Mode Matching and Lasing Characteristics in End-pumped Nd:YAG Laser

Sovannarith Hut[1,*], Sreyleak Ean[1], Seang Hor Eang[2], and Yong Gi Kim[3]

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ABSTRACT

In order to maximize the power output of the laser diode end-pumped Nd:YAG laser, we have discussed the impact of the pump beam's focusing location, the thermal focal length, and the mode-matching effects. This was done by employing various focused spot sizes to pump the Nd:YAG crystal. The optimal focal point for successful extraction of the diode's pump energy is discovered to be 1.5 mm into the crystal. If the length of the laser's resonator is less than the thermal focal length, the production of lasing is easily achieved and the resonator remains stable. The thermal length was precisely determined by measuring the spot size using a charge-coupled device camera. The thermal length measurements were used to identify specific properties of the Nd:YAG crystal, such as a thermal loading of 0.32 and a thermal conductivity of 0.14 W/cm.K. Our investigation revealed that using a focal length of 40 mm and a pump beam spot size of 450 µm yielded the greatest output power, as long as the pump power remained below 13 W. For pump powers more than 13 W, the spot size of 600 µm is the preferable choice.

1. INTRODUCTION

The compact size, excellent efficiency, long lifetime, and remarkable reliability in output power make diode-pumped solid-state lasers a desirable choice of devices, particularly in comparison to flashlamp-pumped solid-state lasers [1]. Numerous innovative techniques were utilized to augment the output and effectiveness of diode-pumped lasers, both side and end-pumping emerging as the primary methods. Diode end-pumped lasers have significant benefits in comparison to side-pumped lasers, particularly in relation to their elevated efficiency and enhanced beam quality [2]. This advantage stems from the improved alignment between the gain profile of the lasing medium and the diode laser, resulting in a more effective overlap. Previous reports have indicated that side pumping achieved a maximum optical to optical efficiency of 29% [3], while end-pumping demonstrated even greater efficiency at 46% [4]. Therefore, the utilization of end-pumped the Nd:YAG lasers is mostly preferred due to their substantial stimulating emission area at 1064 nm, extensive absorption across the pumping wavelength range, which facilitates lower laser threshold, superior thermal conductivity, and resilience against external pressure on the YAG crystal [5].

Several researchers have investigated the impact of various cavity parameters, including the size of the pump beam, cavity length, and reflectivity of the output coupler, based on a wealth of experimental evidence and theories [6, 7]. However, the precise focusing position of the pump beam has often been neglected in these studies. In practical laser systems, the output power is significantly influenced by the accurate focusing position of the pump beam [7]. To enhance laser efficiency, it is imperative to collect data on the precise location at which the pump beam concentrates within the Nd:YAG crystalline [8]. The examination of thermal impacts on laser materials is of the utmost importance in the advancement of high-power solid states lasers. When the laser material is subjected to pump power, it induces a thermal gradient between the central and peripheral areas of the substance. This temperature difference leads to thermal birefringence, accompanied by thermal lensing within the laser material [9]. These thermal effects can significantly impact the laser's power output as well as beam quality, and can even cause material fractures. Therefore, while designing a laser resonator, it is imperative to take into account the temperature effects on the laser's material. Calculations should be conducted to determine the laser's output range, taking into account the limitations imposed by material fracturing [10].

A diode-powered solid-state laser's design depends critically on the spatial overlap of the pumping beam and laser mode in the active materials, since it directly influences the laser efficiency and output power [11]. It has been determined that the relative size that defines the pump

[1]Graduate School, National Polytechnic Institute of Cambodia, Phnom Penh, Cambodia.
[2]Graduate School of Science, Royal University of Phnom Penh, Phnom Penh, Cambodia.
[3]Department of Physics, Kongju National University, Gongju, South Korea.
**Corresponding author:* Sovannarith Hut; Phone: +855-98-393-851; Email: hutsovannarith@npic.edu.kh.

dispersion is of more significance compared to the size of the distribution of the Gaussian beam mode. The investigation of optimizing the mode's size in end-pumping beams has been conducted by the utilization of the pump spot size [12].

This research paper contains experimental data pertaining to the attainment of the best output power of a Nd:YAG laser. The investigation focuses on determining the ideal placements of a laser diode (LD) used for end-pumping inside different cavity lengths. The attainment of superior beam quality and maximum output power can be ascribed to the spatial alignment between the size of the pump beam and the mode of the laser cavity [13]. During this study, we employed distinct pump spot sizes derived from focusing lenses to effectively pump the Nd:YAG crystal at an appropriate location for diverse cavity lengths. To accurately measure the thermal length, we employed a charge-coupled device (CCD) camera to determine the spot size of thermal lengths. By quantifying the thermal length, we were able to evaluate specific parameters of the Nd:YAG crystal, such as thermal loading and thermal conductivity, and compare our results with previous studies. Additionally, the pump spot size of the focusing lens was also examined to achieve mode matching.

