DESIGN AND CONSTRUCTION OF A CW MODE ND:YAG LASER PROTOTYPE.

A THESIS SUBMITTED TO
THE GRADUATE SCHOOL OF NATURAL AND APPLIED SCIENCES
OF
MIDDLE EAST TECHNICAL UNIVERSITY

BY

ERTAN ERYILMAZ

IN PARTIAL FULFILLMENT OF THE REQUIREMENTS FOR THE DEGREE OF
MASTER OF SCIENCE
IN

PHYSICS

AUGUST 2004

Approval of the Graduate School of Natural and Applied Sciences

Prof. Dr. Canan Özgen
Director

I certify that this thesis satisfies all the requirements as a thesis for the degree of Master of Science

Prof. Dr. Sinan Bilikmen
Head of Physics Department

This is to certify that I have read this thesis and that in my opinion it is fully adequate, in scope and quality, as a thesis for the degree of Master of Science.

Assoc. Prof. Dr. Akif Esendemir
Supervisor

Examining Committee Members

Assoc. Prof. Dr. Akif Esendemir	(METU, PHYS)	
Dr. Ali Alacakir	(TAEK)	
Prof. Dr. Raşit Turan	(METU, PHYS)	
Assoc. Prof. Dr. Gülay Öke	(METU, PHYS)	
Assoc. Prof. Dr. Serhat Çakır	(METU, PHYS)	

I hereby declare that all information in this document has been obtained and presented in accordance with academic rules and ethical conduct. I also declare that, as required by these rules and conduct, I have fully cited and referenced all material and results that are not original to this work.

Name, Last name: Ertan, ERYILMAZ

Signature :

ABSTRACT

DESIGN AND CONSTRUCTION OF A CW MODE ND:YAG LASER PROTOTYPE.

Eryılmaz, Ertan
M.S, Department of Physics at Graduate School of Natural and Applied Sciences
Supervisor: Assoc. Prof. Dr. Akif Esendemir

August 2004, 67 pages

In this thesis a theoretical background of Nd:YAG lasers has been presented and key parameters of a design have been stated. Both pulsed mode and CW mode designs have been made; a 500mJ xenon flash lamp has been investigated as the pulsed light source and a 500W tungsten halogen lamp has been used as the continuous light source for optical pumping. Closed cooling system has been constructed. De-ionized water has been used as coolant. The goal has been acomplished by constructing a CW mode prototype. The output power has been calculated. Dependence of output power to the reflectivity of output coupler is simulated and optimum reflectivity is calculated. Theoretical emission bands of Nd:YAG have been observed experimentally.

Keywords: Laser, CW mode Nd:YAG, Pulsed mode Nd:YAG.

ÖZ

SÜREKLİ MODDA ÇALIŞAN ND:YAG LAZER TASARIMI VE PROTOTİP YAPIMI.

Eryılmaz, Ertan

Yüksek Lisans, Fizik Bölümü, Fen Bilimleri Estitüsü

Tez Yöneticisi: Doç. Dr. Akif Esendemir

Ağustos 2004, 67 sayfa

Bu tezde Nd:YAG lazerlerle ilgili teorik altyapı sunulmuş ve tasarım için anahtar parametreler belirlenmiştir. Darbeli mod ve surekli mod tasarimlari yapılmış; darbeli ışık kaynağı olarak 500mJ xenon flaş lamba incelenmiş ve sürekli ışık kaynağı olarak da 500W tungsten halojen lamba optik pompalamada kullanılmıştır. Kapali devre soğutma sistemi üretilmiştir. Soğutucu olarak deiyonize su kullanılmıştır. Sürekli modda çalışan bir prototip yapılarak amaca ulaşılmıştır. Çıkış gücünün çıkış aynası yansıtma oranına bağlılığı simule edilmiş ve en uygun yansıtma oranı hesaplanmıştır. Nd:YAG' teorik ışıma bantları deneysel olarak gözlenmiştir.

Anahtar Kelimeler: Lazer, Sürekli mod Nd:YAG, Darbeli mod Nd:YAG.

To my brother Altan Eryılmaz

He has always been with me and has supported me through my studies.

ACKNOWLEDGMENTS

It is a great chance for me to have family who have always loved me, grew me and supported me through my life.

I would like to express my deepest gratitude to my supervisor, Assoc. Prof. Dr. Akif Esendemir and Dr. Ali Alaçakır, for their guidance, advice, criticism, encouragement throughout the research and for valuable time that I have spent with them since the first days of 2002.

Special thanks to Deniz Bilge Temel who has helped me to start a new age in my life and permitted me to share this age with her.

Murat Aydın is gratefully acknowledged not only for his technical assistance but also for his motivation and support in my bad days.

Thanks to the Department of Physics of Middle East Technical University and head of the department Prof. Dr. Sinan Bilikmen for generous financial assistance to my thesis.

I would like to thank the members of Laser and Electro-Optics Laboratory: İlker Yıldız, R. Salur Kurucu, Necmettin Kenar, Mustafa Kurt, Hilal Göktaş, Gülsüm Başak Ballı and Başak Seçmen for the time we shared and for their positive attitude towards me and my loud friends.

TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

CHAPTER 1

INTRODUCTION

"Let there be Light!" According to an old testament, these are the first words spoken by God. The words emphasize the important role light plays in the process of creation. Historically, light has symbolized growth and vision. Who could have imagined that in the year 2000, light would be used for material removal, telecommunications, diagnostics, and as a host of other applications? Many of these applications have been made possible by the invention of the laser only 40 years ago.

The acronym LASER stands for "Light Amplification by Stimulated Emission of Radiation". Lasers are used in materials processing applications such as drilling, marking, cutting, welding, and altering surfaces and also used in medical subjects such as hair removal, surgery. Laser light has the features of being monochromatic (single wavelength), directional (low divergence), intense (high energy density), and coherent (all photons have the same phase relationship). These features bring the benefits of non-contact and selective material removal, flexibility, reduced cost, and higher processing speeds when used in a suitable application.

Laser light is generated in an optical resonator with minimum requirements of a lasing medium (gas, liquid or solid state host materials), a pump process to achieve population inversion and a resonator cavity to sustain oscillation. Lasing media can be gases

(CO_2 and excimer lasers), solids (diode and Nd:YAG Lasers) or liquids, although few industrial applications of lasers use liquid media. Most typical pump processes take electrical energy and convert it into a population inversion in the lasing medium. This is a condition necessary for laser activity, and it simply means there are more molecules excited to a specific upper state energy level than reside in the lower state energy level. Lasing can then be sustained in the resonator cavity by bouncing the photons off of two mirrors, one of which is less than 100% reflective and which therefore allows light to escape from the oscillator at a fixed rate. In addition, most lasers used for industrial machining deliver the light in high energy pulses that are generated at rates of from several hundred to many thousands of pulses per second.

The important parameters of lasers are the wavelength, pulse repetition rate, pulse length (for pulsed lasers), output energy, total output power, power stability, and beam profile. Different lasers emit from the infrared region of the spectrum well into the UV.

The wavelength is extremely important as light absorption in materials is primarily dependent on the wavelength of light. This fact allows the selectivity inherent in laser applications.

In pulsed lasers the pulse repetition rate influences how fast a job can be done, and therefore the cost. In general, the higher the pulse repetition rate, the lower the output energy for a given laser power, as $W = ER$ where W is the output power in Watts, E is the single shot output energy in Joules, and R is the pulse repetition rate in pulses per second.

The stability is important because long-term operation in an industrial setting requires reproducible results and control.

The pulse length is important as, for a given amount of laser energy, the shorter the pulse length, the higher the peak power on target. In general, the shorter the pulse length, the cleaner the processing in applications like welding.

The beam profile is very important as it determines how the photons are delivered to the parts. Some lasers have a Gaussian beam profile, meaning that the beam has axial symmetry and energy is concentric; increasing in density toward the middle of the beam, and they are generally used in a focal point machining mode. Other lasers, like the excimer, have wide, inhomogeneous beams that require more optical manipulation to get usable photons.

Nd:YAG lasers have a fundamental emission frequency of about 1 micron (10641nm), in the infrared, but through optical conversion techniques it is possible to convert this frequency to higher harmonics by doubling, tripling and even quadrupling the fundamental output. Many of the applications in this industry take advantage of this frequency conversion and use primarily the tripled output at 355 nm wavelength, in the near UV. This allows access to high energy UV photons which are cheaper than the photons acquired from excimer. Also, pulse frequency is many times higher than that of excimer (kilohertz as opposed to a few hundred Hertz with the excimer).

CHAPTER 2

THEORY OF Nd:YAG LASER

2.1. Nd^{3+} Lasers` Principles

Nd:YAG laser is a fundamental four-level laser where lasing takes place between $^4F_{3/2}$ and $^4I_{11/2}$ energy bands. Electrons are excited to the pump bands by absorption of photons from a powerful flashlamp or from a diode laser operating around 800 nm. This is the proper wavelength since the absorbing efficiency of Nd^{3+} is high at this level. The electrons rapidly relax to the upper laser level by phonon emission. Lasing then occurs on the $^4F_{3/2}$-$^4I_{11/2}$ transition. The electrons return to the ground state by rapid non-radiative decay by phonon emission. This process is illustrated in fig-2.1.

When the Nd^{3+} atoms are in thermal equilibrium, the population of the lower level will always be greater than the population of the upper level. Therefore, if a light beam is incident on the Nd^{3+} atoms, there will always be more upward transitions due to absorption than downward transitions due to stimulated emission. Hence there will be net absorption, and the intensity of the beam will diminish on progressing through the medium of Nd^{3+} atoms. This is the process that satisfies an increase in the population of upper levels.

