population of the upper laser level, and give rise to an extra heat load in the laser crystal, so the thermal effect of the gain medium becomes more severe and the laser performance is degraded. The influences of the ETU effect on the threshold, output power, and fractional thermal loading of Nd:YAG 946 nm lasers have been investigated theoretically and experimentally.[13–15]

As is well known the realizing of linear polarization fundamental output is very important for efficient frequency doubling. To achieve this, a number of polarizing elements have to be inserted into the laser cavity. Obviously, the presence of thermally induced birefringence will give rise to depolarization loss and lower the conversion efficiency of the laser. Thermally induced birefringence has been analyzed and several methods have been used to compensate for the depolarization loss.[16–18] Hua *et al.* used a quarter-wave plate to compensate for and reduce the depolarization loss from thermally induced birefringence in an Nd:YAG laser with a polarization output.[16] Wang *et al.* theoretically described the birefringence characteristics in an Nd:YAG rod by taking the thermal lens effect into account and measured the degree of polarization of the probe beam.[17] Mondal *et al.* simply used a Glan-Taylor polarizer to reduce the depolarization loss resulting from thermally induced stress birefringence of solid state Nd: YAG laser.[18] However, the study on the influence of the ETU effect on thermally-induced depolarization loss has not been published previously to the best of authors' knowledge.

In this paper, a diode-end-pumped Nd:YAG laser is built up using a three-mirror folded cavity with a Brewster plate. A theoretical model of a quasi-three-level laser system is developed with consideration of the thermally-induced depolarization loss and the effect of ETU. Based on the theoretical

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investigation of the influences of output transmission and incident pump power on thermally-induced depolarization loss, the linear polarization output performance of Nd:YAG laser at 946 nm is studied experimentally. By optimizing the transmission of output coupler (OC), a 946 nm linearly polarized continuous-wave (CW) single-transverse-mode (TEM_{00}) solid-state laser is demonstrated.

2. Theoretical analysis considering the effect of ETU

In a quasi-three-level laser system, an implicit analytical expression for the laser output (P_{out}) can be derived from the space-dependent rate equation including the effect of ETU[7] and expressed as follows:

$$\frac{2\sigma L_{\mathrm{c}}}{n}\iiint\limits_{\mathrm{crystal}}\frac{2\tau f R r_{\mathrm{p}}\varphi_0+2\dfrac{c\sigma\tau}{n}fN_{\mathrm{a}}^0\Phi\varphi_0^2}{1+\dfrac{c\sigma\tau}{n}f\Phi\varphi_0+\left[\left(1+\dfrac{c\sigma\tau}{n}f\Phi\varphi_0\right)^2+4W\tau^2\left(Rr_{\mathrm{p}}+\dfrac{c\sigma}{n}N_{\mathrm{a}}^0\Phi\varphi_0\right)\right]^{1/2}}\mathrm{d}V=\delta+\frac{2N_{\mathrm{a}}^0\sigma L_{\mathrm{c}}}{n}\iiint\limits_{\mathrm{crystal}}\varphi_0\,\mathrm{d}V, \tag{1}$$

where σ is the stimulated emission cross section, L_{c} is the efficient cavity length, n is the index of refraction in the laser medium, τ is the lifetime of the upper laser level, c is the speed of light in vacuum, N_{a}^0 is the unpumped population density of lower laser level, W is the upconversion parameter, $f=f_{\mathrm{a}}+f_{\mathrm{b}}$ with f_{a} and f_{b} being the fractional population of lower and upper laser level, respectively. $r_{\mathrm{p}}(rz)$ and $\phi(rz)$ are the normalized spatial distribution of pump beam and laser photons, respectively. We assume that the pump beam and laser beam are of the single transverse mode (TEM_{00}) with negligible diffraction in the laser crystal. The spatial distribution of pump beam and the laser beam can be given respectively, by[7,13]

$$r_{\mathrm{p}}(r,z)=\frac{2\alpha}{\pi\omega_{\mathrm{p}}^2[1-\exp(-\alpha L)]}\exp(-\alpha z)\exp\left(-\frac{2r^2}{\omega_{\mathrm{p}}^2}\right), \tag{2}$$

$$\varphi_0(r,z)=\frac{2}{\pi\omega_0^2L_{\mathrm{c}}}\exp\left(-\frac{2r^2}{\omega_0^2}\right), \tag{3}$$