2. EXPERIMENTAL SETUP

2.1. Optimum pump beam's focusing positions

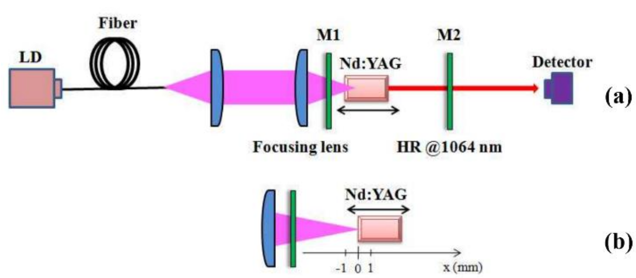


Fig. 1. (a) Schematic diagram depicting the configuration of a Nd:YAG laser with end pumping. (b) The investigation of the dependencies on focusing locations in a Nd:YAG laser with end-pump.

An end-pumped Nd:YAG laser is shown as in Fig. 1(a) in order to provide high output power with high efficiency. The fiber-coupled laser diode (TH-C1722-F6, THALES) used as the pumped source has a numerical aperture of NA=0.22 and a central wavelength of 808 nm. Its core diameter is 400 µm. A laser diode is mounted on a water-cooled block and connected to a chiller (SPEED-650L, SPEED Engineering) and kept a constant temperature at 26ºC. This is because of the wavelength of the LD output beam depends on the temperature of the chiller so we have scanned by seeking for its temperature from 20ºC to 28ºC to get wavelength of 808 nm. The LD was controlled by DC power supply (6651A #J30, Agilent) which provided current from 0 A to 60 A. The laser cavity employed a Fabry-Perot resonator configuration, comprising a crystal made of neodymium-doped yttrium aluminum garnet (Nd:YAG) with specified measurements of 4 mm × 4 mm and a cross-sectional shape and a certain length of 10 mm. The crystal was doped with 1% concentration of neodymium ions. The resonator also included two flat mirrors. The flat mirrors were performed with an end-mirror (M1) of high reflectivity of 99.5% and output coupler mirror (M2) was used with the optimum reflectivity of 66% at 1064 nm. To reduce the impact of pump heating effects, the Nd:YAG crystal is enveloped by indium foil and affixed onto a copper block, ensuring optimal thermal conductivity. The crystal was cooled by thermoelectric cooler (TEC) and kept a constant temperature of 22ºC. Output power of Nd:YAG laser was measured by sensor power meter Scientech (Vector D200, Detector: AC5001).

The pump beam's size of each focal length was pumped inside cavity at position of -1, 0, 1, 1.5, 2 and 3 millimeters, respectively. The 0 millimeter location was assumed to be the interface of the focal point of the focusing beam and Nd:YAG crystal. The lengths of laser cavity were performed under several cavity lengths at 75 mm and 110 mm. The crystal was moved back and forth as displayed in Fig. 1(b). The laser cavity length and the alignment of the optics were maintained despite the Nd:YAG crystal's position being changed.

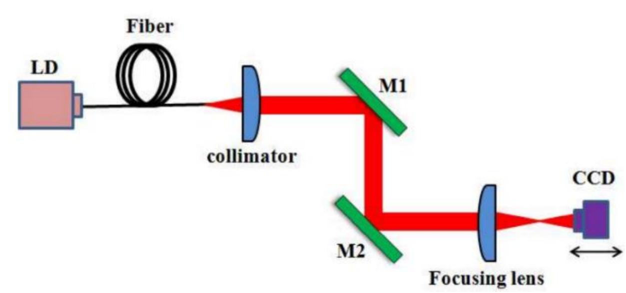


Fig. 2. Experimental setup for the spot size measurement of focal lens.

2.2. Spot sizes measurement experiments

The spot size of the pump LD beam was measured with eight focal lenses by using the CCD camera (FX 33HD, OPHIR OPTRONICS) in order to determine the exact spot size inside Nd:YAG crystal in end-pumped laser diode system. To do that, we have eight lenses with focal lengths of 20, 25.4, 30, 35, 40, 50, 60, and 75 millimeters were pumped the same power of 0.98 W, 2.82 W, 5.22 W, 7.87 W, 10.32 W, 12.82 W and 19.67 W. The LD beam was collimated by a collimator and transmitted the light to the first window (M1) and second mirror (M2). Both mirrors are coated with 95% of transmission and 5% of reflection at 808 nm at angle of 45˚. Each focal lens was placed after the reflection of M2 and measured the spot size by the CCD camera. The CCD was moved its position to seek for the spot size, the smallest diameter of the beam, as illustrated in Fig. 2. The special characteristic of the windows allowed this measurement working with high LD power up to 20 W without damaging CCD.

