Design and Construction of Nd : YAG Laser System

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Abstract:

This paper presents the result of experimental studies on Q-switched flash lamp pumped Nd:YAG laser system with plane parallel resonator with output laser mirror having 35% reflectivity and high reflectivity at the rear mirror. It has found that in a single shot operation, laser output of 96.6 mJoules pulse energy and 40 nsec pulse duration at 1,06 µm wavelength can be obtained.The characteristics of such system are studied as a function of pumping energy. Threshold electrical pumping energy was (4.5) Joule. The output beam diameter was measuredexperimentally to be 3.46 mm at the $1/e^2$ points and the full-angle, far field beam divergence was5.5 mrad.

Keywords:**Q-switched flash lamp pumped Nd:YAG laser, Solid state laser**

تصميم وبناء منظومة ليزر النديميوم – ياك

وصفي حميد رشيد

مركز الليزر والكهروبصريات، دائرة بحوث المواد، وزارة العلوم والتكنولوجيا، بغداد، العراق.

المستخلص:

يقدم هذا البحث نتائج الدراسة العملية لمنظومة ليزر النديميوم- ياك ذو عامل النوعية والتي تم ضخها ضوئيا بواسطة مصباح الزنون . المرنان المستخدم هنا هو مرنان منالنوع المستوى الذي له مرآة خلفية بانعكاسية عالية ومرآة خرج بانعكاسية 35 %. اما ة معدل التكرار هو نبضة منفردة بخرج نبضي مقداره 96.6 ملي جول وعرض نبضة 40 نانوثانية عند الطول الموجي 1.06 مايكروميتر.ان مواصفات النظام قد تم دراستها كدالةلطاقة الضخ الكهربائي ، علما ان طاقة حد العتبة الكهربائية لحصول الفعل الليزري كانت 4.5 جول.تم أجراء قياس عملي لمعرفة قطر الحزمة الليزرية الخارجة والانفراجية لها لتكون 3.46 ملمتر عند نقاط الشدة$1/e^2$ وزاوية الانفراج التامة للمدى البعيد هي 5.5 ملي راد .

الكلمات المفتاحية:ليزر النديميوم ياك المضخ بالمصباح الوميضي ذو عامل النوعية،ليزرات الحالة الصلبة.

1. Introduction

The Nd: YAG laser is by far the most commonly used as type of solid-state laser. Neodymium-dopedyttrium aluminum garnet (Nd: YAG) possesses a combination of properties uniquely favorable for laser operation[1]. The YAG host is hard, of good optical quality, and has a high thermal conductivitycompared to glass. Furthermore, the cubic structure of YAG favors a narrow fluorescent line width, which results in high gain and low threshold for laser operation. Pure $Y_3Al_5O_{12}$ is a colorless, optically isotropic crystal that possesses a cubic structure characteristic of garnets. In Nd:YAG about 1% of $Y^{3+}$is substituted by Nd^{3+}. Some of the important physical properties of YAG are found in Table (1) together with optical and laser parameters [1]. The Nd: YAG laser is a four-level system as depicted by a simplified energy level diagram in Fig. 1. The laser transition, having a wavelength of 1064.1 nm, originates from the R_2 component of the $4F_{3/2}$ level and terminates at the Y_3 component of the $4I_{11/2}$ level. The ground level of Nd:YAG is the $4I_{9/2}$ level. There are a number of relatively broad energy levels,which together may be viewed as comprising pump level 3.

Of the main pump bands shown, the 0.81 and 0.75μm bands are the strongest[2]. The terminal laser level is 2111 cm^{-1} above the ground state, and thus the population is a factor of exp $(\_E/kT) \approx$ exp (-10) of the ground-state density. Since the terminal level is not populated thermally, the threshold condition is easy to obtain[3].

Because the lower level is well above the ground state, threshold condition is easily obtained, with relatively low pump power [2].

The upper laser level, $4F3/2$, has fluorescence efficiency greater than 99.5% and a fluorescence lifetime of 230μs.InFig. 1The fluorescence spectrum of Nd^{3+}in YAG near the region of the laser output with the corresponding energy levels for the various transitions also the absorption of Nd :YAG in the range 0.3 to 0.9μm is given in Fig. 2[4].

TABLE 1: Physical and optical properties of Nd: YAG [1].