where α is the absorption coefficient of laser crystal at the pump wavelength; L is the length of laser crystal; ω_{p} and ω_0 are the pump beam radius and laser beam radius in the laser crystal, respectively; R is the pumping rate and Φ is the total number of laser photons in the cavity, which can be expressed as[13]

$$R=\frac{P_{\mathrm{in}}[1-\exp(-\alpha L)]}{h\nu_{\mathrm{p}}}, \tag{4}$$

$$\Phi=\frac{2L_{\mathrm{c}}P_{\mathrm{out}}}{ch\nu_0T}, \tag{5}$$

where P_{in} is the incident pump power; $h\nu_{\mathrm{p}}$ and $h\nu_0$ are the pump photon energy and laser photon energy, respectively; T is the transmission of OC.

The round-trip loss δ inside the cavity can be written as $\delta=T+\delta_{\mathrm{f}}+\delta_{\mathrm{dif}}+\delta_{\mathrm{dep}}$, where δ_{f}, δ_{dif}, and δ_{dep} denote the intrinsic loss, thermally induced diffraction loss,[8] and thermally induced depolarization loss, respectively. The thermal depolarization loss is an additional loss induced by the polarizer existing in the cavity, which can be derived when the laser operates in the fundamental mode and expressed as[19]

$$\begin{aligned}\delta_{\mathrm{dep}} = 0.585\times\Bigg\{1-\int_0^{2\pi}\int_0^{r_0}\exp\left(-\frac{2r^2}{\omega_0^2}\right)\\ \times\left[1-\sin^2(2\phi)\sin^2(\delta_{\mathrm{phase}})\right]r\,\mathrm{d}r\,\mathrm{d}\phi\Bigg\},\end{aligned} \tag{6}$$

where r_0 is the radius of the laser rod, and δ_{phase} is the polarization phase shift of the light emerging from the laser rod, which can be written as[19]

$$\delta_{\mathrm{phase}}=\frac{n^3\alpha_{\mathrm{t}}(p_{12}-p_{11}-4p_{44})}{6\lambda_0K}\xi P_{\mathrm{in}}\eta_{\mathrm{abs}}\frac{r^2}{r_0^2}, \tag{7}$$

where α_{t} and p_{ij} are the thermal expansion coefficient and elasto-optical coefficient of the laser rod, respectively, λ_0 is the laser wavelength, K is the thermal conductivity, η_{abs} is the absorption efficiency of the pump radiation, and ξ is the fractional thermal loading.

If the effect of ETU is not considered, the fractional thermal loading is expressed as ξ_0, which under the lasing condition is taken as a quantum defect $1-\lambda_{\mathrm{p}}/\lambda_0$, where λ_{p} is the pump wavelength. However, if the effect of ETU is taken into account, the fractional thermal loading ξ is no longer a constant, but becomes[15]

$$\xi=\xi_0\frac{N_{\mathrm{b}}}{N_{\mathrm{bnoETU}}}+1-\frac{N_{\mathrm{b}}}{N_{\mathrm{bnoETU}}}, \tag{8}$$

where N_{b} is the population density in the upper laser level considering the ETU effect and is given by[15]

$$N_{\mathrm{b}}=\iiint\limits_{\mathrm{crystal}}\frac{2\tau f_{\mathrm{b}}Rr_{\mathrm{p}}+\dfrac{2c\sigma\tau}{n}f_{\mathrm{b}}N_{\mathrm{a}}^0\Phi\varphi_0}{1+\dfrac{c\sigma\tau}{n}f\Phi\varphi_0+\left[\left(1+\dfrac{c\sigma\tau}{n}f\Phi\varphi_0\right)^2+4W\tau^2\left(Rr_{\mathrm{p}}+\dfrac{c\sigma}{n}N_{\mathrm{a}}^0\Phi\varphi_0\right)\right]^{1/2}}\mathrm{d}V, \tag{9}$$

N_{bnoETU} is the population density in the upper laser level in the absence of ETU effect and can be written as[15]

$$N_{\mathrm{bnoETU}} = \iiint\limits_{\mathrm{crystal}} \frac{\tau f_{\mathrm{b}} R r_{\mathrm{p}} + \dfrac{c\sigma\tau}{n} f_{\mathrm{b}} N_{\mathrm{a}}^{0} \Phi \varphi_0}{1 + \dfrac{c\sigma\tau}{n} f \Phi \varphi_0} \mathrm{d}V. \tag{10}$$