2.3. Thermal focal lengths measurement experiments

In the setting of solid-state lasers, the power of the pump is partly converted to the heat in the laser substance that produces the temperature gradient and the refractive index nonconformity. Moreover, the laser medium's refractive index changes due to the temperature gradient and stress which causes the phenomenon of thermal lensing [14]. To determine Nd:YAG crystal's thermal length, a He-Ne laser which operates at a wavelength of 632.8 nm was used to measure thermal focal lengths. It was made sure that the probe beam size matched that of the Nd:YAG crystal size with a lens by using a bi-convex lens of 18 mm and focusing lens of 50 mm as illustrated in Fig. 3. The lens was moved its position to obtain expanded beam diameter of 4 mm and a dichroic mirror with strong reflection occurs at a wavelength of 632.8 nm, whereas anti-reflection occurs at a wavelength of 808 nm was used to orient the beam such that it would pass through the Nd:YAG crystal's core. The focusing lens of 75 mm was used to pump LD at a position of 1.5 mm inside the Nd:YAG crystal. The length to reach the spot where the laser material emitted the probe beam had the least observed aperture size during the focal length of the thermal lens was determined using the method of pumping. The measurement of the beam width of the incident beam was conducted by employing the CCD camera in motion, as seen in Fig. 3. The movement of the CCD was done by increasing LD power for each measurement up to 14 W.

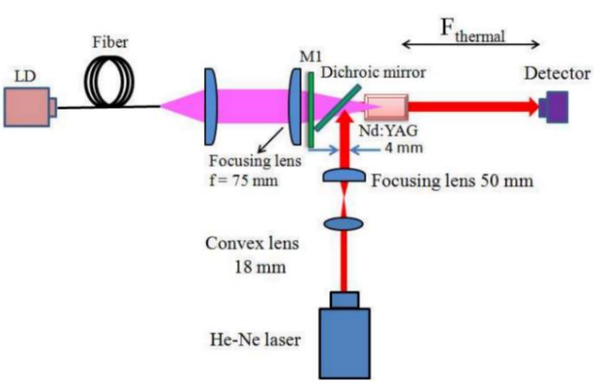


Fig. 3. Diagram for the investigation of thermal lensing phenomena inside a crystal made of Nd:YAG.

2.4. Mode matching experiments

Lens relay system or image relay is used for transferring the light from one region to another. This technique was therefore suitable for measuring the mode size inside the laser cavity. All eight pump spot sizes of focal lenses were used in each measurement at cavity length of 90 mm. To obtain real mode size intra-cavity we have used a beam splitter (BS1), high reflection of 808 nm and high transmittance of 1064 nm at angle of 45°, and the reflectivity of 5% of BS2 to decrease intensity from laser diode as shown in Fig. 4. A bi-convex lens of 200 mm was used in this image relay measurement to maintain the beam size of the object and image, the total distance between the object and the lens is equivalent to twice the length of the focal point of the narrow lens, which measures 200 mm. Therefore, end-mirror (M1) and CCD camera were placed at distance of 400 mm apart from the thin lens. The full setup of mode size measurement was presented in Fig. 4. Thin lens and CCD were moved and kept the constant distance of 400 mm apart until complete 90 mm inside cavity.

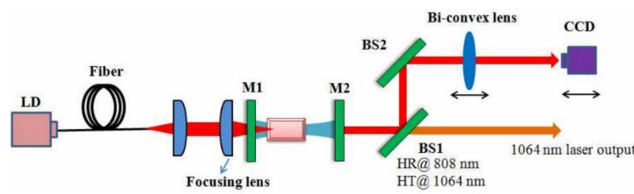


Fig. 4. Experimental setup for the mode matching measurement inside the laser cavity.

3. RESULTS AND DISCUSSION

3.1. Beam spot size measurement of focal lenses

In the Fig. 5, beam spot sizes for lenses with focal lengths of 20, 25.4, 30, 35, 40, 50, 60, and 75 millimeters are 200, 300, 342, 415, 450, 507, 600, and 700 micrometers, respectively. These focused spot beam sizes are the actual pump beam size of LD inside Nd:YAG crystal. Each focal lens was measured its spot size by increasing the LD power up to 20 W and analyzed by CCD camera. From these results, the spot beam sizes were almost the same within an error of 2.62%. So, the focused beam size of the lens does not depend on the how much the power source is.

