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CHARACTERIZATION OF AN ARC LAMP PUMPED, LINEARLY POLARIZED TEM_{00} AND Q-SWITCHED Nd:YAG LASER AT 1064nm FOR OPTICAL TWEEZERS IN INTERACTION FORCE STUDIES IN CARDIO-VASCULAR IMPLANT SURFACES

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The developments in the area of lasers and photonics opened new applications in biology and biotechnology. Solid state lasers can create highly localized traps at its depth of focus using specially designed beam expansion and focusing optics. In the present investigation, we report the design and development of an arc lamp pumped Nd:YAG laser operating at 1064nm with high beam quality for optical tweezers applications. The laser sources can be operated at lower power levels up to 2W and with high beam quality (M^2 factor) for optical tweezers applications. Such laser tweezers can be used effectively for studying the interaction force between arterial cells and implant surfaces and also in the study of cellular and drug biomechanism. The mode limiting aperture is restricting higher order modes and therefore in TEM_{00} mode also, the slope efficiency decreases more. The beam quality should be high for creating a better optical trap for microscopic objects and hence use of mode limiting apertures are highly necessary in the present optical resonator configuration.

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1. Introduction

The developments in the area of lasers and photonics opened new applications in biology and biotechnology. Solid state lasers can create highly localized traps at its depth of focus using specially designed beam expansion and focusing optics. The technique of laser trapping and micro-manipulation of small dielectric particles by lasers is based on the forces of radiation pressure [1]. These are forces arising from the momentum of the light itself. With lasers, however, one can make these forces large enough to accelerate, deflect, guide, and even stably trap small particles. Such optical tweezers use focused laser beams to trap and remotely manipulate dielectric particles, including cells and other biological objects [2–6]. S.K.Sudheer *et al.* reported the slope efficiency and beam quality of arc lamp pumped Nd:YAG lasers for material processing applications [7-9].

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The high intensities and high intensity gradients achievable with continuous wave coherent light beams are responsible for the above effect. Laser manipulation techniques apply to particles as diverse as atoms, large molecules, small dielectric spheres in the size range of tens of nanometers to tens of micrometers, and even to biological particles such as bacteria viruses, single living cells, and organelles within cells. Use of laser trapping and manipulation techniques gives a remarkable degree of control over the dynamics of small particles, which is having a major impact in many of the fields in which small particles play a role.

In the present investigation, we report the design and development of an arc lamp pumped Nd:YAG laser operating at 1064nm with high beam quality for optical tweezers applications. The laser sources can be operated at lower power levels up to 2W and with high beam quality (M^2 factor) for optical tweezers applications. Such laser tweezers can be used effectively for studying the interaction force between arterial cells and implant surfaces and also in the study of cellular and drug biomechanism.

2. Experimental:

The experimental part mainly consists of the design and development of a high beam quality arc lamp pumped Nd:YAG laser, CW and Q-Switched operations.

2.1 Design and Fabrication of an arc lamp pumped Nd:YAG laser with good beam quality.

The Nd:YAG laser consists of an optical resonator, cooling system, power supply and RF driver. These modules have been designed and fabricated. Output characteristics of the beam of the laser fabricated is studied by varying different parameters like pump power, Nd doping concentration, Nd:YAG rod diameter and resonator length to obtain optimum conditions.

Nd:YAG rods of dimensions 3ϕ x 108 mm with three different Nd doping concentrations 0.8 at.%, 0.7 at.% and 0.65 at.% (supplied by VLOC Inc., Florida, USA) have been used for both CW and Q-switched operations. In order to study the effect of rod diameter, an Nd:YAG rod of 4ϕ x 108 mm with Nd doping concentration 0.7 at.% is also used. An intra-cavity Brewster window is used for getting a 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 generation of laser pulses with high peak power. Two apertures are used for limiting the higher order modes.

2.1.1 Laser Resonator

A plane parallel resonator configuration [10] operating in the stable region of stability diagram for the laser has been 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' the resonator length and 'λ' the wavelength of laser [11]. For a fixed resonator length of 860 mm, if one assumes a Fresnel number equal to unity, the aperture size can then be calculated as 0.915 mm. Because of easiness in mechanical fabrication and availability, an aperture size of 1mm is used throughout 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 [12]. The focusing of pump light at the rod can be improved by locating the lamp and rod beyond the foci of the elliptical reflector [13]. The eccentricity of single elliptical cavity is designed so that the major and minor axes of the ellipse are 38 mm and 33 mm respectively. The above calculations of major axis and minor axis and corresponding eccentricity ensure maximum coupling of pump light into the rod.

Cooling of the rod and lamp is accomplished by circulating de-ionized 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. Since the absorption bands of Nd:YAG crystal lie around a central wavelength of 808 nm, 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 this, in the present design, a samarium doped (10%) pyrex glass flow tube is used around the rod. Samarium doped flow tube absorbs radiation in the UV region of broad band emission from arc lamp and re-emits in the visible and near infrared region where Nd:YAG has maximum absorption. Thus the pumping efficiency has been enhanced.

