SPECTROSCOPIC PROPERTIES OF Nd:YAG LASER PUMPED BY FLASHLAMP AT VARIOUS TEMPERATURES AND INPUT ENERGIES

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Dedicated to my beloved family

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ABSTRACT

The purpose of this research was to investigate the temperature and energy input dependency of Nd:YAG laser performance pumped by flashlamp. A commercial laser rod Nd:YAG crystal was utilized as a gain medium. The laser rod was placed parallel to a linear flashlamp filled with xenon gas at 450 Torr. The Nd:YAG crystal together with the flashlamp were flooded with a coolant comprising of a mixture of 60% ethylene glycol and 40% distilled water which covers a range of temperature from -30°C to +60°C. Spectroscopic properties of the Nd:YAG rod under pulsed flashlamp pumping was investigated from the output fluorescence spectrum of the flashlamp radiation and the Nd:YAG rod. The linewidth of each fluorescence line was measured for estimation of effective emission cross section and saturation intensity. The influence of temperature and input energy on fluorescence emission cross section of Nd^{3+}:YAG crystal was studied. The cross section was found to decrease as the temperature and the input energy were increased. The inter-stark emission showed Lorentzian line shape indicating homogeneous broadening. This was attributed to the thermal broadening mechanism of the emission line. The spectral widths and shifts of the emission lines for the three and four level inter-Stark transitions within the respective intermanifold transitions of $^4F_{3/2}\rightarrow{}^4I_{9/2}$ and $^4F_{3/2}\rightarrow{}^4I_{11/2}$ were investigated over the range of 0 to 75 J. The emission lines for the $^4F_{3/2}\rightarrow{}^4I_{9/2}$ transitions shifted towards a longer wavelength and broadened, while the positions and linewidths for the $^4F_{3/2}\rightarrow{}^4I_{11/2}$ transitions remained unchanged with increasing input energy. Finally the temperature dependence of quasi three level laser transitions for long pulse Nd:YAG laser was also investigated. The laser performance at 938.5 nm and 946.0 nm were also found to be inversely proportional with temperature and the slope efficiency was unchanged to temperature. The reduction was due to the mechanism of phonon scattering as well as broadening effect as the temperature increases.

ABSTRAK

Tujuan penyelidikan ini ialah untuk mengkaji pergantungan suhu dan tenaga masukan terhadap prestasi Nd:YAG laser yang dipam dengan lampu kilat. Rod laser komersial kristal Nd:YAG digunakan sebagai medium perolehan. Rod laser diletakkan selari dengan lampu kilat linear yang mengandungi gas xenon pada tekanan 450 Torr. Kristal Nd:YAG bersama lampu kilat ditenggelamkan dalam penyejuk yang mengandungi campuran 60% etilena glikol dan 40% air suling yang meliputi suhu daripada -30°C hingga +60°C. Sifat spektroskopi rod Nd:YAG di bawah pengepaman lampu kilat denyut dikaji daripada spektrum pendarfluor keluaran sinaran lampu kilat dan rod Nd:YAG. Lebar garis setiap garis pendarfluor diukur untuk anggaran keratan rentas pancaran berkesan dan keamatan tepu. Pengaruh suhu dan tenaga masukan terhadap keratan rentas pancaran pendarfluor bagi kristal Nd^{3+}:YAG dikaji. Keratan rentas didapati berkurang apabila suhu dan tenaga masukan bertambah. Pancaran inter-Stark menunjukkan bentuk garis Lorentzian yang menandakan pelebaran homogen. Ini disebabkan oleh mekanisma pelebaran terma bagi garis pancaran. Lebar dan anjakan spektrum bagi garis pancaran peralihan tiga dan empat aras peralihan inter-Stark di antara peralihan pancarongga bagi ${}^4F_{3/2} \rightarrow {}^4I_{9/2}$ dan ${}^4F_{3/2} \rightarrow {}^4I_{11/2}$ dikaji meliputi julat 0 hingga 75 J. Garis pancaran bagi transisi ${}^4F_{3/2} \rightarrow {}^4I_{9/2}$ beranjak ke arah satu panjang gelombang yang lebih panjang dan melebar, sementara posisi dan lebar garis bagi transisi ${}^4F_{3/2} \rightarrow {}^4I_{11/2}$ tetap tidak berubah dengan pertambahan tenaga masukan. Akhirnya pergantungan suhu pada transisi laser kuasi tiga aras untuk laser Nd:YAG denyut panjang juga dikaji. Prestasi laser pada 938.5 nm dan 946.0 nm juga didapati berkadar songsang dengan suhu dan kecerunan kecekapan didapati tidak berubah. Pengurangan ini disebabkan oleh mekanisma serakan fonon dan kesan pelebaran spektrum apabila suhu meningkat.

