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EFFECT OF THE RATIO OF ROD AND LAMP RADII IN CW AND Q-SWITCHED PERFORMANCE OF LAMP PUMPED ND:YAG LASER FOR ULTRA HARD MATERIAL PROCESSING

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We discuss the fabrication of a lamp pumped Q-Switched Nd:YAG laser and the **e**ffect of the ratio of rod and lamp radii in CW and Q-switched performance of lamp pumped Nd:YAG laser for ultra hard material processing. The performance of the laser in CW operation with polarized and unpolarised configurations in both multimode and fundamental modes are compared. The experiments are repeated in Q-Switched operation by changing the repetition rate for different rod radii. The variation of slope efficiency and threshold pump power in the above cases are studied.

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Keywords: Nd:YAG Laser, CW operation, Q-Switching, single elliptical cavity, Geometrical transfer function coefficient

1. Introduction

All applications of the laser in material processing are based mainly on the local conversion of the radiation energy into heat [1]. The impact of laser technology in the processing of naturally grown single and poly crystalline diamonds has revolutionized the field in many respects [2,3]. In the vaporization cutting technique of ultra hard materials using Nd:YAG laser requires intensity in the range 10^6-10^7 W/cm^2. In this scheme, the focused laser beam heats up the surface to the boiling point and generates a keyhole. In order to get extremely high energy density at the ultra hard work piece, the laser beam has to be focused to a very small spot. The focused spot size depends on many factors of laser resonator. The ratio of rod and lamp radii $\frac{r_R}{r_L}$ is one important parameter which determines the focusability of a laser beam. So it is important to characterize an optical pump system for a ultra hard material processing laser by $\frac{r_R}{r_L}$. Side pumping of solid state laser crystals using arc lamps is an efficient technique of optical excitation. The most widely used arrangement to collect and concentrate radiation emitted by an arc lamp into the laser medium is an enclosure comprising of a highly reflective elliptical cylinder with the laser rod and pump lamp at each focus. The pump source is usually assumed to be a cylindrical radiator having a Lambertian radiation pattern and this implies that it appears as a source having constant brightness across its diameter when viewed from any point. The laser crystal is usually in the form of cylindrical rod. In the present investigation the CW and Q-switched performance of a lamp pumped Nd:YAG laser is characterized by the ratio of the rod and lamp radii $\frac{r_R}{r_L}$.

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2. Experimental

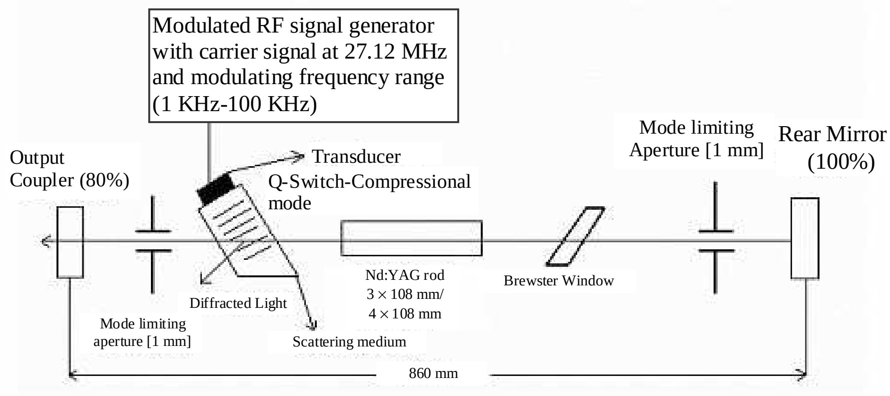

Fig. 1. Experimental arrangement of lamp pumped Q-Switched Nd:YAG laser.

The experimental arrangement used in the present investigation is shown in Fig. 1. The experimental arrangement consists of the optical resonator, cooling system, power supply and RF driver. Nd:YAG rods of dimensions 3ϕ × 108 mm with three different Nd doping concentration 0.7 at.% have been used for both CW and Q-switched operations. In order to study the variation of change in rod diameter 4ϕ × 108 mm rod with Nd doping concentration 0.7 at.% is also used. An intra cavity Brewster window is used for getting polarized output. The laser rod is pumped by a CW Krypton filled arc lamp having maximum electrical input power of 6 kW. The laser rod and arc lamp for pumping are contained in a highly polished, gold-plated elliptical pump chamber. An acousto-optic Q-Switch is used for the generation of laser pulses with high peak power. Two apertures are used for limiting the higher order modes.