The optical resonator comprises of two dielectrically coated plane mirrors placed at a distance 860 mm apart. The stability criterion of the resonator is given by

$$0<g_1g_2<1 \tag{2}$$

$$\text{where } g_1 = 1-\frac{L}{R_1} \text{ and } g_2 = 1-\frac{L}{R_2} \tag{3}$$

For plane mirrors, $g_1 = 1$ and $g_2 = 1$.

As the product lies inside the stable region of stability diagram, the present resonator will operate as a stable one at the designed pump power.

It has been reported [14-16] 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 glass with high damage threshold (20 J/cm^2) is used for obtaining a polarized laser output.

An acousto-optic Q-switch (Model QS27-3C-S, Gooch and Housego, UK) is used for pulsating the CW laser output 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 a 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 a rate of 190 cc / min.

The detailed schematic diagram of the laser resonator is shown in Figure 1.

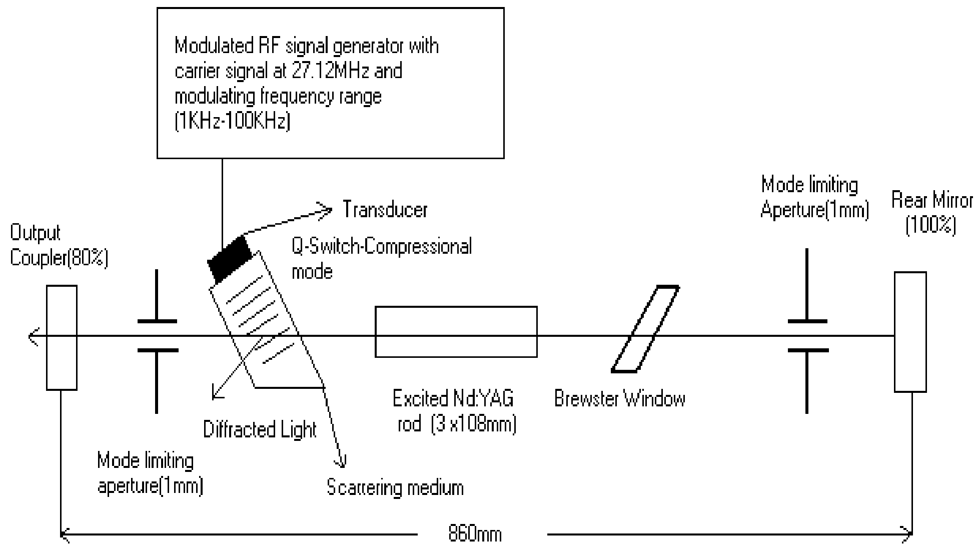

Fig. 1. Detailed schematic diagram of laser resonator.

The acousto-optical Q-switch makes use of mutual interaction between an ultrasonic wave and a light beam in a scattering medium. The light beam that enters in a direction forming a Bragg angle to the wave surface of the acoustic wave in the scattering medium is diffracted. This is in accordance with periodic changes in the refractive index (phase grating) produced by the acoustic wave. A modulated RF signal from RF driver is impressed on the transducer. The laser beam is diffracted when it satisfies the Bragg angle with respect to this phase grating, and is separated in space from the incident light. As a result, loss occurs in the laser resonator and oscillations are suppressed as long as the modulated RF signal is active. The RF signal is impressed for certain duration of time to suspend laser oscillations and during this time Q-value of cavity is low. In the mean time, the population inversion of the Nd:YAG rod is accumulated by continuous pumping using arc lamp. When the RF signal is reduced to zero and the loss to the laser optical resonator is removed, the accumulated energy is activated as laser oscillations in the form of a pulse within an extremely short duration of time. When the modulated RF signal is impressed on the Q-switch, it is possible to obtain Q-switched laser pulses periodically at any desired pulse repetition rate. The various waveforms associated with the Q-switched operation are shown in Figure 2.

In the present investigation, a modulated RF generator capable of using modulating signals with frequency in the range 0-100 kHz is used. Plastic bellows are used between optical elements and the whole system is fixed in a C-carriage optical rail.

2.2 Arc Lamp Power Supply

The arc lamp power supply is designed to deliver a maximum electrical power of 6 kW to the arc lamp. The switching devices used are insulated gate bipolar transistors (IGBT) which are very sensitive to operating temperature. Cooling is provided by forced air given to the power supply. For initiating the discharge between anode and cathode of the arc lamp a trigger voltage of 27 kV is generated internally. A relay mechanism is incorporated in the system to remove boost and trigger voltages after a period of five seconds, when the lamp ignition fails.

2.3 Laser Cooling System

The interior of the elliptical reflector is cooled using chilled de-ionized water with a minimum resistivity of 300 kΩ. A water-to-water heat exchanger along with solenoid valves are used for cooling. If the coolant contains ions, there is a chance for the failure of ignition. Hence the purity of the de-ionized water has to be monitored and ensured periodically. The heat exchanger has two inputs and two outputs which are meant for primary and secondary water cooling circuits. The hot de-ionized water from laser pump chamber is supplied to the first input of heat exchanger where it will be conductively contacted by chilled water at 16 °C circulated through the secondary cooling circuit. A temperature difference of 7°C between primary supply and secondary exit temperatures is obtained. The primary water supply condition is designed to maintain a maximum temperature of 18 °C and a flow rate of 20 litre/min. The secondary cooling circuit is designed to provide the laser pump chamber with de-ionized cooling water at a maximum temperature of 25 °C and at a flow rate of 20 litre/min at a delivery pressure of 6.0 bars.