For a diode-end-pumped 946 nm Nd:YAG laser with a three-mirror folded cavity configuration and a Brewster plate in the cavity, the thermally induced depolarization loss can be calculated using Eqs. (1)–(10) and the parameters: $\lambda_{\mathrm{p}} = 808$ nm, $\lambda_{\mathrm{l}} = 946$ nm, $\omega_{\mathrm{p}} = 200$ μm, $\omega_0 = 140$ μm, $L_{\mathrm{c}} = 284$ mm, $L = 5$ mm, $\delta_{\mathrm{f}} = 0.012$, $n = 1.82$[7] $c = 3 \times 10^8$ m/s, $h = 6.626 \times 10^{-34}$ Js, $\eta_{\mathrm{abs}} = 0.9$, $\alpha = 450$ m^{-1},[7] $\sigma = 4 \times 10^{-24}$ m^2,[7] $\tau = 230$ μs,[7] $f_{\mathrm{a}} = 0.0065$, and $f_{\mathrm{b}} = 0.6$,[7] $N_{\mathrm{a}}^0 = 0.897 \times 10^{24}$ m^{-3} (1 at.% doping concentration),[19] $W = 2.8 \times 10^{-22}$ m^3/s,[9] $p_{12} - p_{11} - 4p_{44} = 0.284$,[19] $\alpha_{\mathrm{t}} = 7.5 \times 10^{-6}$ K^{-1},[7] and $K = 13$ W/mK.[19]

Figure 1 shows the calculated thermal depolarization losses versus the transmission of OC with and without the ETU effect at a pump power of 25 W. It can be seen that the thermal depolarization losses increase with the augment of output transmission when the ETU effect is taken into account. In contrast, when the ETU effect is ignored, the thermal depolarization loss is a constant of 0.02 as the output transmission increases. The calculated thermal depolarization losses versus pump power with and without the effect of ETU at an output transmission of 6% are shown in Fig. 2. It can be seen that the thermal depolarization loss increases with the augment of pump power in the absence of the effect of ETU, but the thermal depolarization loss in the presence of the ETU effect becomes more severe than in the absence of the ETU effect at high pump powers. In consequence, it is necessary to investigate the influence of the output transmission on thermal depolarization loss with consideration of the ETU effect in order to achieve the optimum linear polarization output.

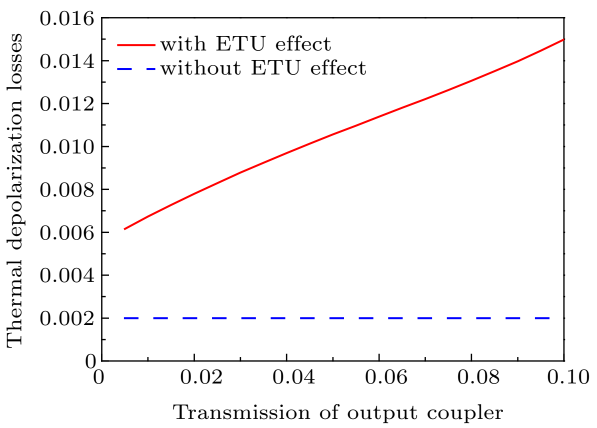

Fig. 1. (color online) Thermal depolarization losses versus output transmission at a pump power of 25 W with (red solid curve) and without (blue dashed curve) ETU effect.

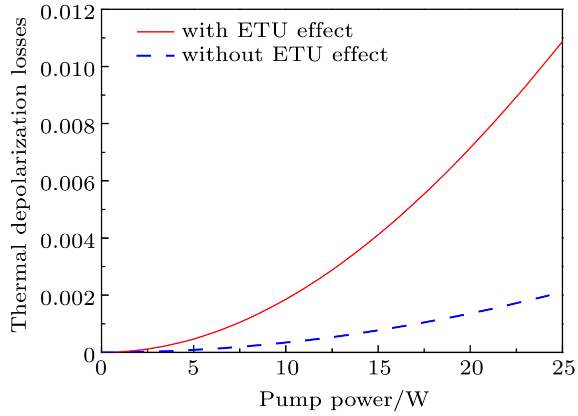

Fig. 2. (color online) Thermal depolarization losses versus pump power at an output transmission of 6% with (red solid curve) and without (blue dashed curve) ETU effect.

3. Experimental setup and results

The experimental setup of a diode-end-pumped CW 946 nm Nd:YAG laser is schematically depicted in Fig. 3.

