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Effect of Material Irradiated Type and Spot Size on Spot Center Temperature of a Diode-Pumped Solid State Laser

This article presents an experimental study of measuring the temperature of the center spot of DPSS green laser, which emits a light beam with a center wavelength of (532 nm), and its changing with the laser spot dimensions and the type of material. The optical properties of this laser were studied, for example, the threshold current value was determined to be 62mA at room temperature. The results showed that the temperature of the center of the spot decreases logarithmically with increasing laser spot size. Moreover, by studying the spectral power distribution with the laser spot dimensions, it is observed that the density of the power spectral distribution drops in an inverse exponential function with increasing spot size. Finally, the results showed that the temperature of the of the spot center increases as the density of the power spectral distribution increasing.

Keywords: Temperature distribution; Nd:YVO$_4$ laser; Thermal lensing; Laser Beam
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1. Introduction

The significant development in solid-state laser technology over the past several years has been the result of numerous technical developments across many different fields, correspondingly increasing interest in using semiconductor diode lasers to excite solid-state lasers made of materials impregnated with transparent rare earth ions [1-3]. Laser diode-pumped solid state is commonly called DPSS laser. The resultant diode pumped laser has much better spectrum and spatial properties than the laser diode itself, these lasers' benefits include their high efficiency, long lifespan, stability, small design, and superb beam quality [4]. In numerous scientific uses, high power DPSS lasers have taken the role of ion lasers and flash lamp pumped lasers, and now they are considerably used in green and other color laser pointers. The DPSS lasers is widespread used several field such as information technology, science, industry, as well as in the military [5]. Because of its exceptional qualities, namely a high absorption coefficient and a wide absorption bandwidth at the pumping wavelength, as well as a large stimulated emission cross section at the laser wavelength, the Nd:YVO$_4$ crystal has gained the most interest among the several laser crystals suited for DPSL [2]. Additionally, by coupling the diode-pumped Nd:YVO$_4$ crystals with NLO crystals (LBO, BBO, or KTP), the resultant frequency can be changed from near infrared to green, blue, or even ultraviolet light [6]. Laser is used as a heat source in many industrial applications such as cutting, perforating, welding, annealing, etc. [7-9], and medical applications such as surgical operations, skin disease therapy, eye treatment, etc. [10,11]. This requires determining the amount of heat produced in the material as a result of the laser beam’s absorption. Thus, in order to make the best and most efficient use of lasers in a variety of applications, several theoretical and practical research have attempted to understand the heat distribution in the laser beam and the factors controlling it. For instance, many of the studies focused on the analysis of the impact of various laser parameters on temperature distributions across workpiece employing finite element model [7,12]. An important element in the stability and part quality of the laser beam melting process is temperature fields, which have been studied through numerically and experimentally in references [13,14]. In reference [15], the influence of uniform and Gaussian heat flux distribution in various beam diameters, power and velocity on bending angle was simulated for two types of lasers including Nd:YAG and CO$_2$ lasers. Many studies have attempted to understand how heat is distributed across in biological tissues when using lasers for medical therapy in order to reduce tissue damage brought on by excessive heat. Most of these studies have focused on the effects of several factors, including time of exposure, power, wavelength, spot size, on the temperature distribution in skin tissues and the thermal response of skin tissues when exposed to a laser source, using finite element technique numerical computations [11,16,17].

Measuring the laser spot size is not as easy as it may seem at first glance, especially if we want our measurements to be accurate and decisive. There are two meanings associated with the term "laser spot size". In the first, the diameter of the laser beam when it leaves the laser device or is in an area far from the laser is meant, and in the second, the size of the spot on the focal plane while focusing with the lens. It is important to distinguish two cases because the measurement method is different. The laser beam's diameter varies continuously as it propagates along its optical path. The following formula determines the beam's radius along the propagation z-axis for a Gaussian beam [21].