3. CW Performance

In order to study the performance of the laser in CW operation, the modulated RF generator connected with the Q-switch is switched OFF and the arc lamp power supply is switched ON.

3.1 Variation of CW performance with Nd doping concentration

The laser is operated in the following three modes.

1. Un-polarized multimode operation (without using any mode limiting apertures and Brewster window).
2. Polarized multimode operation (by using Brewster window and without using any mode limiting apertures).
3. Polarized TEM_{00} mode operation (by using mode limiting apertures and Brewster window).

The output power is measured for different input pump powers for these three modes of operation. All output power measurements are carried out using laser power meter (Model Nova, Ophir Optronics, Israel). USBI software is used for continuous data logging for an interval of 1 hour. Each data point in the present study is the mean value obtained from continuous data taken for 1hour. The electrical to optical slope efficiency curves are plotted (Figure 2-4). The experiments are repeated with laser rods of different Nd doping concentrations.

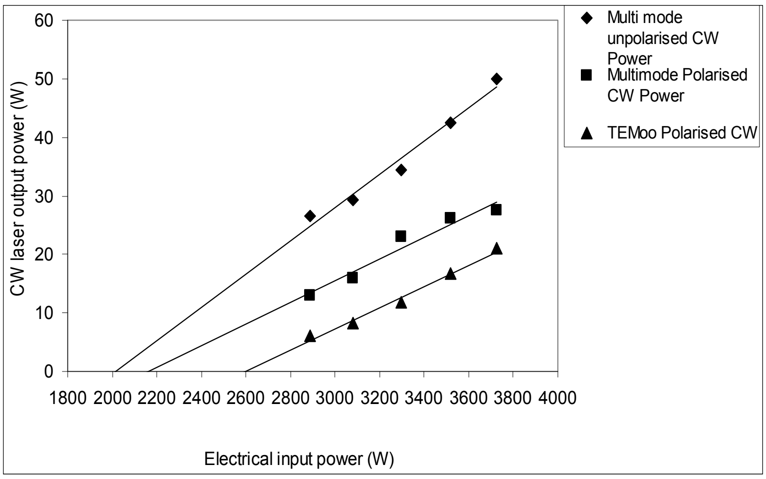

Fig. 2. CW laser output power Vs. input electrical power for 0.8 at.% Nd doping concentration.

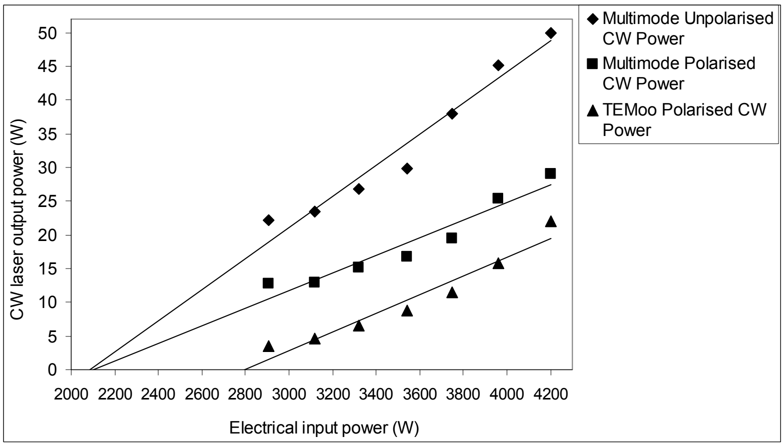

Fig 3: CW laser output power Vs. input electrical power for 0.7 at.% Nd doping concentration.

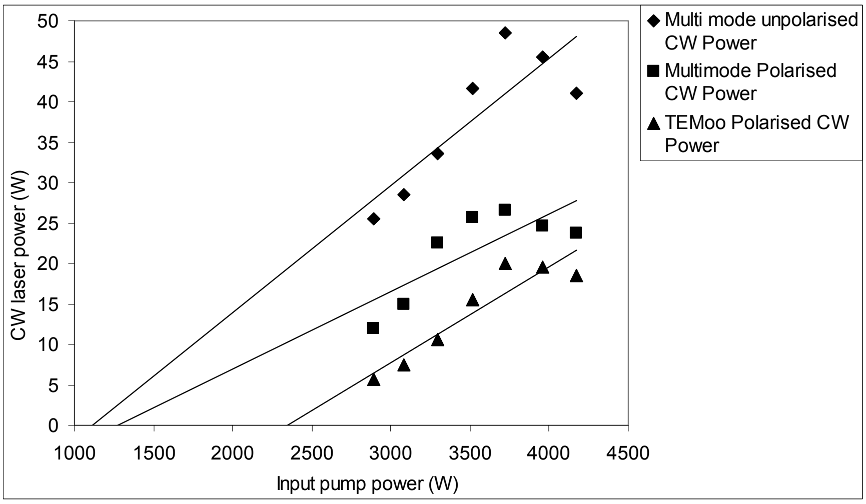

Fig. 4: CW laser output power Vs. input electrical power for 0.65 at.% Nd doping concentration.