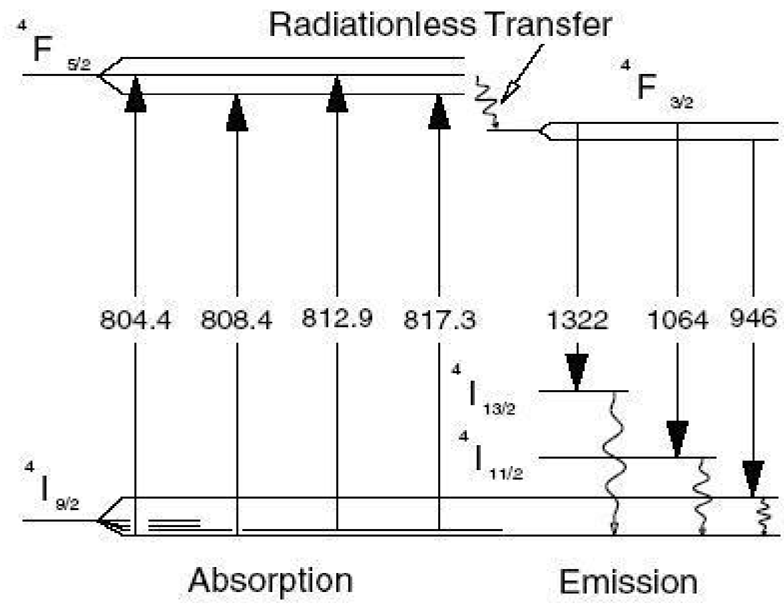

Figure-2.1.: Absorption and emission levels of Nd:YAG

The population inversion process is achieved by means of pumping sources like xenon flash lamp, arc lamp or diode lasers. Before pumping the population at thermal equilibrium is like Planck's probability distribution fig-2.2.a.

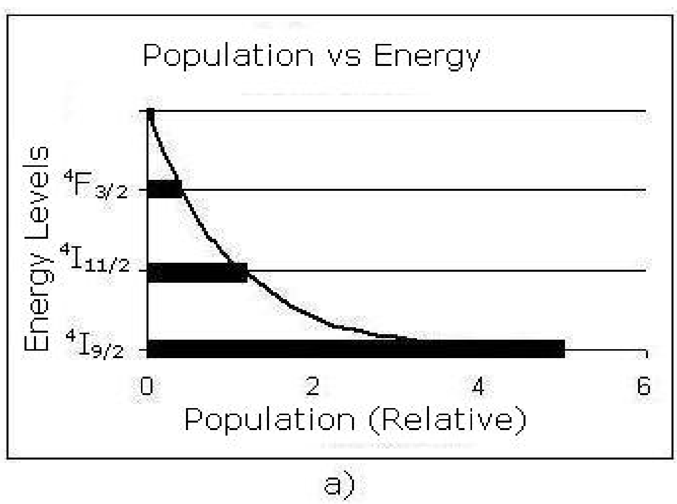

Figure-2.2a: Population vs. Energy bands before population inversion

With the pumping source the higher energy levels are populated so that the population distribution is converted fig-2.2.b. By making spontaneous emissions Nd^{3+} atoms turn to their ground levels.

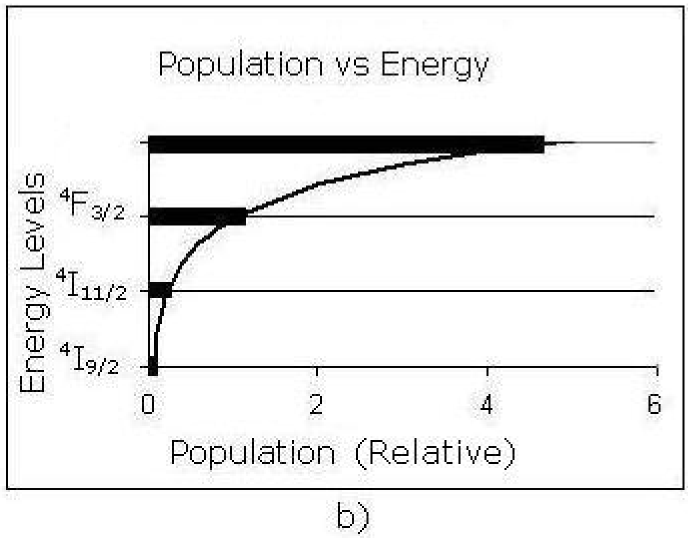

Figure-2.2b: Population vs. Energy bands after population inversion

Amplifying the beam requires that the rate of stimulated emission transitions exceeds the rate of absorption (threshold condition). This implies that $N(^4F_{3/2})$ must exceed $N(^4I_{11/2})$. This is a highly non-equilibrium situation.

Population inversion is the gain mechanism for Nd^{3+} laser. The transition rates of spontaneous emission, stimulated emission and absorption are:

Spontaneous emission;

$(^4F_{3/2} \text{->} {}^4I_{11/2})$: $dN^4F_{3/2}/dt = dN^4I_{11/2}/dt = A_{21} N\,^4F_{3/2}$ 2.1

Stimulated emission;

$({}^4F_{3/2} \rightarrow {}^4I_{11/2})$: $dN^4F_{3/2}/dt = dN^4I_{11/2}/dt = B_{21}N^4F_{3/2}u(v)$ 2.2

Absorption;

$({}^4F_{3/2} \rightarrow {}^4I_{11/2})$: $dN^4I_{11/2}/dt = dN^4F_{3/2}/dt = B_{12}N^4I_{11/2}\, u(v)$. 2.3

Where *u(v)* is the energy density of the light at frequency *v* and A, B are Einstein coefficients.