$$w(z) = w_o\sqrt{1+(\frac{\lambda Z_R}{\pi w_o^2})^2} \qquad (1)$$

where w_o represents the beam radius and Z_R represents the Rayleigh length, which is given in the form of

$$z_R = \frac{\pi w_o^2}{\lambda} \qquad (2)$$

The waist value of the Gaussian beam focused using a lens with focal length *f*, see Fig. (1), is given as [21]

$$w_f = \frac{\lambda f}{\pi w_o} \qquad (3)$$

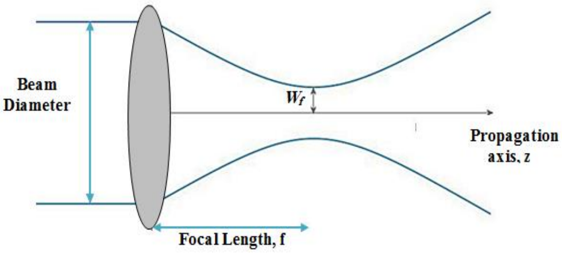

Fig. (1) A lens with a focal length *f* is used to focus the light beam

Therefore, the size of the focal point could be quite tiny, and in this case the beam size will vary very quickly along the axis of dissemination. Since determining the focal plane of a laser beam requires a high degree of accuracy in the location of the sensor's image plane and a method for altering this position, measuring the focused spot size of a laser beam is almost an art in and of itself. To calculate the magnitude of the laser spot size, there are three general definitions known for the diameter of the laser beam represented by FWHM, 1/e^2, D4σ.

The FWHM is measured at the midpoint of the maximum value (also called the beam width at mid-power) from the beam intensity distribution curve along the pre-determined axis of propagation passing through the center of the beam, this is often the point with the highest level of intensity. FWHM corresponds to the distance between the two points closest to the peak that contains 50% of the maximum beam intensity [22]. Some people prefer to use other ratios of the maximum intensity of the beam to determine its width, and the common ratio 13.5% leads us to define the diameter of the beam as 1\e^2 of the maximum intensity, this approximation results from simplifying the equation that describes the radial distribution of the Gaussian beam. Since the definitions of both 1\e^2 and FWHM are computed from the distribution of intensity along one axis, therefore it does not consider the general appearance of the beam and thus the exact size of the laser light spot. The D4σ is the most often used definition for laser beam widths. In essence, the diameter (D4σ) is equal to four times of the standard deviation of the laser beams main axis' intensity distribution. It is computed using the laser beam's second kind of intensity distribution form [22].

The spectral power distribution (SPD) is given by the following relationship:

$$M = \lambda = \frac{P}{A\Delta\lambda} \quad W/m^3 \qquad (4)$$

where P is the radiant flux power and A is the area of the spot

Study of SPD is crucial for applications in optical sensing systems where optical properties such as transmittance, reflectivity, and absorption are important. As well as the sensor's response to the wavelength of the incident light [23].

This work aims to quantify the spot center temperature of a diode-pumped solid-state (DPSS) laser experimentally, considering both the type of irradiated materials and its spot size.

2. Experimental Part

The laser used in this study is a DPSS emitting a green light at 532 nm. Figure (2) depicts the main components of a microchip laser, which primarily consists of an Nd:YVO$_4$ crystal acting as the active medium which is optically pumped using a laser diode with a wavelength of 808 nm. The emitted wavelength (1064 nm) is passed through a KTP crystal, which is used as a frequency doubling medium, efficiently converting into a highly visible green. The primary axes of KTP and Nd:YVO$_4$ crystals are rotated by 45° toward one another for effective frequency doubling, because KTP exhibits an interaction of type II [18]. Despite the crystals are coated in a way that only allows green light (532 nm) to emerge from the cavity, the resultant green light still has some traces of 1064 nm. Therefore, the infrared filter is used to prevents 808 nm and 1064 nm light from exiting the laser [19,20].

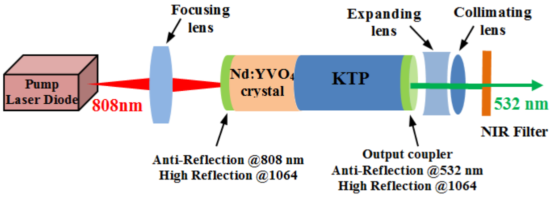

Fig. (2) DPSS green laser structure

Figure (3) depicts the schematic diagram of experimental system used for determining the temperature of the spot center of the DPSS laser. The wavelength of the DPSS laser (532nm) displays a spectral line of up to Δλ=30nm and an output optical output power of up to 180mW.

A precision thermal sensor with a resolution of ±0.1°C was used to monitor the temperature at the center of the laser light as a function of spot size with black and white backgrounds, because the color of the screen is of great importance in the issue of heat absorption or reflection The current was manually adjusted using a laser injection current controller providing a maximum current of 250 mA with a resolution of ±0.1 mA. An AS-M890A multimeter was used to measure the current. The laser spot size was measured by scanning the laser spot penetrating a small aperture in both the horizontal and vertical directions. The spot size was determined precisely through the precise variation of the vertical and horizontal scanning that was within a millimeter.