Chemical formula	Nd :Y_3Al5O_{12}
Weight % Nd	0.725
Atomic % Nd	1.0
Nd atoms/cm^3	1.38×10^{20}
Melting point	1970°C
Knoop hardness	1215
Density	4.56 g/cm^3
Rupture stress	$1.3–2.6 \times 10^6$ kg/cm^2
Modulus of elasticity	3×10^6 kg/cm^2
Thermal expansion coefficient	
[100] orientation	$8.2 \times 10^{-6°}C^{-1}$, 0–250°C
[110] orientation	$7.7 \times 10^{-6°}C^{-1}$, 10–250°C
[111] orientation	$7.8 \times 10^{-6°}C^{-1}$, 0–250°C
Linewidth	120 GHz
Stimulated emission cross section	
$R_2 - Y_3\, \sigma = 6.5 \times 10^{-19}$ cm^2	
$4F_{3/2} - 4I_{11/2}\sigma = 2.8 \times 10^{-19}$ cm^2	
Fluorescence lifetime	230 μs
Photon energy at 1.06μm	$h\nu$= 1.86×10^{-19} J
Index of refraction	1.82 (at 1.0μm)

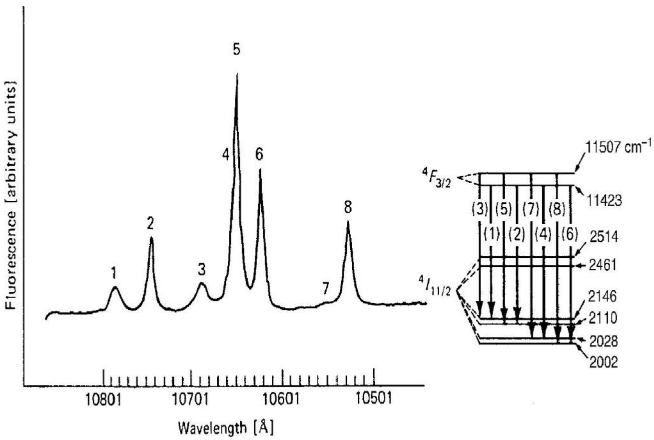

Fig. 1 Fluorescence spectrum of Nd^{3+}in YAG at 300K in the region of 1.06 μm [4].

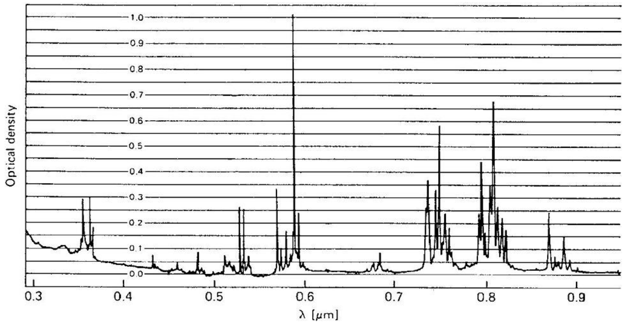

Fig. 2 Absorption spectrum of Nd:YAG from 0.3 to 0.9μm [4].

2. Spot size and divergence angle determination of 1.064μm beam

The "beam diameter" is defined as "the distance across the center of the beam for which the irradiance (I) equals $1/e^2$ of the maximum irradiance, ($1/e^2 = 0.135$). The "spot size (w)" of the beam is "the radial distance (radius) from the center point of maximum irradiance to the $1/e^2$ point". If a laser beam is centered upon a circular aperture, the fraction of beam power transmitted through the aperture (pinhole) is given by [5]:

$$T = 1 - e^{-2(r/w)^2} \quad \text{........ (1)}$$

Where; T = the Fractional transmission.

r = the radius of aperture (Pinhole).

w = the spot size (radius of beam at $1/e^2$ points) then;

$$w = \sqrt{\frac{2r^2}{\ln(\frac{1}{1-T})}} \quad \text{........(2)}$$

The beam diameter is determined by measuring the transmission of the beam through an aperture.The far-field beam divergence of a laser is the constant beam divergence angle at a large distance from the laser output aperture. Near the laser this beam divergence is not constant. Thus, measurement made in the near field cannot be used to predict Far-field behavior of the beam [6, 7]. The basic principle of beam-divergence measurement is that the wave front of a laser beam have the same shape at the focal point of a positive lens as in the far field [5, 6].Thus, measurements made at such a focal point are far-field measurements. The beam divergences are determined by measuring the beam diameter at the focal point of a positive lens and then calculating the divergence angle.

The chosen lens should have a focal length of at least 10 times the diameter of the beam at the lens to reduce spherical aberration. The experimental arrangement is illustrated in Fig. 3.