3.2. Output power dependance on focusing positions

The investigation involved analyzing the relationship between the output power and the positioning of the pump beam at various locations. Fig. 6 and 7 depict the spatial locations of the focusing beam at intervals of -1, 0, 1, 1.5, 2, and 3 millimeters to the gain medium with cavity lengths of 75 mm, 110 mm, and a focusing lens of 40 mm and 50 mm, respectively. Fig. 6 indicates that by employing a 40 mm focal length and achieving a focused spot with a diameter of 450 µm within the Nd:YAG crystal, the maximum continuous wave (CW) 6.57 W of output power was reached. This occurred at 19.67 W of pumping power, specifically when the focusing point was positioned 1.5 mm within the crystal. The optical efficiency and slope efficiency values were recorded as 33.40% and 40.25%, respectively. Additionally, the optical efficiency and the slope efficiency at the 2 mm focusing position was 32.74% and 39.46%, and at the 1 mm position were 29.48% and 35.54%, respectively. When the pump beam's focusing position continued increasing to 3 mm inside the crystal, the output power was getting reduced. Moreover, if the pump beam position at -1 mm was in front and outside the Nd:YAG crystal, the power was also low. Similar to this, Fig. 7 illustrates how the pump beam was concentrated with a 50 mm focal length, producing a 507 µm focused point inside the crystal. The slope efficiency of the focusing positions at -1, 0, 1, 1.5, 2, and 3 millimeters, given a pump power of 19.67 W was 20.90%, 26.58%, 31.26%, 31.52%, 31.06% and 30.50%, respectively. So, the highest output power was at the position between 1 mm and 2 mm of the focusing position inside the Nd:YAG crystal.

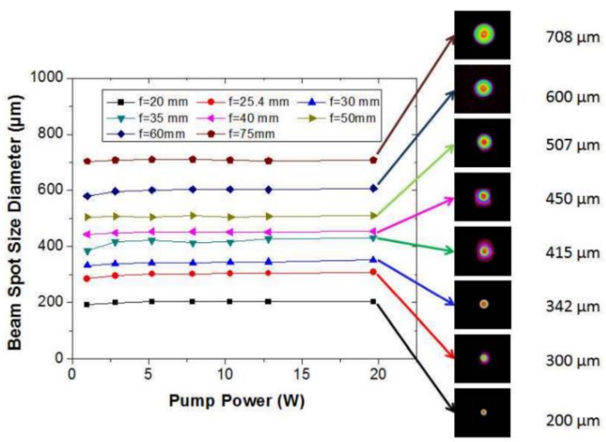


Fig. 5. Beam spot size measurements of eight focal lenses as a function of LD pump power.

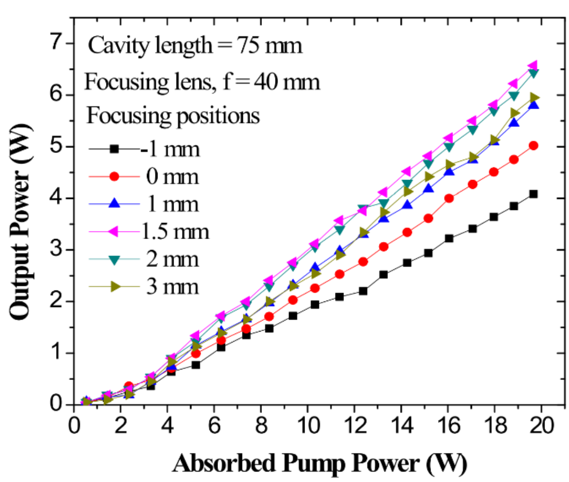


Fig. 6. Output power of CW laser for several focusing positions inside Nd:YAG crystal with a reflectivity of 66% OC.

We have done many experiments with focusing lens positions with different cavity lengths and focusing lenses. Most of the highest power position was at a position of 1.5 mm inside the crystal as explained in Fig. 6 and 7 because the majority of the pump power is absorbed in close proximity to the terminal surface of the rod. This implies that the gradient-index lens exhibits its highest strength at proximity to the pump face, whereas the end effects are observed at the initial face of the crystal [15]. In other words, the obtained outcome aligns with the observations made throughout the experiment cited in reference [8], which confirmed that the optimal focusing position was 1 mm inside the crystal.