A plane parallel resonator configuration [4] operating in the stable region of stability diagram for the laser is developed. In order to generate extremely good quality TEM_{00} beam which is required for generating high energy density, a low value of Fresnel number N is selected. The Fresnel number determines the number of modes oscillating inside the resonator and is defined as

$$N = \frac{a^2}{L\lambda} \tag{1}$$

where ‘a’ is the aperture size of the intra cavity mode limiting aperture, ‘*L*’ is the resonator length and ‘λ’ is the wavelength of laser [5]. For a fixed resonator length of 860 mm, if we assume a Fresnel number equal to unity, the aperture size can be calculated to be 0.915 mm. Because of easiness in mechanical fabrication and availability, an aperture size of 1mm is used through out the studies for which the Fresnel number is 1.0928. The laser rod represents a limiting aperture for an incoming beam. Diffraction effects at the edges of the amplifier rod will give rise to Fresnel rings which can strongly disturb the beam uniformity. Single elliptical cavity is used for pumping which is very efficient. Cooling of the rod and lamp is accomplished by circulating DI water in flow tubes which surround the crystal and the lamp. The arc lamp emits light in a broad spectral range containing UV, visible and IR regions. The absorption bands of Nd:YAG crystal lie with a central wavelength of 808 nm and so the unwanted UV radiation from arc lamp has to be filtered out. If UV radiation from the arc lamp falls continuously on the rod, the optical properties of rod will be degraded which is called solarization. This will reduce the life of the rod. To overcome in the present design, Samarium doped (10%) Pyrex glass for the rod flow tube is used for the rod. Samarium doped flow tube has the property of absorbing radiation in the UV region of broad band emission from arc lamp and re-emit in the visible and near infrared region where Nd:YAG has maximum absorption. Thus the pumping efficiency has been enhanced. It has been observed [6,7,8] that the line spectrum from Krypton is a better match to Nd:YAG than the line spectrum of Xenon, since two of its strongest emission lines (760 nm and 811 nm) are strongly absorbed by the laser crystal. This fact justifies the choice of Krypton arc lamp for the present studies. The Krypton arc lamp used has a cold-fill pressure of 2 atmospheres and it operates at a maximum lamp current of 32 A and a voltage of 180 V. The material of lamp is fused silica doped with Cerium which will absorb unwanted UV emission and re-emit in the near infrared region so that the radiation will be absorbed by the Nd:YAG crystal. A mechanical shutter is used for stopping laser oscillations temporarily without turning off the arc lamp. A Brewster window made of BK7 material with high damage threshold (20 J/cm^2) is used generating the polarized laser output. An acousto-optic Q-switch is used for pulsating the CW laser output. The Q-Switch used in the present study is Model QS27-3C-S (Gooch and Housego, UK) with a carrier frequency of 27.12 MHz which is intended for use in linearly polarized lamp pumped Nd:YAG lasers operating at 1064 nm. The interaction medium of Q-Switch is coated with antireflection coating (hard multilayer dielectric) with reflectivity 0.2% per surface. The damage threshold is greater than 500 MW/cm^2. The Voltage Standing Wave Ratio (VSWR) is 1.2:1 and maximum CW drive power is 100 W. De-ionized water cooling is provided at the rate of 190 cc/min. In order to study the effect of the ratio of radii of rod and arc lamp $\frac{r_R}{r_L}$ experiments are conducted using two Nd:YAG rods with diameter 3 mm and 4mm having equal length and same Nd doping concentration of 0.7 at.%. The CW laser output power is measured at different input pump power for rods with 3 mm and 4 mm diameter. The experiment is repeated for unpolarised-multimode and polarized-TEM$_{00}$ modes. The laser is operated in the Q-Switched mode using both 3 × 108 mm and 4 × 108 mm rods. Q-switched laser output power at different frequencies are measured and slope efficiency curves are plotted as shown in Fig. 4.