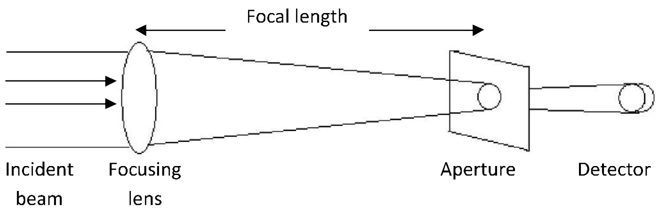

Figure3. Experimental arrangement for measuring beam divergence.

3. Experimental work

The Nd: YAG oscillator was a flash lamp pumped Q-switched. The flashlamp is electrically pulsed to produce a high value of radiation flux in a given spectral band. The type of flashlamp selected should be able to supply the maximum spectral output in the absorption bands of the laser rod [8, 9]. At such condition the flashlamp used to pump Nd: YAG rod, was a pulsed Xenon-gas filled lamp, having a 40-60% conversion efficiency of electrical input energy to optical radiant energy, and thus provides a better match to the absorption lines of Nd: YAG near 808 nm.

The flashlamp has 3.5mm inner diameter and 40 mm arc length. The power supply of the pulsed Nd: YAG is designed to store an electrical energy in the capacitor and to deliver that energy in the form of ignition electric pulse to the flash lamp in order to excite the active laser medium. A flashlamp power supply consists of high-voltage DC charging supply, used to charge the energy-storage capacitor to the proper operating voltage, a pulse-forming network (PFN) and a trigger circuit. The pulsed power supply was made to produce up to

750V output voltage to derive the flashlamp and controlled by a suitable variac transformer to obtain different input energy. The trigger circuit in our system is of external trigger type which provides about 10 kV via a trigger transformer kind (TR-80), delivers a trigger pulse to ionize the flashlamp gas and begin the discharge across a wire looped around the lamp(trigger wire). Q switching is a common technique to generate a pulse with peak power of short duration [10], to acts as a shutter inside the laser cavity. The Q-switching adopted here is a passive Q-switching storable absorber, dye foil of BDN-1 type (from ISKRA Co.).

We can design and construct the Nd: YAG power supply by taking into account many considerations in that purpose, such as the type, size of the flash lamp, the energy E_o to be discharged and the current pulse duration t_p, specified as the time between the points on the leading and trailing edges of the pulse at 10% of its peak amplitude, which must be lower than the lifetime of the Nd: YAG material upper laser state~230 µsec [7, 11].Accordingly, the power supply should be constructed by adopting the following equations, to get the value of capacitor C, inductor L, and charging voltage V to yield a critically damped case. These equations are [1, 12]:

$$C = (0.09 \times E_o \times t_p / K_o)^{1/3} \quad \text{.........} \quad (3)$$

$$L = t^2_p / 9C \quad \text{.........} \quad (4)$$

$$V = (2E_o / C)^{1/2} \quad \text{.........} \quad (5)$$

Where, K_o is the lamp-impedance parameter given by:

$$K_o = 1.28 \times \left(\frac{F}{G}\right)^{0.2} \times \frac{S}{d} \quad \text{.........} \quad (6)$$

Where F = the gas -fill pressure in torr.

G = a constant has the value of 450 torr for Xenon gas.

S = the arc length in mm.

d = the inside bore diameter in mm.

The resonator is a plane-parallel configuration, with 99% reflectivity for the back mirror and 35% reflectivity for the front mirror at the desired wavelength (1.064µm).The Nd: YAG rod of 4mm diameter and 50mm length. Fig.4shows a photograph of the Q-switched Nd: YAG laser.The pulse duration was determined by using a PIN Silicon photodiode type (SGD-100A) from (EG & G company), having a responsitivity equal to≈0.5 A/W and its rise time is 9 nsec.

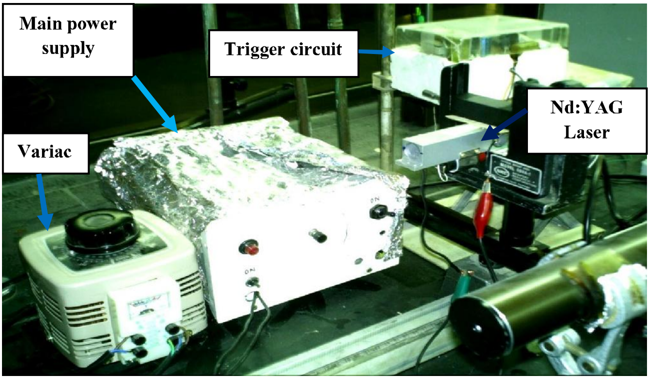

Figure 4. Photograph of the Q-switched Nd: YAG laser

Fig.5illustrated the output optical energy of the Nd:YAG laser as a function of the electrical pumped energy. The maximum output energy was obtained with 96.6 mJ.