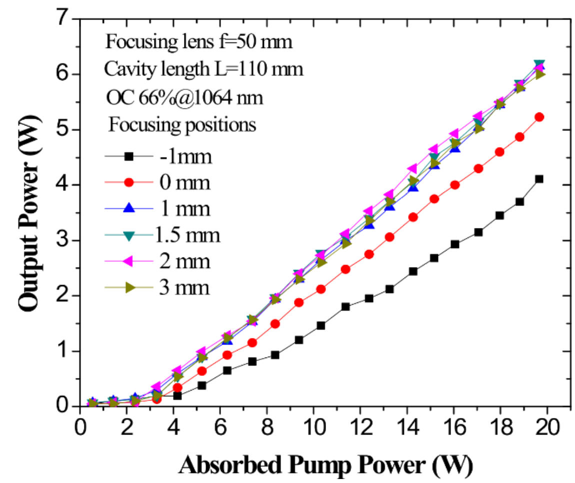


Fig. 7. Output power of CW laser for several focusing positions inside crystal.

3.3. Thermal focal length

By utilizing a combination of experimental and theoretical data, it is feasible to precisely determine the focusing distance with a laser medium, the thermal lens. The provided calculation allows for the deduction of the potential laser output power range [16]. The thermal focal length of the Nd:YAG laser crystal was evaluated in relation to the pump power of LD, or laser diode. The concentrated spot sizes of the thermal lens were obtained using a CCD camera. Haung et al.[17] has proposed their paper about focal length measurement and expressed theoretical thermal focal length as follows:

$$f_{th} = \frac{2\pi k_c \overline{\omega_p^2}}{\xi(P_{in}).P_{in}.dn/dT} \tag{1}$$

where, $\xi(P_{in})$ is thermal loading. P_{in} is the pump power, refractive index dependency on temperature is expressed as dn/dT , thermal conductivity is expressed as k_c , and average pump beam radius is expressed as $(\overline{\omega_p^2})$ within a Nd:YAG crystal. The focusing lens of 40 mm with the spot size of 450 µm was used for pumping inside crystal and the parameters for calculation thermal focal length were shown in Table 1. Nd:YAG crystal thermal focal length and spot size were measured in different pumped powers as listed in Table 2. From these results we drew a fitting carve of Eq. (1) as displayed in Fig. 8(a) decreased exponentially as the pump power increased. Furthermore, in Fig. 8(b) we have made a comparison of our measurement to four authors' theories of Huang et al. [17], K.N. Kim [18], Lae et al. [10], Yan et al. [19] that all parameters were used in Table 1. As a result, our experimental results and Huang et al. showed the best agreement and can be utilized for predicted value.

From this consequence, we could determine the thermal loading, denoted as ξ, which refers to the temperature that causes an effect on the Nd:YAG crystal, as displayed in

Fig.9. Based on our real measurements of thermal focal lengths, we used Huang et al. of Eq. (1) to find out the real values of thermal loading. The thermal loading was 0.306, 0.316, 0.320, 0.318, 0.311, 0.328, and 0.341 for focal thermal lengths of 125 cm, 94 cm, 82 cm, 60 cm, 49 cm, 44 cm, and 32 cm, respectively. These results have emphasized that the decreasing of thermal lengths was not much influence on thermal loading and it was 0.32 in average value. This result strongly agreed with the reference data of Tidwell et al. [10, 20], who have mentioned the documented value of the thermal loading to be 0.30.

Table 1. Presents the parameters utilized in the computation of the thermal focal length of a lens [16]

Property	Symbol	Value
Thermal conductivity	k_c	10.46 (W/m.K)
Thermal loading	η, η_α, ξ	0.3
Absorption coefficient	α, α_T	7.5× 10^{-6}(K^{-1})
Reflective index	n	1.82
Photoelastic coefficient	C_ϕ	−0.0025
Photoelastic coefficient	C_r	0.017
Poisson's ratio	υ	0.3
Thermal-optics coefficient	dn/dT	7.3× 10^{-6}(K^{-1})

Table 2. The variation of spot size beam and thermal focal length with respect to pump power

Pump power (W)	Spot size beam (μm)	Thermal focal length (cm)
3.70	630	125
4.70	610	94
5.75	450	82
7.90	372	60
9.90	320	49
11.90	250	44
13.80	170	32