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LIST OF ABBREVIATIONS

CCPS	-	Capacitor Charger Power Supply
FWHM	-	Full Width at Half Maximum of Amplitude
HR	-	High Reflectivity
IR	-	Infrared Radiation
LASER	-	Light Amplification of Stimulated Emission of Radiation
ND:YAG	-	Neodymium Yttrium Aluminum Garnet
OC	-	Output Coupler
PFN	-	Pulse Forming Network
RE	-	Rare Earth

LIST OF SYMBOLS

A_{21}	-	Spontaneous Emission Rate
$a(k)$	-	Annihilation Operator
$a^{+}(k)$	-	Creation Operator
B_{21}	-	Stimulated Emission Rate
B_{12}	-	Induced Absorption Rate
c	-	Speed Of Light In Vacuum
E	-	Energy Level
ΔE	-	Energy Level Difference
E_{out}	-	Output Laser Energy
E_{th}	-	Threshold Energy
ΔE^{strain}	-	Crystal Strain Broadening
ΔE^{D}	-	Direct One phonon Processes
ΔE^{M}	-	Multiphonon Decay Processes
ΔE^{R}	-	Raman Phonon
f	-	Fractional Population Coefficient
g_1	-	Degeneracy Of The Lower Level
g_2	-	Degeneracy Of The Upper Level
$g(\nu)$	-	Line Shape Function
g_0	-	The Small Signal Gain Coefficient
$g(sat)$	-	Saturated Gain Coefficient
G_m	-	Single-Pass Gain For Intensities Lower Than Saturation Intensity
h	-	Planck’s Constant
J	-	Joule
k_B	-	Boltzmann’s Constant
$H_{e\text{-}sp}$	-	Hamiltonian Of Single Phonon Transition

H_{ep}	-	Hamiltonian Of Raman Scattering
I_s	-	Saturated Intensity
L	-	Passive Losses Of The Cavity
L_m	-	Scattering, Diffraction and absorption Losses
M	-	Mass Of Crystal
n	-	Refractive Index
N	-	Population Of Atoms Or Ions
n_{av}	-	Number of phonons
Δn	-	Population Inversion
N_u	-	Total Population Of The Upper laser Level
N_0	-	Total Population Of The Lower Laser Level
N_g	-	Total Dopant Concentration
P_{in}	-	Electrical Input Power
$P_f(th)$	-	Emission Power Density At Threshold
Q_k	-	Normal Coordinates
R_{out}	-	Reflectivity Of The Output Coupler
S	-	Spontaneous Emission Rate
T	-	Temperature
t	-	Time
T_D	-	Deby Temperature
$U(v)$	-	Stimulating Radiation Field
u	-	Displacement Of The Lattice
V_{ep}	-	Energy Of The Electron-Phonon Interaction
W_e	-	Direct Phonon Emission
W_{sp}	-	Transition Rate of Single Phonon Absorption Or Emission
W_R	-	Transition Rate Of The Raman Scattering
W_a	-	Direct Phonon Absorption
W_P	-	Pumping Rate
v	-	Frequency
v_0	-	Center Frequency Of Transition Light
Δv	-	Bandwidth of Transition Line
v_t	-	Velocity Of Transverse Vibration Mode
v_l	-	Velocity Of Longitudinal Vibration Mode

$\delta(E)$	-	Thermal Shift
σ	-	Stimulated Emission Cross Section
τ	-	Radiation Lifetime
β	-	Branching Ratio
λ	-	Emission Wavelength
ε	-	Local Strain
η_1	-	Pump Efficiency
η_2	-	Pump Source Efficiency
η_3	-	Coupling Pump Light Efficiency
η_4	-	Power Absorption Efficiency
η_s	-	Slope Efficiency
γ	-	Total Losses Per Pass In The Cavity
δ	-	Internal Round Trip Cavity Losses
θ	-	Effective pumping Coefficient
NSP_i	-	The number of supporter nodes for master node i^{th}
NTJ_j	-	The total number of tasks of job j
N_{jd}^{p}	-	The maximum number of tasks of job j that can be submitted in provider node p of domain d
$n_{Ab\,i}$	-	The number of aborted tasks

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CHAPTER 1

INTRODUCTION

1.1 Overview

The word LASER stands for Light Amplification of Stimulated Emission of Radiation. The principle of the stimulated emission in addition to absorption and spontaneous emission was first introduced by Albert Einstein in 1916. He explained that in the presence of the field of excited photons, other atoms were stimulated to emit additional photons. The frequency of the emitted radiation was related to the difference in the atomic energy levels (Natarajan 2005).