The decrease in the slope efficiency observed for polarized multimode and polarized TEM_{00} mode operations may be due to the additional losses to the cavity oscillations offered by the Brewster window. However, the presence of mode limiting apertures has no significant effect on the slope efficiency. Thermally induced birefringence inside the rod can cause partial depolarization of the TEM_{00} mode [17].This may severely affect the output power, especially in the presence of an intra-cavity Brewster window which will reject part of the depolarized beam. Due to this reason the output power in polarized TEM_{00} mode decreases. For all the three modes of operation the slope efficiency is minimum for 0.7 at.% Nd concentration (Figures 2 - 4).

The variation of threshold pump power in CW operation with different Nd doping concentrations is plotted in Figure 5.

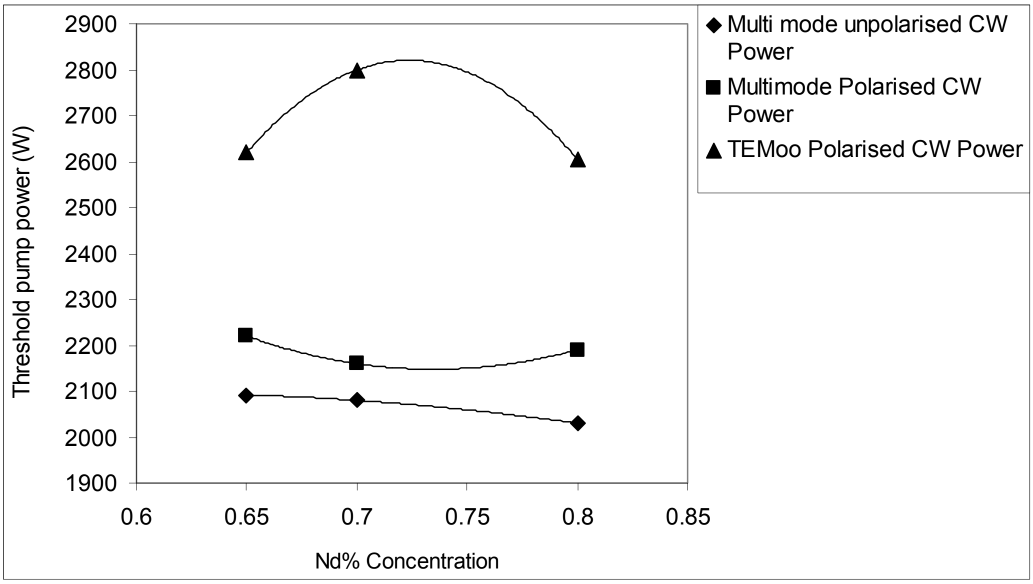

Fig. 5. Threshold pump power Vs. Nd concentration.

The threshold pump power shows higher values in the case of polarized and fundamental modes of operations as the cavity losses increases in these modes compared to multimode unpolarized operation. In the laser crystals with Nd doping concentration of 0.8 at.% and 0.65 at.% the slope efficiency decreases in the order unpolarized-multimode, polarized-multimode and polarized-TEM_{00} mode. In 0.7 at.% Nd doped crystal slope efficiency is minimum for polarized-multimode operation. The threshold pump power is found to be minimum for the case of unpolarized-multimode operation as explained earlier. Since the cavity loss is maximum in the case of TEM_{00} polarized mode of operation, it has maximum threshold pump power.

A parameter η_T is introduced which is defined as the ratio of polarized-TEM_{00} power to polarized- multimode power given by

$$\eta_T = \frac{\text{Polarized TEM}_{00}\text{ Power}}{\text{Polarized multimode Power}} \tag{4}$$

The variation of η_T with arc lamp current for different Nd doping concentrations of Nd:YAG rod is plotted (Figure 6).

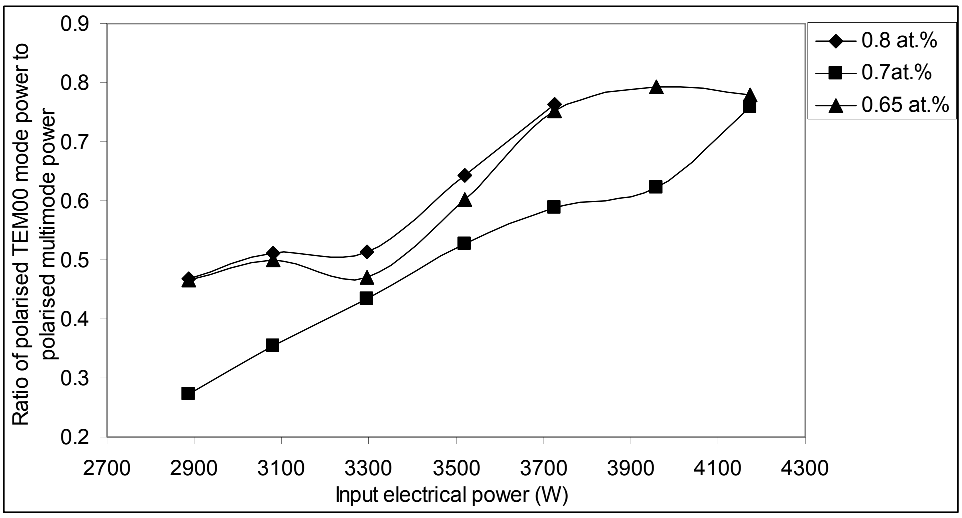

Fig. 6. Variation of η_T with input electrical power for different Nd doping concentrations of Nd:YAG rod.