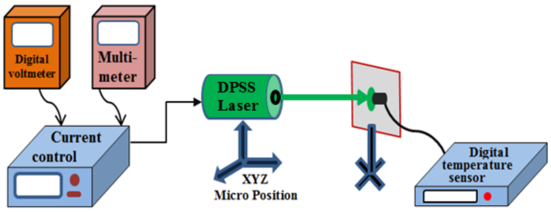

Fig. (3) Schematic diagram of the experimental setup

3. Results and Discussion

Figure (4) shows the photoelectric characteristics of a DPSSFD laser for the relationship between the output optical power from the laser versus the injection current. It is noted that the threshold current (which can be found from the intersection of the extension of the curve in the linear region with the current axis) is equal to 62mA. The stimulated emission occurs above this current. Therefore, the laser must be operated with a current higher than 62mA to ensure that the laser operates normally.

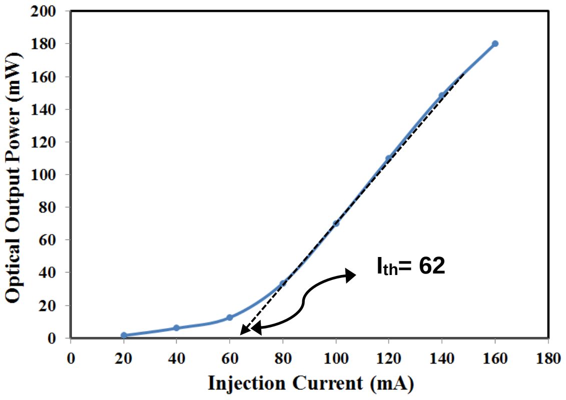

Fig. (4) Optical output power versus injection current of DPSS Laser

After operating the laser with a constant current of 75 mA and at an almost constant temperature while changing the spot size of the laser, the temperature of the spot center was measured in two cases of the screen on which the laser spot is incident.

The first is a white screen and the second is a black screen in order to compare the heat generated in the two cases of black and white. Figure (5) shows the relationship between the laser spot dimensions and the heat generated in the center of the spot. It is found that the temperature of the center of the spot decreases with the increase in the size of the spot. Moreover, in the cases of the white screen and the black screen, the equation of change for both cases is shown in the figure, as the amount of change in the temperature of the center of the laser spot with the spot size. The change is -14.625°C/m^2 for a black screen, while the change for a white screen is -11.636°C/m^2. The reason for the difference in temperatures is due to the high absorbency and emissivity nature of the black surface. The reason for taking two completely different colors in terms of absorbance of the screen on which the laser spot falls is to take into account other objects that differ between black and white in the case of treating these objects or cells optically to choose the average temperature of the center of the spot for the laser in treating these contrasting objects.

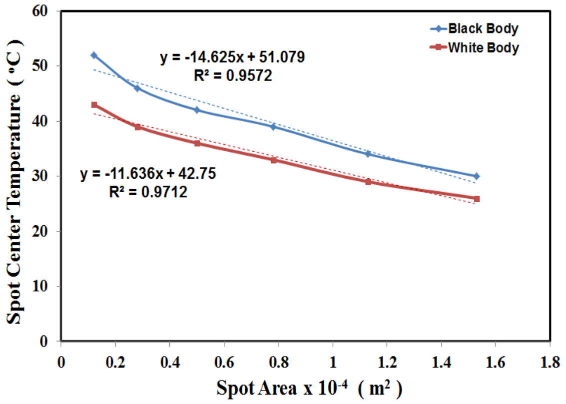

Fig. (5) Variation of spot center temperature with the spot area

Figure (6) represents the relationship between the average temperature extracted for the two curves in Fig. (5) versus the spot size of the laser. The equation of change for the curve is given by the following formula:

$$T_{avg} = -7.466\, ln(A) + 32.704 \qquad (5)$$

where T_{avg} represent the average spot center temperature, and *A* is the spot area

Through this relationship, it is possible to find the temperature of the center of the laser spot at any size. For example, if we have a sample of living cells with a number of 100,000 cells and the average diameter of one cell is 10 μm, the total area of this sample will be approximately 100 mm^2, or 10^{-4} m^2. Therefore, when a laser spot with a size of 10^{-4} m^2 is shined, the temperature of the sample will It will rise to about 40°C, and it can be increased by increasing the injection current of the laser.