Generally speaking, a laser constructed from three principle parts, a pump source, a gain medium, and an optical resonator which includes two or more mirrors, as shown in Fig. 1.

In this research xenon filled flashlamp was used as a pump source, because it is the most efficient gas at converting electrical energy to optical energy and it is cheaper than other gasses (Perlman 1966; Koechner 2006). The flashlamp power supply was based on the series simmer mode triggering method and energized the flashlamp with high energy. A Nd:YAG crystal is used as laser medium which is a neodymium (Nd^{3+}) doped yttrium aluminum garnet (YAG). The Nd:YAG can produce more than 30 laser lines in the near-IR spectral region (Koechner 2006).

An optical resonator was aligned in a simplest form contained two parallel mirrors placed in between the gain medium which provide feedback of the light. The mirrors were coatings to determine their reflectivity properties.

For terrestrial applications, laser systems are mainly used in temperature range from -60 to 60°C (Rapaport 2000). Other optical elements in a typical laser resonator (e.g. mirrors, beam splitters, etc) show no variation in optical properties over a wide range of temperature. However, ambient temperature and the heat generated by the gain medium of flashlamp pumping lead to thermal broadening and shifted of laser lines which seriously effect on gain amplification, threshold power, frequency stability, and thermal tunability of the lasers and obstruct the lasing performance (Sardar 1998; Sardar 2000; Rapaport 2002; Zhao 2005).

In this research laser performance of Nd:YAG laser pumped by flashlamp was investigated.

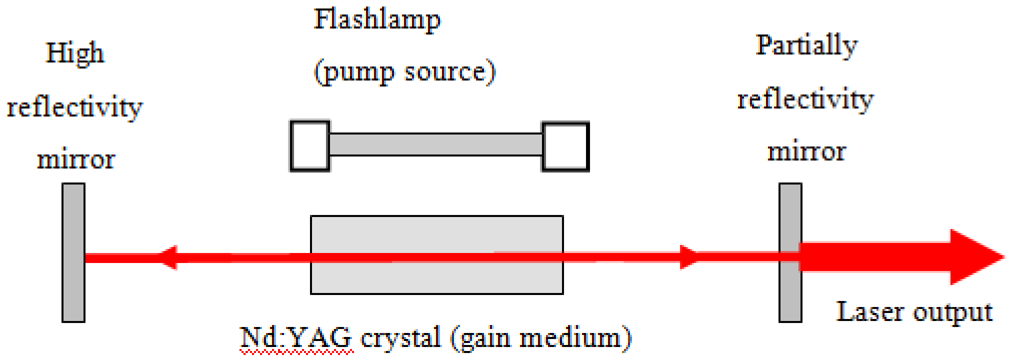

Figure 1.1 Schematic diagram of flashlamp pumped Nd:YAG laser .

1.2 Problem Statement

Nowadays most simultaneous generation of multi-wavelength are generated by diode pump solid state lasers. The drawbacks of these operations is that they are continuous or quasi continuous. These operations are difficult to control and in addition they have low peak power (Saiki 2011).

Furthermore in quasi three level lasers, in which the ground level has significant thermal population, laser transition suffering from significant re-absorption. This phenomenon increases the internal loss in the gain medium and therefore population inversion would emerge at strong pump intensities. As a result additional heat is generated on the crystal (Lupeia 2002; Eichhorn 2008).

Some parameters such as laser threshold, output power, internal loss, linewidth of the laser line are dependent on temperature, hence heat generation can dramatically influence the laser performance (Sardar 1998; Dong 2003; Dong 2005; Turri 2009). Furthermore in most high power solid state lasers variation of emission cross section with temperature has a serious affect on the laser performance. Consequently extra heat leads towards damaging optical components in intracavity and vary stability of the output energy over the temperature range of interest. Furthermore in increasing the power of the laser normally involve in increasing the pump power. To date no many works have been reported on the influence of temperature base on the voltage of falshlamp or the input energy of the laser. Therefore the novel work claimed from this study is dependent on these results.

1.3 Research Objective

Since Nd^{3+}:YAG laser performance is dependent on the temperature and pumping energy (Pourmand 2012) careful investigation on the phenomena of linewidths and shifts of several lines of $^4F_{3/2}\rightarrow{}^4I_{11/2}$ and $^4F_{3/2}\rightarrow{}^4I_{9/2}$ intermanifold transition lines is required. In addition changes of laser output energy with temperature also is a crucial issue in solid state laser materials.