It is observed that the ratio (η_T) of the polarized-TEM$_{00}$ power to polarized-multimode power increases with increase in input electrical power in all the three cases of Nd doping concentration of active medium. This indicates that at higher values of pump power, the energy concentrates more towards the axial region of Nd:YAG rod. In the case of rod with 0.7 at.% doping concentration, η_T increases almost linearly with input electrical power whereas for 0.8 at.% and 0.65 at.% doped rods, it shows fluctuations.

3.2 Q-switched Operation

For studying the performance of laser in Q-switched operation, the modulated RF generator connected to the Q-switch is switched ON and laser pulses are generated at various Q-switch frequencies. Investigations have been carried out in the frequency range from 4 kHz to 12 kHz since the peak power of laser pulses are found to be much lower as a result of increase in pulse width when the frequency increases beyond 12 kHz.

The Q-switched output power is measured for different values of input electrical pump power and is repeated for Q-switch frequencies of 4 kHz, 6 kHz, 8 kHz, 10 kHz and 12 kHz. All measurements have been carried out for the polarized-TEM$_{00}$ mode. The electrical to optical slope efficiency curves are plotted for the above Q-switch frequencies (Figures 7, 8 and 9). These studies have been carried out for all the three different Nd doping concentrations of 0.8 at %, 0.7 at.% and 0.65 at.%.

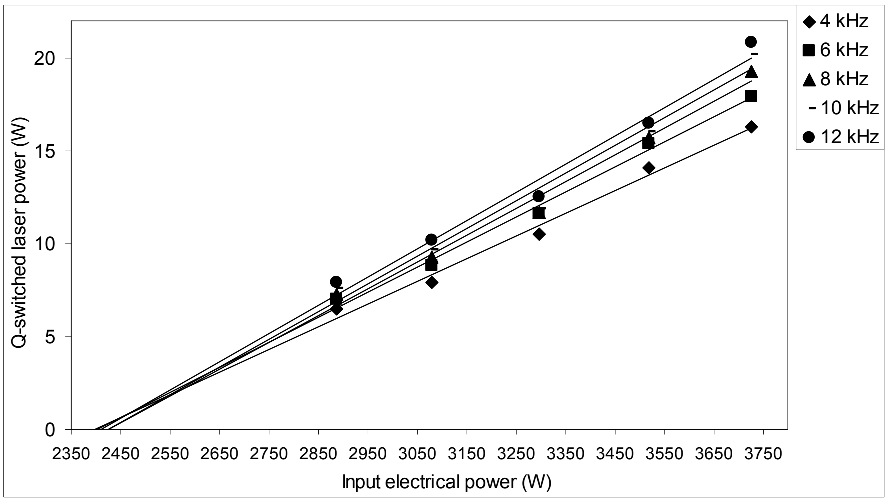

Fig. 7. Q-switched output power Vs. input electrical power to arc-lamp with 0.8 at.% doping concentration.

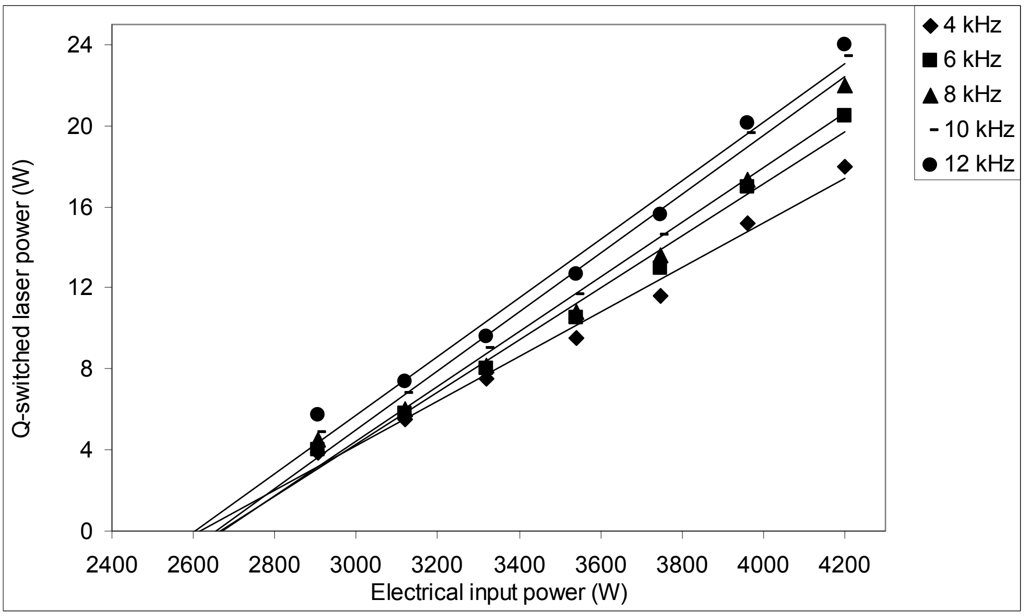

Fig. 8. Q-switched output power Vs. input electrical power to arc-lamp with 0.7 at.% doping concentration.