Fig. 10 showed the thermal conductivity k_c , a property of a material to conduct heat, which relies on the pump power. To calculated thermal conductivity, F. Song et at.[21] used the real value of thermal length to calculate the values of thermal conductivity in thermal length's equation. Similarly, we enable to compute the thermal conductivity from Eq.(1) by substituting the real value measurement of thermal lengths. At a pump power of 3.7 W, 4.7 W, 5.75 W, 7.9 W, 9.9 W, 11.9 W, and 13.8 W, respectively, the thermal conductivity with values of 0.128 W/cm.K, 0.123 W/cm.K, 0.131 W/cm.K, 0.132 W/cm.K, 0.134 W/cm.K, 0.145 W/cm.K, and 0.122 W/cm.K was achieved. So we could say that thermal conductivity of Nd:YAG is about 0.13 W/cm.K in average. This value is fit to Xie et al. [13] who mentioned that YAG has a 0.13 W/cm.K thermal conductivity. Furthermore, W. Koechner in his book showed that thermal conductivity of YAG is 0.14 W/cm.K[16]. These citations strongly agree with our result of 0.13 W/cm.K. As a result, we were able to measure the thermal focal length of the thermal lens using the CCD camera approach and obtain extremely precise findings.

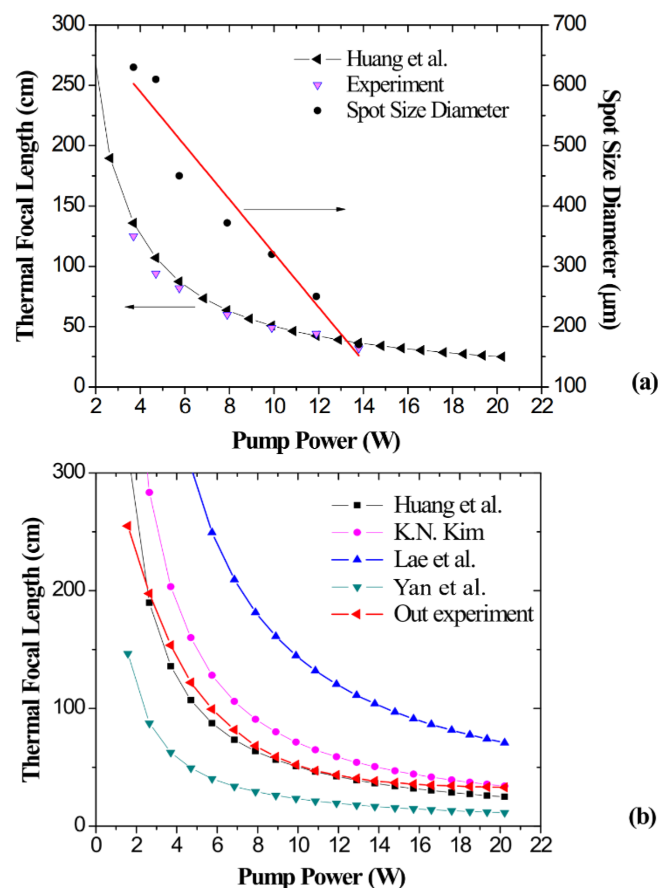


Fig. 8. (a) thermal length measurements by using CCD camera when increasing pump power. (b) The evaluation of theoretical calculations made by several authors in relation to experimental data for different pump powers.

3.4. Output power dependence on mode matching

Fig. 11, 12, and 13 show the CW power generated as an expression of the absorbed pumped power for various pump spot sizes with an output coupler that has a 66% reflectivity and cavities that are 110 mm and 130 mm in length, respectively. All focused spot sizes of focal lenses were pumped inside the Nd:YAG crystal at a position of 1.5 mm.

Fig. 11 demonstrates that the laser achieved a maximum output power of 4.13 W and a slope efficiency of 38% when the pump power was 13.36 W and the pump spot size was 450 µm. When the pump power exceeded 13 W, the output power significantly decreased as a result of the unstable laser resonator and thermal lens effects. However, when using a pump spot size of 600 µm, the resulting output power was 6.29 W, with a slope efficiency of 38.54% at a pump power of 19.67 W. Based on the findings of the fitting curve for output power in Figure 12(a), maximum output of power was seen when the pump spot size was 450 µm, the pump power was 13.26 W, and the cavity length was 110 mm. When the pump spot size was less than 400 µm or greater than 500 µm, the output power was significantly reduced. No lasing action was observed at pump spot sizes less than 300 µm. The greatest output of power of 6.29 W was recorded at a pump spot size of 600 µm and a pump power of 19.67 W, as shown in Fig. 12(b). In Fig. 12(a), the output power had the same characteristics as the pump power of 13.26 W. Specifically, there was no lasing seen when the pump size was less than 300 µm. Similarly, when the length of the cavity was extended to 130 mm, as seen in Figure 13, an output power of 3.17 W was attained, which is the highest possible level with a pump power of 11.3 W and a pump spot size of 450 µm. In addition, in Figure 14, with cavity lengths of 110 mm, 130 mm, and 150 mm, a pump power of 5.22 W, and a pump spot size of 450 µm, the maximum output powers obtained were 1.24 W, 1.15 W, and 0.95 W, respectively.