3. Results and discussion

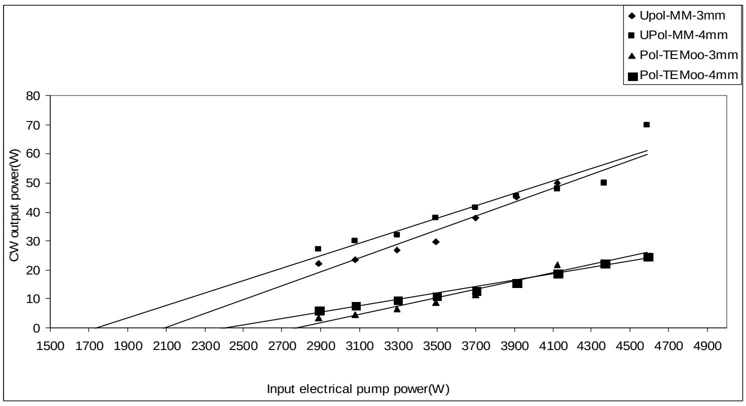

Fig. 2. Slope efficiency curves with 3 × 108 mm and 4 × 108 mm rods with 0.7% doping concentration and aperture size 1mm.

The slope efficiency curves are plotted and are shown in Fig. 2. The slope efficiency and threshold pump power are calculated from the curves and given in Table 1.

Table 1. Variation of slope efficiency and threshold pump power with 3 × 108 mm and 4 × 108 mm rods with 0.7% doping concentration and aperture size 1mm.

No	mode of operation	slope efficiency(%)		threshold pump power(W)	
		3 × 108 mm	4 × 108 mm	3 × 108 mm	4 × 108 mm
1	unpolarized multimode	2.3899	2.1411	2100	1740
2	Polarized- TEM$_{00}$ mode	1.4351	1.1034	2792	2428

The slope efficiency in both unpolarised- multimode and polarized- TEM_{00} mode are higher for 3ϕ × 108 mm rod for which $\frac{r_R}{r_L}$=0.5 compared to 4ϕ × 108 mm rod where $\frac{r_R}{r_L}$=0.67. The threshold pump power is lower for 4ϕ × 108 mm rod where as the maximum unpolarised-multimode power is higher. This behavior is explained by considering the geometrical transfer function coefficient η_{ge} for both the rods. The geometrical transfer function coefficient η_{ge} is calculated by considering what fraction of the energy radiated by the lamp into an angle d_α is trapped by the crystal. The lamp is assumed to be a cylindrical radiator having a Lambertian pattern. This implies that it appears as a source having constant brightness across its diameter when viewed from any point. Integration over all angles will give us an expression for the above coefficient [9,10].

$$\eta_{ge} = \frac{1}{\pi}\left[\alpha_0 + \left(\frac{r_R}{r_L}\right)\Theta_0\right] \qquad (2)$$

where $\frac{r_R}{r_L}$ is the ratio of rod radius to that of lamp ,α_0 is the angle measured from the lamp axis, and Θ_0 is the angle measured from the laser rod diameter and

$$\sin\Theta_0 = \left(\frac{r_L}{r_R}\right)\sin\alpha_0 \qquad (3)$$

It is reported that the transfer efficiency η_{ge} is increasing as the ratio $\frac{r_R}{r_L}$ increases [11]. More unpolarised multimode power generated in the case of 4ϕ × 108 mm rod may be due to the higher value of η_{ge}. The lower polarized-TEM_{00} output power in the case of 4ϕ × 108 mm rod may be due to the fact that the same mode limiting aperture (1 mm) is used for both 4ϕ × 108 mm and 3ϕ × 108 mm rods. The arc lamp used is also the same in both cases. Therefore the separation between rod and lamp surfaces is less for 4ϕ × 108 mm rod compared to the other. The pumping by arc lamp can be considered to be side pumping by a beam with a top-hat (or flat-top) intensity profile. As a result the pump energy absorbed by the peripheral cylindrical layer of rod is more than that by the central portion since the doping concentration is uniform through out the volume. As the aperture size is only 1 mm, more unpolarised-multimode power is cut off for selecting the polarized-TEM_{00} mode which is really generated less in 4ϕ × 108 mm rod compared to that in 3ϕ × 108 mm rod. This also explains the lower threshold pump power for 4ϕ × 108 mm rod. There may be chances of higher polarized-TEM_{00} output power if an aperture size larger than 1 mm is used for selecting TEM_{00} mode in 4ϕ × 108 mm rod. The variation of the ratio of polarized-TEM_{00} power to polarized-multimode power (η_T) with input arc lamp current is plotted for 3ϕ × 108 mm and 4ϕ × 108 mm rods and is shown in Fig. 3.