The pump source is a fiber-coupled diode laser with a central wavelength of 808 nm a maximum output power of 30 W and a core diameter of 400 μm. The pump is coupled into the Nd:YAG crystal with a spot radius of 200 μm via two lenses each with a focal length of 30 mm. To overcome the thermal effect caused by the deformation of the Nd:YAG crystal face, a composite Nd:YAG rod is used. The composite Nd:YAG rod has a diameter of 3 mm and a length of 11 mm, which consists of a 5-mm-long 1 at.% Nd-doped part in the middle with two 3-mm-long undoped end caps. Both end faces of the Nd:YAG rod are anti-reflection (AR) coated at 946 nm ($R_{946\ \mathrm{nm}} < 0.25\%$) and high-transmission (HT) coated at 808 nm ($T_{808\ \mathrm{nm}} > 90\%$). The Nd:YAG rod is tightly wrapped with an indium foil for reliable heat transfer and mounted in a copper block, which is temperature controlled by a temperature controller with an accuracy of ± 0.01 °C (Model YG-4S, Yuguang). To reduce the reabsorption loss, the temperature of Nd:YAG rod is controlled at 12 °C.

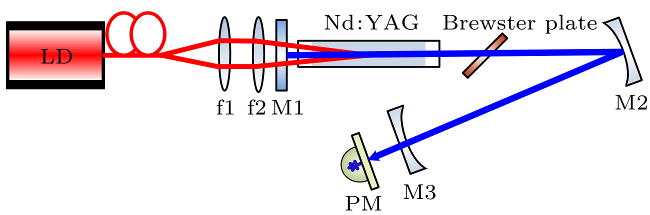

Fig. 3. (color online) Experimental setup of CW 946 nm Nd:YAG laser.

A three-mirror folded cavity with a plane mirror (M1) and two plano-concave mirrors (M2, M3) is designed and built. The Brewster plate is inserted into the cavity as a polarizer to realize linear polarization output. To suppress the 1.06 μm emission, the input coupler (M1) was coated for HT at both

808 nm and 1.06 μm ($T_{808\ \mathrm{nm},1.06\ \mu\mathrm{m}} > 95\%$) and high reflection (HR) at 946 nm ($R_{946\ \mathrm{nm}} > 99.5\%$). The radii of both plano-concave mirrors are 100 mm. M2 is coated for HR at 946 nm ($R_{946\ \mathrm{nm}} > 99.5\%$). The output coupler (M3) is coated to be of partial transmission at 946 nm that will be optimized experimentally to mitigate the effect of ETU and improve the laser performance. Considering that the measured thermal focal length of the laser crystal is 35 mm at a pump power of 25 W,[20] the cavity length between M1 and M2, and that between M2 and M3 are designed to be 120 mm and 170 mm, respectively, for the following three purposes. The first purpose is that laser beam radius is 140 μm and the optimum pump-mode matching can be realized.[8] The second purpose is that the cavity stability condition of $A + D$ approaches to 0 at a pump power of 25 W, the resonator is thermally insensitive and the influence of the thermal lensing effect can be weakened. The third purpose is that there is a beam waist with a radius of 80 mm between M2 and M3, and efficient frequency doubling can be achieved when a nonlinear crystal is sandwiched between mirrors M2 and M3.

In order to study the influence of thermally induced depolarization loss on the polarization output performance of CW 946 nm Nd:YAG laser, several OCs with transmissions of 0.6%, 3%, 6%, 7.5%, and 10% are used in the experiment. The plots of 946 nm output power versus the transmission of OC at a pump power of 25 W are shown in Fig. 4, where solid circles represent experimental data and the solid and dashed curve denote the theoretical predictions obtained using the equations and parameters in Section 2. The solid curve is the theoretical prediction with taking the ETU effect into account. It can be seen that the theoretical predictions are in good agreement with experimental results and the optimum transmission of OC is 6%. For comparison, here we also give a dashed curve that represents the theoretical predictions in the absence of the ETU effect, and we can find that it is not in accordance with experimental results.

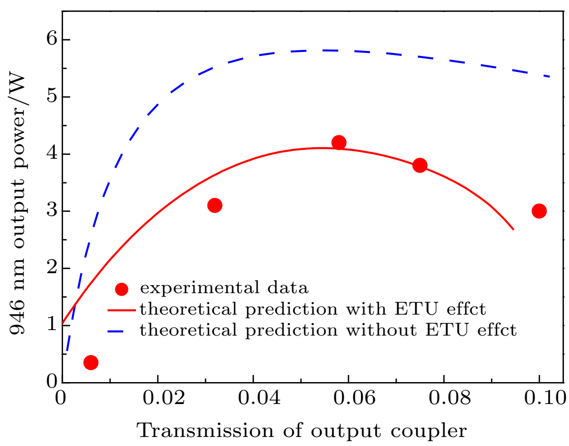

Fig. 4. (color online) Plots of experimental and theoretical output of 946 nm laser versus transmission of OC at a pump power of 25 W.