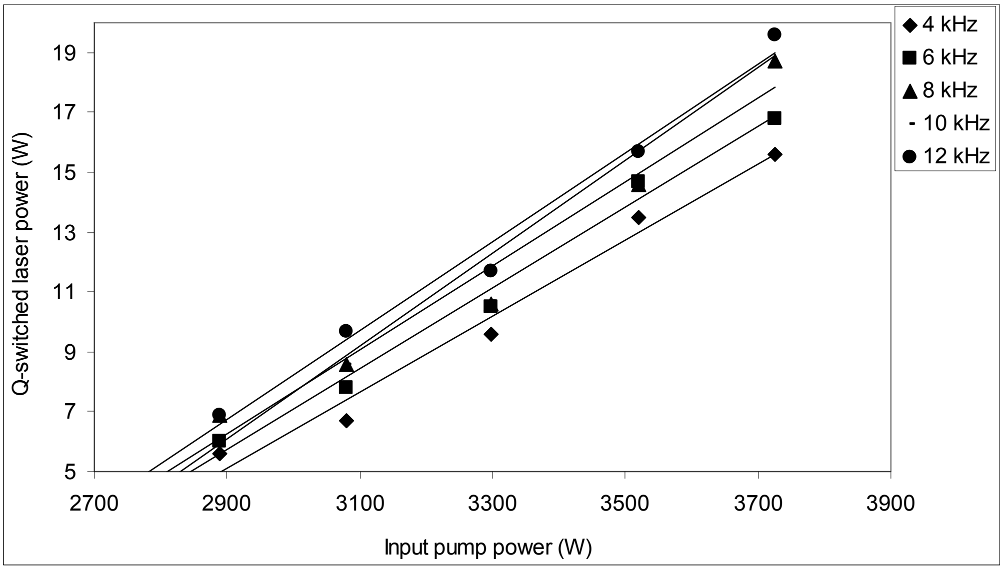

Fig. 9. Q-switched output power of laser Vs. input electrical power to arc-lamp with 0.65 at.% doping concentration.

The slope efficiency is found to be increasing with Q-switch frequency up to 10 kHz as the energy storage capacity of the laser crystal increases with increase in Q-switch frequency. But the threshold pump power is not showing such a variation when Q-switch frequency increases. This is true for all the three Nd doping concentrations used in the experiments. The variation of threshold pump power of Q-switched Nd:YAG laser with various Nd concentrations of active medium is given in Figure 10.

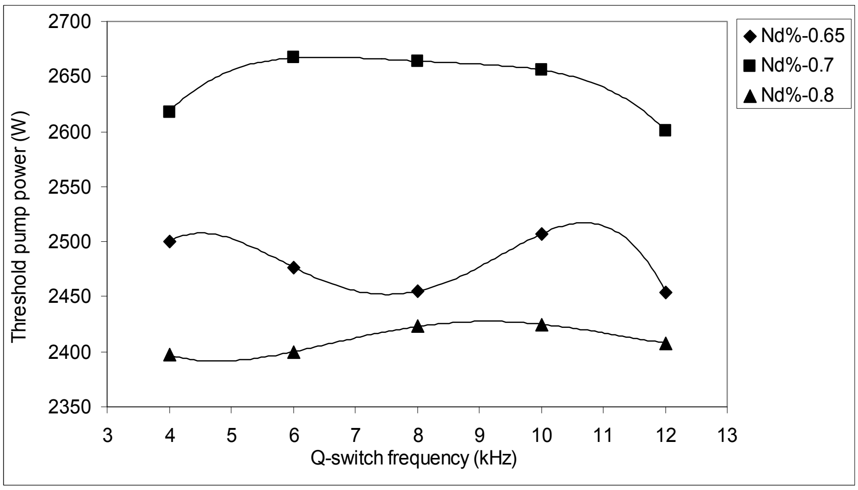

Fig. 10. Variation of threshold pump power in Q-switched operation at different Nd concentrations.

The threshold pump power is the lowest for the Nd concentration of 0.8 at.%. This is due to the higher number of excited Nd^{3+} ions in the crystal resulting from the higher doping concentration. The crystal with 0.7 at.% doping concentration shows a higher threshold pump power compared to that of others.

3.3 Variation of the Ratio $\frac{P_{av}}{P_{cw}}$ with Input Pump Power at Various Nd Doping Concentrations of Active Medium

The behavior of a Nd:YAG laser in both CW and Q-switched operations at the same pump power has distinct differences and a study of the ratio of average power (P_{av}) to CW power (P_{cw})

gives useful inferences. In CW and Q-switched operations of the laser, the ratio $\frac{P_{av}}{P_{cw}}$ is found to vary with input pump power for Nd doping concentrations of 0.8 at.%, 0.7 at.% and 0.65 at.% (Figures 11, 12 and 13).