Figure (7) represents the relationship between the spectral power distribution (SPD) versus the average temperature of the laser spot center. It can be seen that there is a non-linear increase in (SPD) with the increase in the temperature of the spot center, and when the spectral density of the laser spot rises to reach the value 275 GW/m^3, the average temperature of the center of the laser spot reaches to 47°C. The reason for this is that if the size of the laser spot is small, it leads to an increase in the number of photons per unit area and thus an increase in the temperature of the area on which the photons strike. Figure (8) represents the relationship between the spectral power distribution (SPD) versus the spot size of the laser. It is noted from this curve that (SPD) decreases when the laser spot size increasing. The change equation can be written as:

$$SPD = 33.249A^{-1.001} \qquad (6)$$

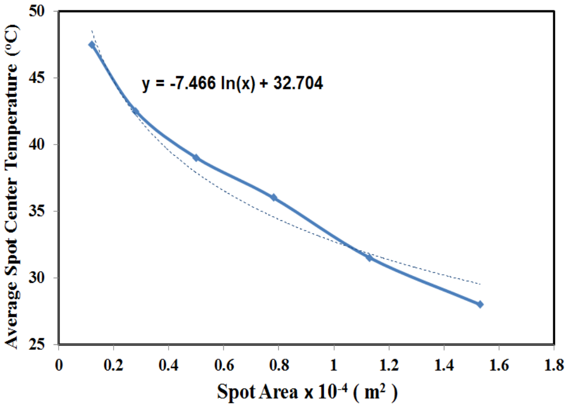

Fig. (6) Variation of average spot center temperature with the spot area

Finally, the results of this work could be used for medical and life applications in studying the effect of the temperature of the laser spot on the performance of bacteria, living cells, and enzymes.

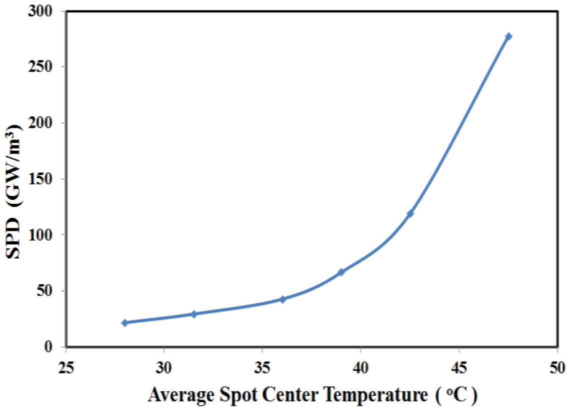

Fig. (7) Variation of spectral power distribution with the average spot center temperature

4. Conclusions

The following conclusions can be obtained from this work: For the DPSSFD green laser, the laser spot dimensions can be controlled by controlling the distance of the lens from the laser light exit. By studying the temperature of the center of the laser spot, we found that the temperature of the center of the spot decreases logarithmically with increasing laser spot size. We also found that by studying the spectral power distribution with the laser spot dimensions, the density of the power spectral distribution exponential decreases with increasing spot size, Finally, it was found that the temperature of the center of the spot increases when the density of the power spectral distribution increasing.

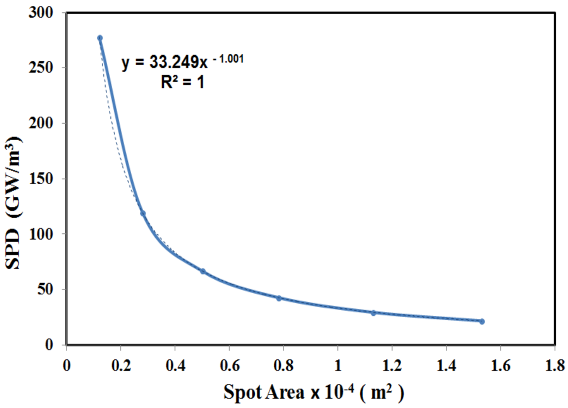

Fig. (8) Variation of spectral power distribution with the spot area

References

[1] B. Davarcioglu, “An Overview of Diode Pumped Solid State (DPSS) Lasers”, *Int. Arch. Appl. Sci. Technol.*, 1(2) (2010) 1-12.