Using an OC with an optimum transmission of 6%, the curves of the output power of 946 nm laser versus incident pump power with and without Brewster plate in the cavity are measured as shown in Fig. 5. The circles and squares represent the measured linear polarization and non-polarization output power, respectively. Solid and dashed curve represents the theoretical predictions with and without thermal depolarization loss, respectively. It can be seen that the theoretical predictions are in good agreement with experimental results. Owing to the thermal depolarization loss, the output power is reduced when the Brewster plate is in the cavity. The measured maximum linear polarization and nonpolarization output power are 4.2 W and 5.6 W at a pump power of 25 W, with optical–optical conversion efficiencies of 16.8% and 22.4%, respectively.

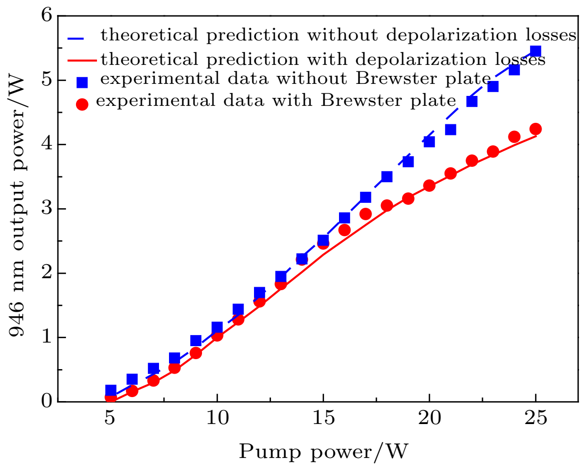

Fig. 5. (color online) Plots of 946 nm laser output power versus incident pump power at output transmission of 6% with and without Brewster plate in cavity.

The beam quality factors of the linearly polarized 946 nm laser at an output power of 4.2 W are measured using a laser beam analyzer (Model M^2-200, SPIRICON) as shown in Fig. 6. The measured beam quality factors of 946 nm laser are $M_x^2 = 1.13$ and $M_y^2 = 1.21$. The 946 nm Nd:YAG laser is in CW TEM_{00} operation.

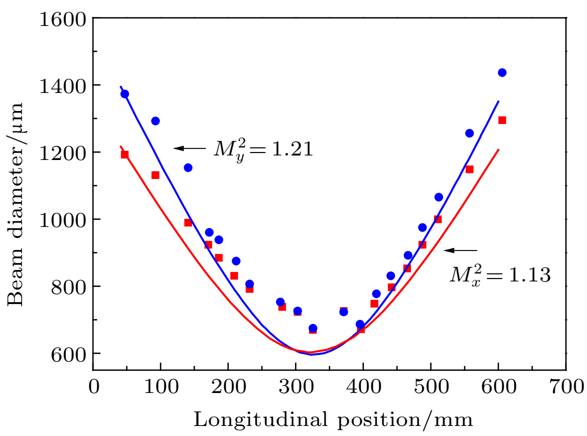

Fig. 6. (color online) Measured beam quality factors of 946 nm laser.

4. Conclusions

A diode-end-pumped Nd:YAG laser is built up using a three-mirror folded cavity with a Brewster plate in the cavity. A theoretical model of quasi-three-level laser system with consideration of the thermally induced depolarization loss and the effect of ETU is developed, and the influences of output transmission and incident pump power on thermal depolarization loss are theoretically analyzed. In order to improve the linear polarization output performance of Nd:YAG laser at 946 nm, the dependence of the output power at 946 nm on output transmission is studied experimentally and theoretically. The theoretical predictions are in good agreement with experimental results. Using an OC with an optimum transmission of 6%, a CW TEM_{00} linear polarization output power of 4.2 W at 946 nm is obtained with an optical–optical conversion efficiency of 16.8%. The measured beam quality factors of 946 nm laser are $M_x^2 = 1.13$ and $M_y^2 = 1.21$. The present investigation is helpful in improving the linear polarization output performance of 946 nm laser, and in achieving a high-efficient frequency-doubled 473 nm blue laser as well.

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