The relation between Einstein coefficients are:

$$B_{12}N^4I_{11/2}u(v) = A_{21}N^4F_{3/2} + B_{21}N^4F_{3/2}u(v) \qquad 2.4$$

In thermal equilibrium at temperature T population ratio of energy levels:

$$\frac{N^4 I_{11/2}}{N^4 F_{3/2}} = \frac{g_2}{g_1}\exp\left(-\frac{hv}{kT}\right) \qquad 2.5$$

g_2 and g_1 are degeneracies of levels ${}^4F_{3/2}$ and ${}^4I_{11/2}$. Using Planck's blackbody radiation formula it can be written that

$$g_1 B_{12} = g_2 B_{21}$$
$$\frac{A_{21}}{B_{21}} = \frac{8\pi h v^3}{c^3} \qquad 2.6$$

Einstein's analysis considered the interaction of an ideal atom with a featureless white light spectrum. In practice the interaction of real atoms with sharp emission lines with an even narrower band of light that will eventually become the laser mode will be interested.

The interaction between an atom with a normalized line shape function g(v) and a source of light whose emission spectrum is much narrower than the spectral line width of the atomic transition will be considered. In this case, the rates of absorption and stimulated emission are modified to equation 2.7 respectively[1].:

$$W_{12} = B_{12}N^4I_{11/2}u(v)\ g(v)$$

$$W_{21} = B_{21}N^4F_{3/2}u(v)\ g(v) \qquad 2.7$$

The light source is considered to have a delta function spectrum at frequency v with total energy density u(v) per unit volume. u(v) is related to the intensity *I* of the optical beam by[1]

$$I = u(v)c/n \qquad 2.8$$

where *n* is the refractive index of the medium. This means that the net stimulated rate downwards from level $^4F_{3/2}$ to level $^4I_{11/2}$ is given by[1]

$$W_{21net}=(N^4F_{3/2}-N^4I_{11/2})B21xg(v)xIxn/c \qquad 2.9$$

it is assumed that the levels are non-degenerate so that $B_{12}=B_{21}$.

For each net transition a photon of energy *hv* is added to the beam. The energy added to a unit volume of beam per unit time is thus W_{21net} *hv.* Consider a small increment of the light beam inside the gain medium with length *dx*. The energy added to this increment of beam per unit time is $W_{21net}hvdx$ *times (cross section area of* *beam)*. Remembering that the intensity equals the energy per unit time per unit area, we can write[1]:

$$dI = W_{21net}\, h\nu\, dx$$

2.10

$$dI = (N^4F_{3/2} - N^4I_{11/2}) B_{21}\, g(\nu)\, h\nu\, I\, (n/c)\, dx$$

The gain mechanism is illustrated in fig-2.3.

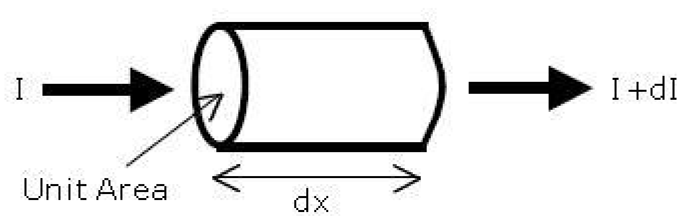

Figure-2.3: Gain in laser medium

Than the gain coefficient y can be given by[1]:

$$y(\nu) = (N^4F_{3/2} - N^4I_{11/2}) B_{21}\, g(\nu)(n/c)h\nu \quad 2.11$$

This result shows that the gain is directly proportional to the population inversion, and also follows the spectrum of the emission line. By expressing B_{21} in terms of A_{21}, we can re-write the gain coefficient in terms of the natural lifetime t $(=A_{21}^{-1})$ as[1]

$$y(\nu) = (N^4F_{3/2} - N^4I_{11/2})\, \lambda^2\, g(\nu) / (8\Pi n^2 t) \quad 2.12$$

where λ is the wavelength of the emission line. This is the required result. Eq.2.12 tells how to relate the gain in the medium to the population inversion using experimentally measurable parameters: λ,t, n and g(v).

The gain coefficient y is defined by[1]

$$I(x) = I(0)e^{yx} \quad 2.13$$

Thus the intensity grows exponentially within the gain medium fig-2.4.

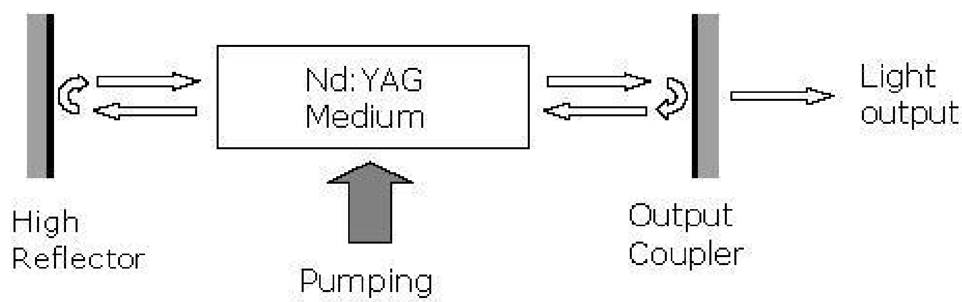

Figure-2.4: Gain process, resonator and Nd:YAG medium

Light, in the cavity, passes through the gain medium (Nd:YAG) and is amplified. It then bounces off the end mirrors and passes through the gain medium again, getting amplified further. This process repeats itself until a stable equilibrium condition is achieved when the total round trip gain balances all the losses in the cavity. Under these conditions the laser will oscillate. The losses are from output coupler(useful), from absorption in the optical components (including the laser medium), scattering, and the imperfect reflectivity of the other mirror(useless).