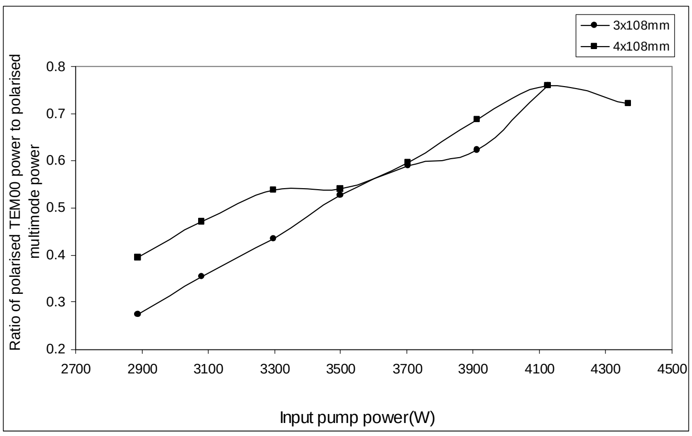

Fig. 3. Variation of the ratio of TEM_{00} power to polarized multimode power(η_T)with pump power with different diameter of Nd:YAG rod.

The ratio η_T varies almost linearly in the case of $3\phi \times 108$ mm rod where as it fluctuates in the case of $4\phi \times 108$ mm rod. These fluctuations may be due to the mismatch of size of rod and aperture. The slope efficiency and threshold pump power are calculated and shown in Table 2.

Table 2 Variation of slope efficiency and threshold pump power in Q-switched operation with 3×108 mm and 4×108 mm rods with 0.7% doping concentration and aperture size 1 mm.

Q-Switch frequency(kHz)	Slope Efficiency (%)		Threshold pump power(W)	
	Rod diameter-3 mm	Rod diameter-4 mm	Rod diameter-3 mm	Rod diameter-4 mm
4	0.8	0.4745	2452	2373
6	0.8847	0.5775	2405	2412
8	0.8997	0.5671	2329	2316
10	0.9097	0.6386	2378	2372
12	0.9135	0.6289	2180	2338

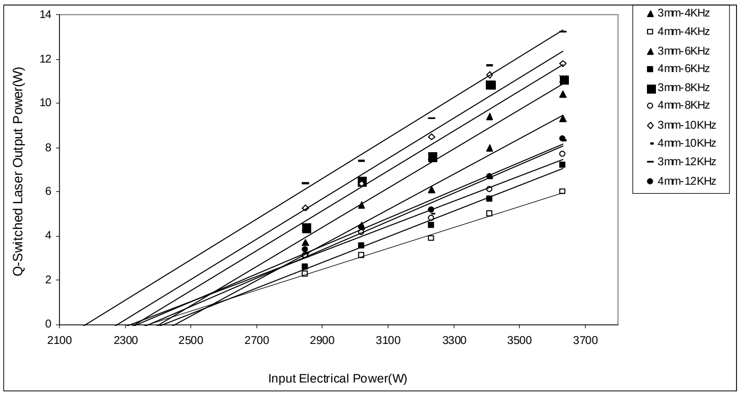

Fig. 4. The slope efficiency curves in Q-switched operation with $3\phi \times 108$ mm and $4\phi \times 108$ mm rods with 0.7% doping concentration and aperture size 1mm.

The variation of slope efficiency and threshold pump power are plotted and shown in Figs. 5 and 6 respectively.