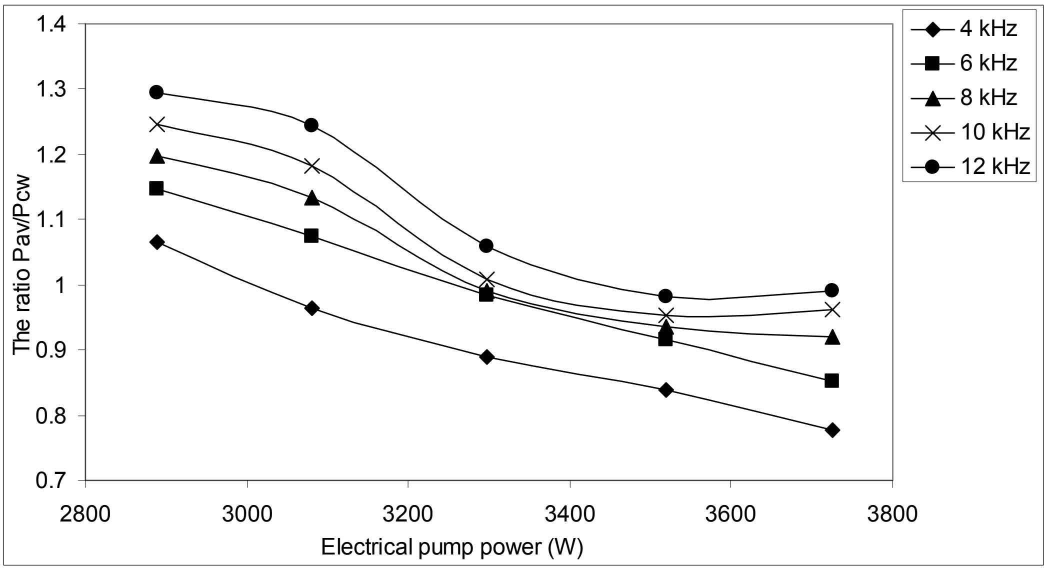

Fig. 11. Variation of the ratio $\frac{P_{av}}{P_{cw}}$ *with electrical pump power to arc-lamp for 0.8 at.% doping concentration.*

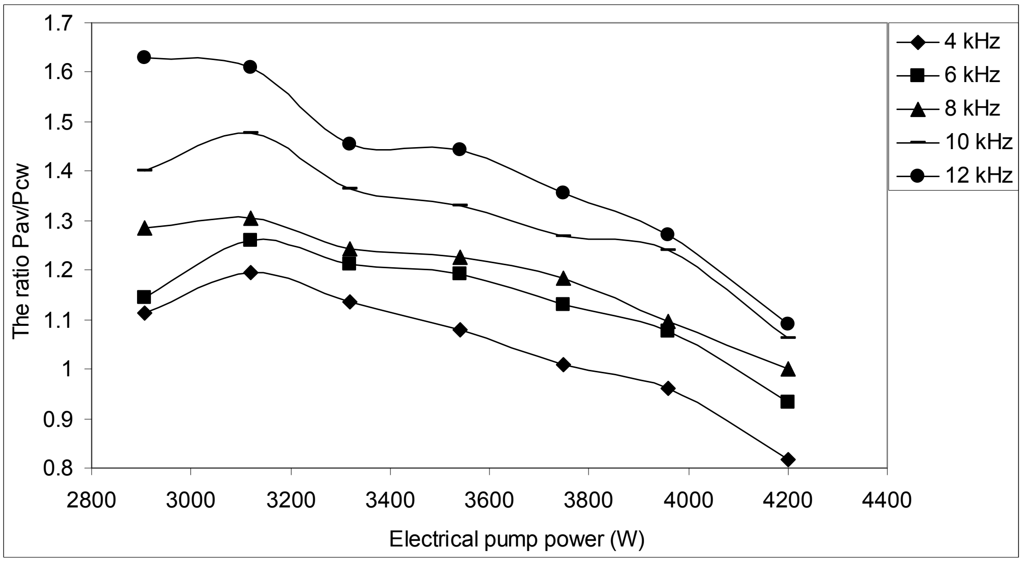

Fig. 12. Variation of the ratio $\frac{P_{av}}{P_{cw}}$ *with electrical pump power to arc lamp with 0.7 at.% doping concentration.*