2.2. YAG as a Host Medium

The properties of Nd:YAG makes it the most preferred type of solid-state laser medium. "Neodymium-doped Yttrium Aluminum Garnet" has properties favorable for laser operation. The host YAG has good optical quality, is hard and has a good thermal conductivity. It has a cubic structure which yields a narrow fluorescent linewidth. This narrow fluorescent linewidth results in high gain and low threshold for laser operation. In addition, in Nd:YAG, since neodymium substitutes for yttrium no charge compensation is required [2].

2.2.1. Physical Properties

The YAG structure is stable in a large temperature range; from low temperatures to melting point. The hardness of YAG is high enough that while fabricating no serious breakage problems occur[2].

$Y_3Al_5O_{12}$ is optically isotropic and colorless crystal, and has a cubic structure. In Nd:YAG 1% of Nd^{3+} substitute Y^{3+}. Since the radius of Nd^{3+} and Y^{3+} are different (3%) large doping concentration of Nd^{3+} is not possible. This is limited by either the solubility limit of Nd^{3+} or the distorted lattice of YAG. Some of the physical properties of YAG are listed in table 2.1 and 2.2 together with optical properties [2].

Table 2.1.: Optical Properties of Nd:YAG

Linewidth	4.5^0A
Stimulated emission cross section	$\sigma_{12}=6.5\text{x}10^{-19}\text{cm}^2$
Relaxation time ($^4I_{11/2} \rightarrow {}^4I_{9/2}$)	30ns
Radiative lifetime ($^4F_{3/2} \rightarrow {}^4I_{11/2}$)	550μs
Spontaneous fluorescence lifetime	230μs
Photon energy at 1.06μm	hv = $1.86\text{x}10^{-19}$J
Index of refraction	1.82 (at 1.0 μm)
Absorption coefficient	0.03cm^{-1}

Table 2.2: Physical Properties of Nd:YAG

Chemical formula	Nd: $Y_3Al_5O_{12}$
Weight % Nd	0.725
Atomic % Nd	1
Nd atoms/cm^3	$1.38 \text{ x } 10^{20}$
Melting point	1970 C
Knoop hardness	1215
Density	4.56g/cm^3
Rupture Stress	$1.3\text{-}2.6 \text{ x } 10^3 \text{ kg/cm}^2$
Modulus of elasticity	$3 \text{ x } 10^3 \text{ kg/cm}^2$
Thermal expansion coefficient	
[100] orientation	$8.2\text{x}10^{-6} \text{ C}^{-1}$, 0-250 C
[110] orientation	$7.7\text{x}10^{-6} \text{ C}^{-1}$, 10-250 C
[111] orientation	$7.8\text{x}10^{-6} \text{ C}^{-1}$, 0-250 C

2.2.2. Laser Properties

The energy level diagram of Nd:YAG laser is illustrated in fig-2.1. The 1064nm wavelength laser transition originates from R_2 component of $^4F_{3/2}$ level and terminates Y_3 level of $^4I_{11/12}$ level. Due to Boltzmann distribution, at room temperature only 40% of $^4F_{3/2}$ population is at R_2. The rest is at R_1. The lasing level is R_2 and R_2 population is replenished by R_1 with thermal transitions. The ground level is $^4I_{9/2}$. The pump bands 0.81μm and 0.75μm are the strongest. The terminal laser level is 2111cm^{-1} above the ground level [3]. Since the terminal level is not populated thermally the threshold condition is easy to obtain [2].

The upper laser level's ($^4F_{3/2}$) fluorescence efficiency is greater than 99.5% [3] and radiative lifetime of 230μs [4]. The branching ratio from $^4F_{3/2}$ is [2];

$$^4F_{3/2} \rightarrow {}^4I_{9/2} = 0.25$$
$$^4F_{3/2} \rightarrow {}^4I_{11/2} = 0.60$$
$$^4F_{3/2} \rightarrow {}^4I_{13/12} = 0.14$$
$$^4F_{3/2} \rightarrow {}^4I_{15/2} < 0.01 \qquad 2.14$$

The branching ratio shows that all the ions are transferred to the pump bands from the ground level and 60 percent of the ions at the upper laser level cause fluorescence at the $^4I_{11/2}$ level[2].

2.2.3. Thermal Properties of Nd:YAG

The thermal properties of Nd:YAG is illustrated in table 2.3 [7].