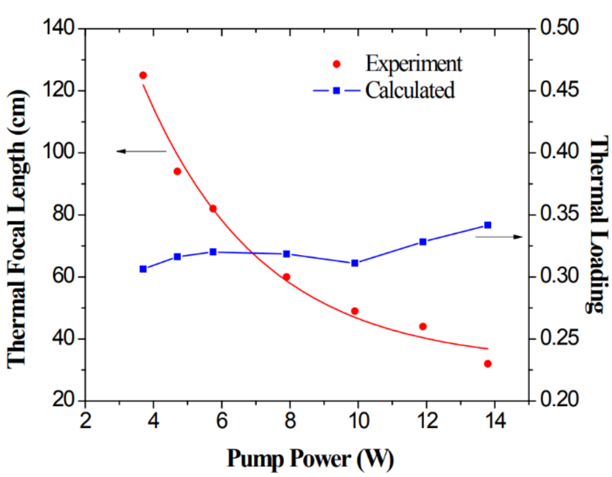


Fig. 9. Experimental measurement of the thermal lens's focal length and a theoretically predicted value for thermal loading.

Therefore, the pump spot size of 450 µm had a good match with the mode size in these laser cavities. So if we used the pump spot size of focusing lens for end-pumping Nd:YAG laser, the mode size inside the laser cavity and the focusing beam has to match to get optimum output power. However, if the focusing spot size of focal lens is smaller or bigger than the mode size, the lasing efficiency is low. Thus, mode matching is very critical for producing high efficiency of laser.

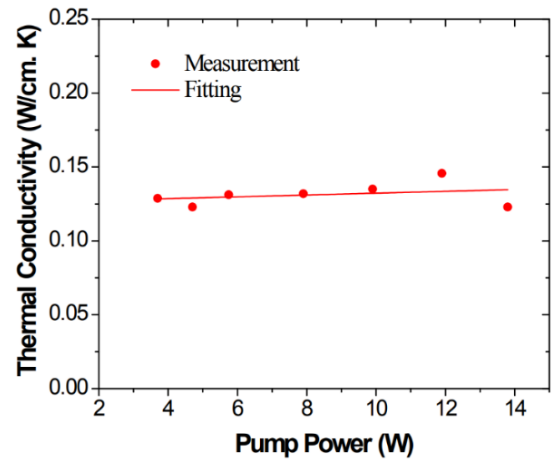


Fig. 10. Nd:YAG crystal thermal conductivity with absorbed pump power.

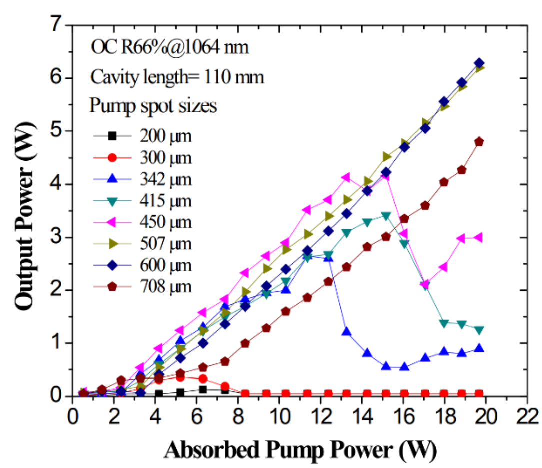
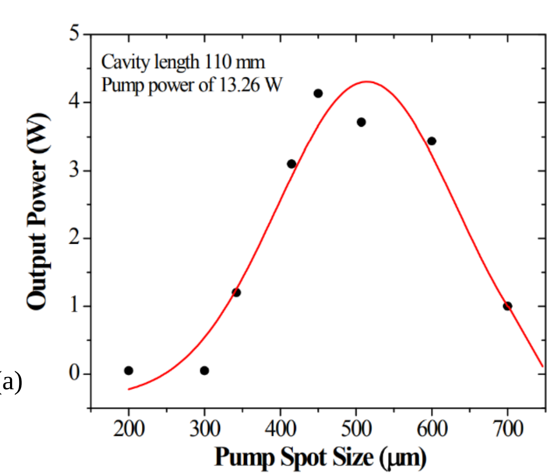


Fig. 11. The connection between pump power that is absorbed and output power for different pump spot sizes has a focusing location of 1.5 mm within the Nd:YAG crystal with a 110 mm long chamber.