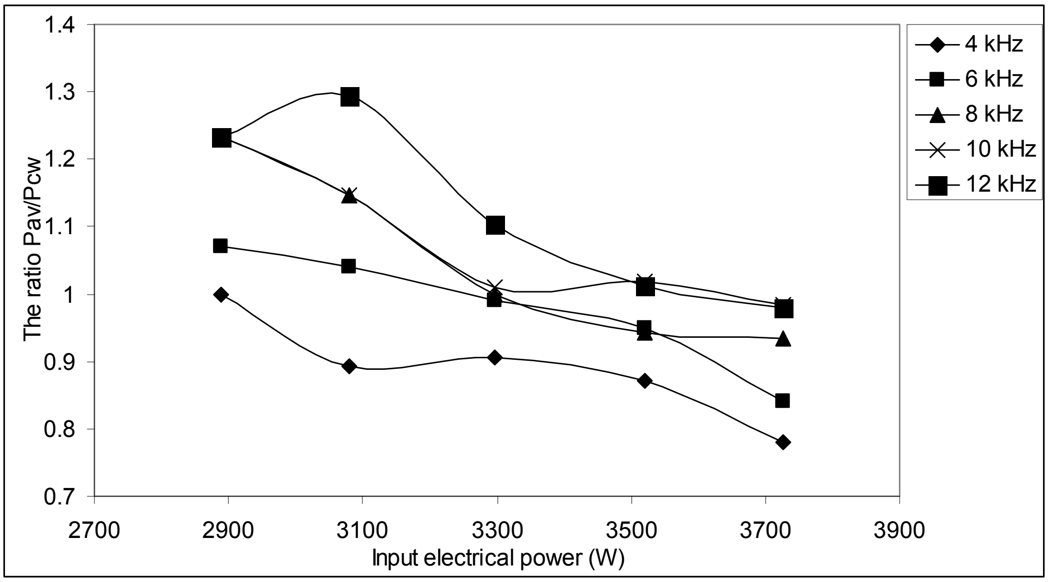

Fig. 13. Variation of the ratio $\frac{P_{av}}{P_{cw}}$ *with electrical pump power to arc-lamp for 0.65 at.% doping concentration.*

In the three cases of Nd doping concentrations, the ratio $\frac{P_{av}}{P_{cw}}$ is found to decrease with input pump power from the initial values. This indicates that the energy storage capacity of the laser crystal is low at higher pump powers. In the case of crystals with doping concentration 0.7 at.% and 0.65 at.%, the ratio $\frac{P_{av}}{P_{cw}}$ tends to have a maximum value at a particular pump power of ~3100 W in almost all higher values of Q-switch frequencies. This indicates that at this pump power, the efficiency of Q-switching is maximum. Results have been reported regarding the studies of laser characteristics in both CW and Q-switched operations with crystal like Nd:YAG and Nd:YVO_4 using laser diode pumping as excitation [18-20]. But such experimental setups are costly compared to the present one which utilizes an arc lamp as excitation source. S. Mutzenich *et al.* proposed a method of attaining all-optical beam control in an optofluidic device by displacing an optically trapped micro sphere though a light beam emitted from a Q-Switched 7.5 ps TEM_{00} Nd:YVO_4 laser. The micro-sphere causes the beam to be refracted by various degrees as a function of the sphere position, providing tunable attenuation and beam-steering in the device [21].

4 Conclusions

As the Brewster window is offering additional losses to the cavity oscillations the slope efficiency is decreasing in the polarized mode of operation. The mode limiting aperture is restricting higher order modes and therefore in TEM_{00} mode also, the slope efficiency decreases more. But the beam quality should be high for creating a better optical trap for microscopic objects and hence use of mode limiting apertures are highly necessary in the present optical resonator configuration. The threshold pump power shows higher values in the case of polarized and fundamental modes of operations as the cavity losses increases in these modes compared to multimode unpolarized operation. In the case of laser crystals with Nd doping concentration 0.7 at.% and 0.65 at.% the slope efficiency is decreasing in polarized and fundamental modes of operation and threshold pump power is increasing in these two modes similar to the case of 0.8 at.% doping concentration.

The slope efficiency is found increasing with Q-switch frequency as the energy storage capacity of the laser crystal is increasing with higher Q-switch frequency where as the threshold pump power is not showing much variation when Q-switch frequency is changing. Here also, the slope efficiency is found increasing with the repetition rate and is showing almost similar threshold pump power in all the repetition rates. The ratio $\frac{P_{av}}{P_{cw}}$ is found decreasing with input pump power in almost all Q-switch frequencies with an Nd concentration of 0.8 at.%. But there is a slight increase in the ratio was noted at higher frequencies in the case of Nd concentration of 0.7 at.%. This initial increase is more in the case of Nd concentration of 0.65%. The slope efficiency is found to increase with Q-switch frequency in the three cases of Nd concentrations. After reaching a maximum value, the slope efficiency is saturating at higher repetition rates. The threshold pump power remains almost the same for a fixed Nd concentration as the Q-switch frequency changes. It is noted that the threshold pump power is minimum for 0.8 at.% Nd concentration and maximum for 0.7 at.% concentration. In CW operation, the threshold pump power is found maximum for polarized TEM_{00} polarized operation and minimum for multimode unpolarized operation. In TEM_{00} operation, the threshold pump power is maximum for 0.7 at.% Nd concentration and almost same in the case of 0.65 at.% and 0.8 at.% while in multimode polarized and unpolarized operation, it is minimum with 0.8 at.% Nd concentration. The ratio $\frac{P_{av}}{P_{cw}}$ decreases with input pump power in all cases of Nd concentrations though the rate of decrease is less in Nd concentration of 0.7 at.%. The authors are planning to extent the experimental works using arc lamp pumped Nd:YAG lasers at 532nm and diode pumped Nd:YAG and Nd:YVO_4 lasers at 1064nm and 532nm to get better efficiency.

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