Table 2.3: Thermal Properties of Nd:YAG

Property	Units	300K	200K	100K
Thermal conductivity	$W\ cm^{-1}\ K^{-1}$	0.13	0.21	0.58
Specific heat	$W\ s\ g^{-1}\ K^{-1}$	0.59	0.43	0.13
Thermal diffusivity	$cm^2\ s^{-1}$	0.046	0.10	0.92
Thermal expansion	K^{-1}	7.5	5.8	4.25
$\partial n/\partial T$	K^{-1}	$7.3x10^{-6}$	---	---

2.2.4. Different Laser Transitions

Under normal operating conditions Nd:YAG laser oscillates on the strongest $^4F_{3/2} \rightarrow {}^4I_{11/2}$ transition at 1064nm. But it is possible to obtain oscillations at other wavelengths by using a dispersive prism in the resonator, by using a specially designed resonant output coupler [5] or by using a highly selective dielectrically coated mirrors [6]. By using these elements it is possible to suppress undesired oscillations and provide suitable conditions for the oscillations at desired wavelengths. With these techniques over 20 transitions have been in made in CW mode, table 2.4 [2].

Table 2.4: Main room temperature transitions of Nd:YAG

	Wavelength (μm)	Peak effective cross section [10^{-19} cm^2]	Measured CW laser threshold
$^4F_{3/2} \rightarrow {}^4I_{9/2}$	0.939	0.81	
	0.946	1.34	
$^4F_{3/2} \rightarrow {}^4I_{11/2}$	1.0520	3.1	2.08
	.	.	
	1.0641	8.80	1.00
	.	.	
	1.1225	0.72	2.36
	1.319	1.50	1.60
$^4F_{3/2} \rightarrow {}^4I_{13/12}$	1.335	0.92	
	1.357	0.88	

2.3. Optical Pumping

The primary objective in the application of pump sources is to convert electrical energy to radiation and to generate high radiation fluxes in desired spectral bands. There are several of optical pump sources for solid state lasers. These sources may be

i) Noble gas discharge lamps,
ii) Metal vapor discharge lamps,
iii) Filament lamps,
iv) Semiconductor diodes

or even sun can be used as an optical pump source. These pump sources can be either linear or helical. The geometry of the pumping source determines the resonator cavity design.

The main parameter in choosing a pump source is the emission spectra of the source. In order to have high output efficiency the spectral emission of the source must be suitable to the spectral absorption bands of the Nd:YAG crystal. The spectral absorption of Nd:YAG is shown in fig-2.5 [8].

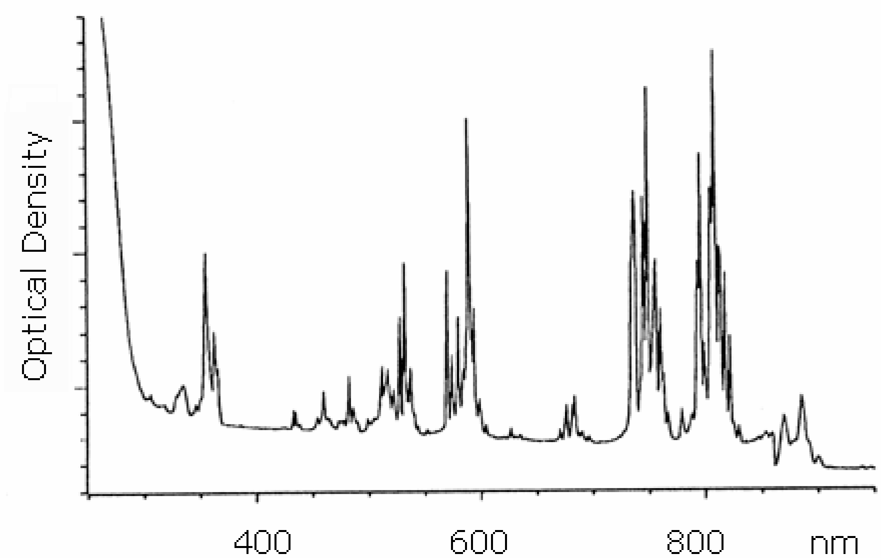

Figure-2.5: Spectral absorption of Nd:YAG

Also, the operation mode of the laser is a very fundamental parameter in choosing the pump source. Nd:YAG laser can both be operated in pulsed mode and in CW mode. For pulsed mode operation flash sources are necessary whereas for CW mode operation arc lamps or tungsten halogen lamps are suitable.

2.3.1. Flash Lamps

Flash lamps are used in pulsed Nd:YAG lasers. This sort of lamps is filled with noble gases. The geometry of flash lamp is generally linear. Helical types are also used fig-2.6 [8]. Standard linear lamps have long discharge tubes with wall thickness of 1mm-2mm, bore diameters varies between 3mm to 19mm, and lengths from 5 cm up to 1 m. Flash lamps are filled with noble gasses like xenon at pressure of 300 to 700 torr. The reason why xenon is used is because of its efficiency; it gives higher radiation energy for a given electrical energy than other gasses [2].