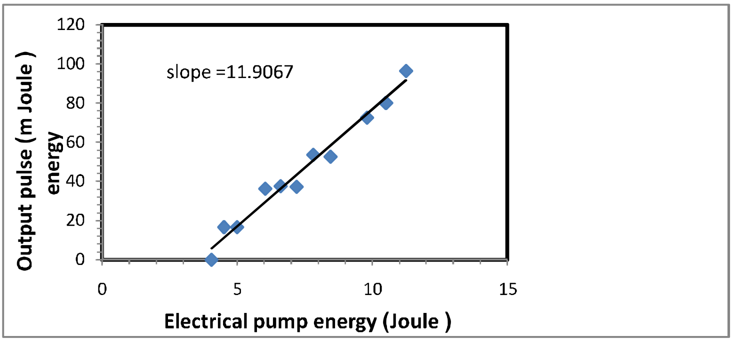

Figure 5. Output optical energy versus the electrical pump energy.

The signal was recorded by using a 100 MHZ storage oscilloscope type Tektronix model TDS220 and the pulse energy was measured by using a Joule meter type Gentec/Solo PE and Fig.6 represents the pulse duration of the output Nd:YAG laser.

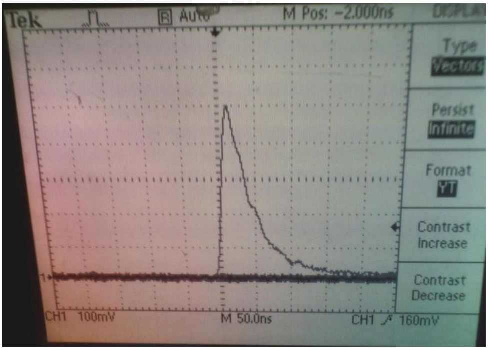

Figure 6. The Nd: YAG pulse duration (40 nsec at FWHM).

In the following we illustrate the procedure used experimentally to determine full-angle far field beam divergence and the diameter for 1.06μm laser output beam.

First of all we must get the diameter of focused spot size in order to introduce the divergence angle of the 1.064μm beam.In measuring the diameter of focused spot; a positive convex lens kind (BK-7) was used to focus the pump beam onto a calibrated aperture (pinhole), located at the focal plane of the lens. The two energy measurements, with the pinhole and without it, is then used in equation (2)to determine the diameter of the focused spot, then this diameter and the focal length of the lens are used in the following equation to determine the divergence angle of the 1.064μm beam[12,13].

$$\theta = \frac{d}{F} \quad \ldots\ldots\ldots\ldots \quad (7)$$

Where; d = Diameter of the focused spot.

F = Focal length of lens.

θ = Full-angle, far-field beam divergence.

and Table (2) shows the data extrapolated from these measurements.And in order to get the diameter of the 1.06µm laser beam we used the same procedure illustrated previously in the case of the diameter of the focused spot but without using a lens. Table (3) also shows these data with accordance to equation (2). It is well to note that all of these data were extrapolated by repeating the experiment different times to take the mean value and by removing the unexpected value.

Table 2: Values for focused spot size and beamdivergence angle for 1.064µm (by using a lens).

Lens Focal length(F)	**30 cm**
Radius of aperture (r)	**1 mm**
Energy with aperture and lens	**37.8 mJ**
Energy with aperture removed	**40 mJ**
Transmittance(T)	**0.947**
Diameter of focused spot(2 w) at $1/e^2$ points	**1.65 mm**
Full-angle, far field beam divergence(θ)	**5.5 mrad**

Table 3: Values for beam diameter at the $1/e^2$ points of 1.064 µm (without using a lens).

Radius of aperture (r)	**1 mm**
Energy with aperture	**19.4mJ**
Energy with aperture removed	**40 mJ**
Transmittance(T)	**0.486**
Beam diameter of at 1/e2 points(2 w)	**3.46mm**

Conclusion

The design, construction and operation of apulsed single shot passive Q-switched Nd:YAG laser system has been presented.We report a Q-switched Nd:YAG laser transmitter employing an oscillator-only design producing 96 mJ pulse output optical energy, 40 ns pulse width, characterized at a single shot with optical efficiencies of over 11.9%.The threshold electrical energy for getting the lasing action was about 4.51 Joule with 16.5 mJoule opticaloutput energy. In such system the peak power is about 2.4 Mwatt. The resulting output energy and the threshold energy for our system come approximately with the design consideration of the electrical and optical aspects in such system.Experimentally procedure isusedto determine the diameter of full-angle far field beam divergence and the diameter for 1.06μm laser output beam.

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