[2] V.J. Pinto Robledo et al., “Experimental study of the dynamics of a diode-pumped Nd:YVO_4 laser under periodic modulation of losses”, *Rev. Mex. Fis. E*, 58 (2012) 150-155.

[3] R.M. Ibrahim et al., “Temperature-dependency performance of InGaAsP semiconductor laser amplifiers”, *Dig. J. Nanomater. Biostruct.*, 16(2) (2021) 385-392.

[4] L. Shang et al., “A Nd:YVO_4/LBO Intracavity Frequency Doubling Laser Pumped by a Diode-Laser”, *Adv. in Comp. Sci. Res.*, 94 (2019) 112-114, *Int. Conf. on Big Data Electron. Commun. Eng. (BDECE 2019)*.

[5] S. Li et al., “Thermal effect investigation and passively Q-switched laser performance of composite Nd:YVO_4 crystals”, *Opt. Laser Technol.*, 68 (2015) 146-150.

[6] C. Jung et al., “Linearly-polarized Nd:YVO_4/KTP microchip green laser”, *Opt. Exp.*, 17(22) (2009) 19611-19616.

[7] A. Joshi, et al., “A Study of Temperature Distribution for Laser Assisted Machining of Ti6Al4V Alloy”, *Proced. Eng.*, 97 (2014) 1466-1473.

[8] T. Bergsa et al., “Optimized Temperature Distribution for Laser Hardening with Freeform Mirrors”, *Lasers in Manufact. Conf. (LiM)*, 24-27 June 2019, 1-7.

[9] M. Kubiak et al., “Research on Yb:YAG Laser Beam Power Distribution Used in Hybrid Processes”, *Acta Physica Polonica*, 139(5) (2021) 598-601.

[10] B. Sheeba and P. Myvizhi, “Application of laser in medical field”, *Int. J. Pure Appl. Math.*, 119(12) (2018) 3983-3990.

[11] P. Wongchadakul et al., “Simulation of temperature distribution in different human skin types exposed to laser irradiation with different wavelengths and laser irradiation intensities”, *Songklanakarin J. Sci. Technol.*, 41(3) (2019) 529-538.

[12] F. Njihia1 et al., “Analysis of Temperature Distribution in Laser Assisted Metal Polymer (LAMP) Joining”, *J. Sustain. Res. Eng.*, 4(1) (2017) 1-11.

[13] J. Schilp et al., “Investigations on Temperature fields during laser beam melting by means of process monitoring and multiscale process modeling”, *Adv. Mech. Eng.*, 6 (2014), doi: 10.1155/2014/217584.

[14] H. Ding et al., “Study on Three-Dimensional Temperature Field Induced by Laser Irradiation with Different Intensity Distribution”, *Adv. Intellig. Sys. Res.*, 168 (2019) 64-68.

[15] M. Riahia et al., “Experimental and numerical study of heat flux distribution in laser forming of bi-layer sheets”, *J. Comput. Appl. Res. Mech. Eng.*, 4(1) (2014) 67-79.

[16] K.M. Shurrab and M.S. El-Daher, “Simulation and Study of Temperature Distribution in Living Biological Tissues under Laser Irradiation”, *J. Lasers Med. Sci.*, 5(3) (2014) 135-139.

[17] K. Chen et al., “Simulation of temperature distribution in skin under laser irradiation with different wavelengths”, *Int. J. Light Electron Opt.*, 125 (2014) 1676-1679.

[18] E. Garmire, “Nonlinear optics in daily life”, *Opt. Exp.*, 21(25) (2013) 30532-30544.

[19] A.S. Elsafty et al., “Spectral characteristics of a microchip Nd:YVO$_4$ laser”, J. Opt, 52 (2023) 1717-1723.

[20] J. Galang et al., “A green laser pointer hazard”, *Int. Laser Safety Conf.*, (2011) 296-300.

[21] M. Safuan Mat Yeng et al., “The Determination of Laser Spot Size of an Optical Tweezers by Stuck Bead Method”, *J. Sci. Technol.*, 9(3) (2017) 70-74.

[22] H.J. Eichler et al., **“Laser Physics and Applications”**, Springer-Verlag (Berlin, 2004).

[23] O. Svelto, **“Principles of Lasers”**, 5th ed., Springer Science + Business Media (2010).