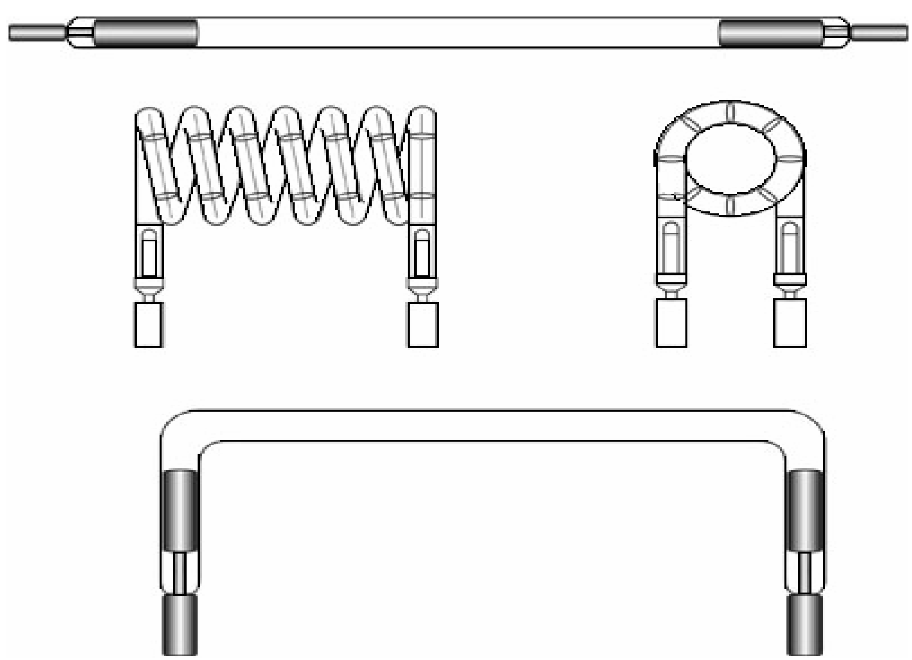

Figure-2.6: Flash lamps with various geometries.

2.3.1.1. Electrical Characteristics of Flash Lamps

All electrical discharges in gaseous media, including flashlamps and arc lamps, have common characteristics. At low values of voltage applied to the gas, there is no current flow. When the voltage is increased, the current remains essentially zero until some relatively high voltage is reached, at which point a very small current begins to flow because of a small amount of ionization that is always present. This current increases slowly until a point called the breakdown voltage is reached. This is the value at which a large number of gas molecules become ionized. The conductivity of the gas is increased and the electrons are accelerated to the velocities at which they can ionize more molecules through collisions. Thus, as the current increases, the resistance of the gas decreases and the voltage required to sustain the discharge actually decreases with increasing current. This is a condition called negative resistance.

The impedance characteristics of a flashlamp determine the energy-transfer efficiency from the capacitor bank to the lamp. The impedance is a function of time and current density. Flashlamp electrical characteristics can be discussed in three distinct areas of operation, which occur sequentially as the electrical discharge through the lamp develops.

The electrical characteristics of flashlamps are characterized by three different operating regimes.

2.3.1.2. Triggering

Triggering is the initiation of an electrical discharge in the gas contained in the flashlamp. The triggering begins with a spark streamer that crosses the gap between the electrodes and creates a conductive path between them. The voltage drop across this path should be less than the voltage supplied by the external circuit, so current will begin to flow through the lamp. Triggering must be reliable and repeatable. The triggering system initiates the arc as a thin streamer of current flow between the electrodes.

2.3.1.3. Unconfined Discharge

After the flashlamp is triggered, a relatively low value of current flows through the gas. The resistance of the gas is still relatively high, and the electrical discharge undergoes expansion. The discharge in this regime is still a streamer, not filling the lamp, and is said to be unconfined.

The discharge region then begins to expand. As the power supply drives the lamp through this regime, the current increases and the resistance of the lamp drops. The streamer grows in diameter until it fills the tube. The expansion time is fast, usually taking 5 to 50 microseconds. The time for the expansion depends on the amount of charge available from the power supply. In the region of unconfined expansion, the presence of the walls of the envelope exerts little or no influence on the characteristics of the discharge [8]. During this phase, the lamp resistance decreases rapidly as a function of time, as Fig-2.7 illustrates this situation.

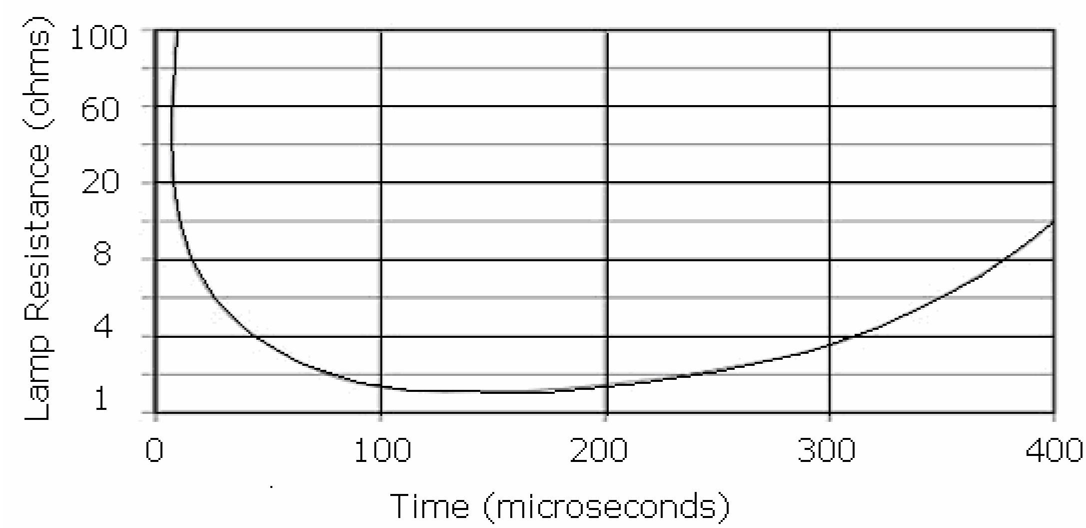

Fig-2.7: Typical behavior of the electrical resistance of a small flashlamp during a current pulse with duration of a few hundred microseconds[8].