Accurate information on temperature effects would be possible to deal with varying stability of the output energy over the temperature range of interest. Thus for investigation to achieve these objects, the following works was performed:

i. Investigation on spectroscopy properties of flashlamp and the Nd:YAG rod in different temperatures and input energies.

ii. Investigation on broadening effect and shifted of center line at different temperature and input energies.

iii. Estimation of stimulated emission cross section of the Nd:YAG quasi three level laser at different temperature and input energy.

iv. Align of an optical resonator to produce simultaneous generation of 938 and 946 nm wavelengths.

v. Characterize the performance of quasi three level laser transitions for long pulse Nd:YAG laser at various temperature.

1.4 Scope of Study

This study basically focused on both aspects, theoretical and experimental work based on Nd:YAG laser system. The system comprises of two parts. The first part is energizing a laser crystal and stabilizing the stimulating emission of fluorescence radiation. The second part is measurement of fluorescence and laser radiation by spectrometer.

A commercial laser rod Nd:YAG laser crystal is utilized as a gain medium. The doping level of the laser rod is 1 at. % with dimension of 4 mm in diameter and 70 mm in length. The laser rod is enclosed in a ceramic reflector. The laser rod is placed parallel to a linear flashlamp filled xenon gas at 450 Torr. The rod is excited using side pumping technique by a homemade power supply (Zainal 2010). The driver is triggered by simmer mode technique. A capacitor bank with capacitance of

150 μF is charged by maximum voltage of 1000 V thus the input energy is varied between 0 to 75 J.

Intensive emitted light by flashlamp dissipates heat to the laser rod and the flashlamp itself. Therefore the Nd:YAG crystal together with the flashlamp are flooded with a coolant comprised of the mixture of 60 % ethylene glycol and 40 % distilled water. Such particular coolant covers the range of temperature from -30 °C to +60 °C. A thermocouple is connected to the heat sink of alumina ceramic to measure the temperature of cooling system.

The fluorescence radiation after pumping is emitted at one end of the laser rod. The light is detected by a CCD camera. The spectroscopic properties were analyzed via a Wavestar version 1.05 software. The resolution of this detection system is 0.5 nm so it can resolve most of the transition lines appeared from the pumping rod.

The dual wavelength laser operation at 938 and 946 nm are generated simultaneously by using laser resonator mirrors precise coating at 946 nm with reflectivity at 75 %.

1.5 Significance of study

A variety of laser materials has been developed, among which the most standard host is the yttrium aluminum garnet (YAG). Owing to remarkable laser properties of Nd^{3+} doped YAG crystal, such as high mechanical strength, thermal conductivity, optical transparency over a wide spectral region, adequate fluorescence lifetime for storage energy and high stimulated emission cross section, it has been utilized for a long time in solid-state laser industry (Kumar 2004).

During the last decade wavelengths in the blue light region have attracted much attention because of their practical applications such as high density data storage, colour displays, Raman spectroscopy, underwater communication, high resolution printing and medical diagnostics. One important way to produce blue lasers is resulted from either second harmonic generation of 946.0 and 938.5 nm wavelengths or sum frequency generation of 946.0 with 938.5 nm in quasi three level Nd:YAG laser (Dimov 1991; Wang 1999) . Therefore the stimulated emission cross section and output energy for two lines of 938.5 and 946 nm were quantified as a function of temperature and input energy. These observations are new and may contribute towards new design architecture of quasi three level laser systems.

Therefore the stimulated emission cross section and output energy for two lines of 938.5 and 946 nm were quantified as a function of temperature and input energy. These observations are new and may contribute towards new design architecture of quasi three level laser systems. In addition a critical parameter in such a laser system design is a fundamental understanding of the temperature and input energy dependent mechanisms or material properties that ultimately contribute to a change in laser performance.

Several works have been done on spectroscopic properties and stimulated emission cross section of Nd:YAG crystals at the major line of 1064 nm pumped by diode lasers. However, to the best of our knowledge, few studies have been conducted on the main lines of quasi three level lines at 938 and 946 nm wavelengths induced by a flashlamp pumped Nd:YAG laser. Therefore, in this thesis we reported the experimental evidence that stimulated emission cross section of Nd:YAG crystal at these wavelengths was affected by the temperature and the input energy. In addition input energy dependency of intensity, linewidth and wavelength position of quasi three level and four level system transitions was investigated. However, to the best of our knowledge similar studies has not been reported up to now. Finally, in the present research simultaneous oscillation of dual wavelength Nd:YAG laser at 938 and 946 nm pumped by flashlamp was introduced. Besides, laser performance of quasi three level transitions at 938 and 946 nm versus temperature and input energy was studied.

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