(a)



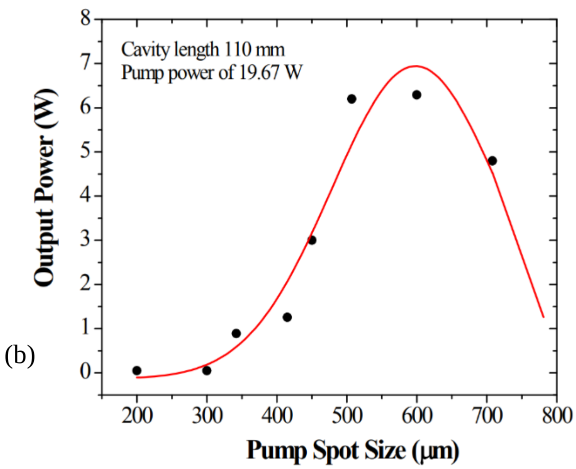


Fig. 12. The connection between pump power that is absorbed and output power spot size for crystal with a 110 mm long chamber and pump powers of (a) 13.26 W and (b) 19.67 W.

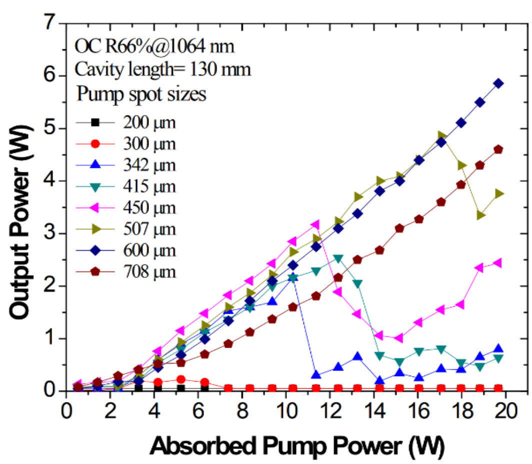


Fig. 13. The connection between pump power that is absorbed and output power for different pump spot sizes has a focusing location of 1.5 mm within the Nd:YAG crystal with a 130 mm long chamber.

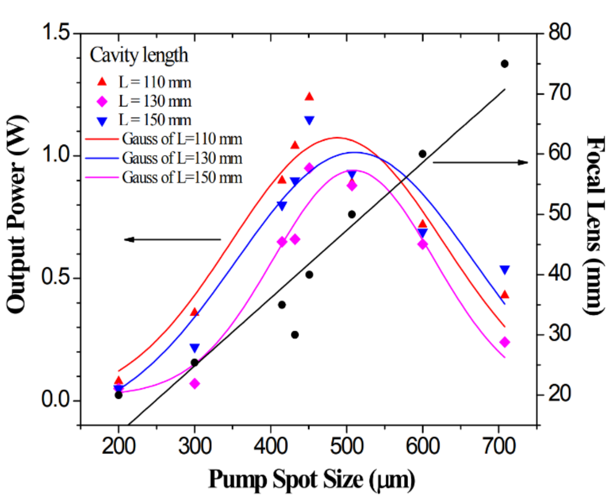


Fig. 14. The connection between pump power and output power when it is absorbed is 5.22 W for different spot sizes of the chamber's length of 100 mm, 130 mm, and 150 mm.

4. CONCLUSIONS

To accomplish the optimum power output of a Nd:YAG laser that is pumped from one end, several factors were considered, including the mode-matching effects through the use of different focused spot sizes in the crystal, the output coupler's reflectivity, the pump beam's location for focusing, and the thermal lensing effects. It was found that determining the exact position inside the laser medium was crucial for obtaining higher laser power in the end-pumped Nd:YAG laser. With a cavity length of 75 mm, an output coupler reflectivity of 66%, and a pump power of 19.67 W, the optimal location, which was 1.5 mm from the crystal surface, produced the greatest output power of 6.57 W and a slope efficiency of 33.40%.

To accurately quantify the thermal length, a charge coupled device camera was employed to ascertain the size of the thermal lengths' spot. At a pump power of 3.7 W, the size of the concentrated spot was measured to be 630 µm, and the thermal focal length was determined to be 125 cm. The size of the concentrated spot dropped in a linear manner, however the thermal focal length reduced exponentially with an increase in the pump power. The thermal length measurements were used to identify specific properties of the Nd:YAG crystal, such as a thermal loading of 0.32 and a thermal conductivity of 0.14 W/cm.K. These values were consistent with previous research and documented values.

Our investigation revealed that using a focal length of 40 mm and a pump beam spot size of 450 µm yielded the greatest output power, provided that the pump power remained below 13 W. When the power of the pump exceeds 13 W, it is more advantageous to use a spot size of 600 µm.

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