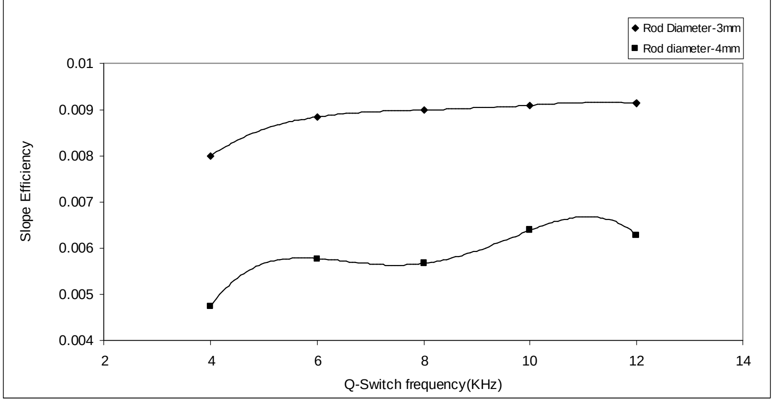

Fig. 5. Variation of Slope efficiency with 3×108 mm and 4×108 mm rods with 0.7% doping concentration and aperture size 1mm.

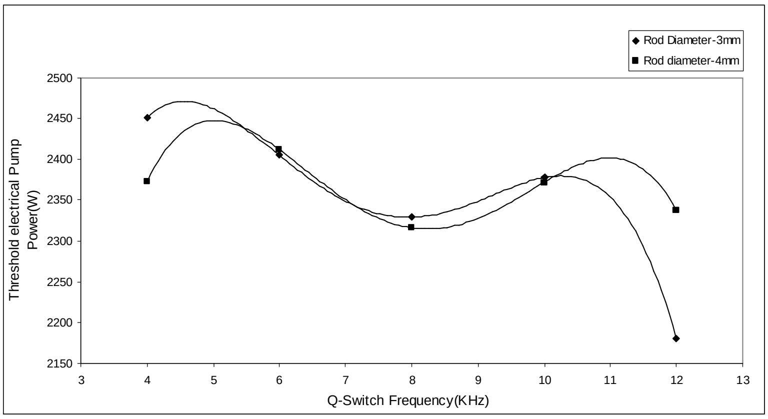

Fig. 6. Variation of threshold pump power with 3 × 108 mm and 4 × 108 mm rods with 0.7% doping concentration and aperture size 1mm.

It is observed that the slope efficiency is higher for 3ϕ × 108 mm rod compared to the other. This may be due to the pumping of 4ϕ × 108 mm rod in the peripheral volume of cylindrical geometry and the reduction in polarized-TEM_{00} operation due to the smaller size of the aperture. The slope efficiency is not varying much with Q-Switch frequency in both the rods. The threshold pump power is fluctuating almost in the same fashion in both the rods. However it is observed that at lower frequencies the threshold pump power is higher for 3ϕ × 108 mm rod where as for 4ϕ × 108 mm rod it is higher at higher Q-Switch frequencies.

4. Conclusions and future prospects

It is observed that in CW operation, the slope efficiency in both unpolarised-multimode and polarized- TEM_{00} mode are higher for 3ϕ × 108 mm rod compared to 4ϕ × 108 mm rod. The threshold pump power is lower for 4ϕ × 108 mm rod where as the maximum unpolarised-multimode power is higher. The ratio η_T varies almost linearly in the case of 3ϕ × 108 mm rod where as fluctuations are observed in the case of 4ϕ × 108 mm rod. It is noted that in Q-Switched operation, the slope efficiency is higher for 3ϕ × 108 mm rod compared to the other. The slope efficiency is not varying much with Q-Switch frequency in both the rods. The threshold pump power is fluctuating almost in the same fashion in both the rods. All these results indicates the suitability of 3ϕ × 108 mm Nd:YAG rod for laser system fabrication for ultra hard material processing applications where one require good power stability. The authors assume that the use of laser diodes at wavelength 808 nm for pumping Nd:YAG rods can result better solutions for the above application where there is a scope for the studies on the effect of the ratio of pump beam waist to cavity beam waist.

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