The rapid decrease in resistance arises from the increasing ionization of the gas and the radial expansion of the plasma.

2.3.1.4. Wall-Stabilized Plasma Regime

This is the most important regime, since it encompasses most of the duration of the pulse and covers the period when most of the light is emitted.

This regime is characterized by high values of current flow. It is encountered only in pulsed operation because of the high current density. The values of current for continuous-arc lamps are much lower. In this regime of flashlamp operation, the plasma has expanded to fill the tube, or may still be expanding, but at a rate influenced by its distance from the wall. The plasma is stabilized by the proximity of the wall. The current-voltage relation in this regime is a very important characteristic, because it establishes the requirements for properly selecting a flashlamp. It also strongly influences the design of the circuits for driving the flashlamp.

Simplified approximations that yield acceptable working parameter for the time-dependent functional relationship between voltage and current in a flashlamp are [8]:

$$V = \pm K_0 \times I^{1/2} \qquad 2.15$$

This may be used in circuit-design calculations. Where K_0 is called the lamp-impedance parameter. It has the units of [ohm-ampere$^{1/2}$]. It describes the characteristics of the impedance for a particular lamp and depends on the lamp dimensions and the gas fill.

The lamp-impedance parameter is given by the equation:

$$K_0 = 1.28 \times (F/G)^{0.2} \times (S/d) \qquad 2.16$$

where F is the gas-fill pressure in torr, G has the value 450 for xenon and 850 for krypton, S is the arc length in millimeters, and d is the inside bore diameter in millimeters[8]. Values of K_0 are specified in some manufacturers' data sheets. The value of K_0 may also be measured by flashing the lamp at some reasonable energy loading and monitoring the voltage and current at some time during the pulse.

As it is seen, the electrical resistance of the lamp is a function of time during the pulse, starting at very high values, dropping rapidly during the early stages of the pulse to a low value (perhaps one ohm or so), and then increasing toward the end of the pulse. The value of the resistance may be one or a few ohms during the wall-stabilized regime. The typical behavior of the electrical resistance of a flashlamp during a pulse lasting a few hundred microseconds has been shown in Fig-2.7. This nonlinear behavior of the resistance will affect the design of the power supply.

The electrical resistance, *R(t)*, of a flashlamp [8] as a function of time, *t*, is a function of the electrical current, *I(t)*, the lamp inside diameter, *d*, and the lamp length, *L*, between electrodes according to:

$$R(t) = 1.28\,(L/d)\,[I(t)]^{-1/2} \qquad 2.17$$

Thus the behavior shown in the figure is dominated by the variation of the electrical current as a function of time. The pulse shape for the current for a typical flashlamp pulse with duration of a few hundred microseconds is shown in Fig-2.8. One of the functions of the power supply is to supply this current pulse.

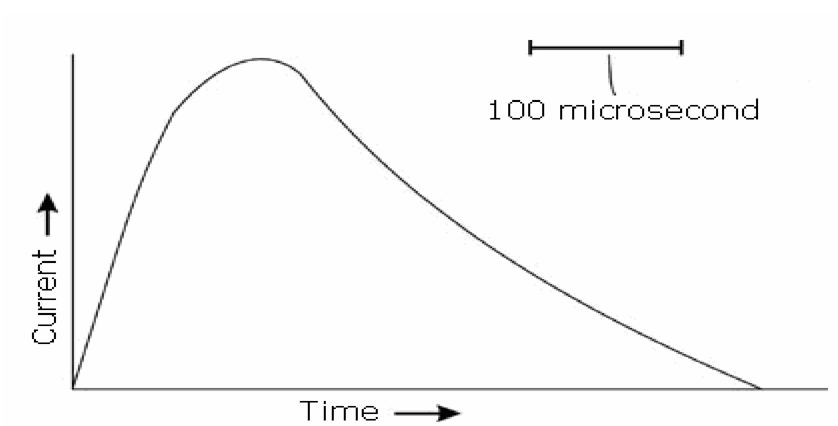

Figure-2.8: Typical waveform for a flashlamp current pulse lasting a few hundred microseconds.

2.3.2. Tungsten Halogen Lamps

In order to construct a CW mode Nd:YAG laser krypton arc lamp or quartz halogen (tungsten) lamps can be used. Although krypton arc lamps have more suitable spectral emissions, they are expensive and they require special and expensive power supplies. Tungsten halogen lamps are quite cheap and they can be run with a simple DC power supply or even house line can be used.

A tungsten halogen lamp converts electrical energy to optical energy by a physical process known as halogen cycle fig-2.9.

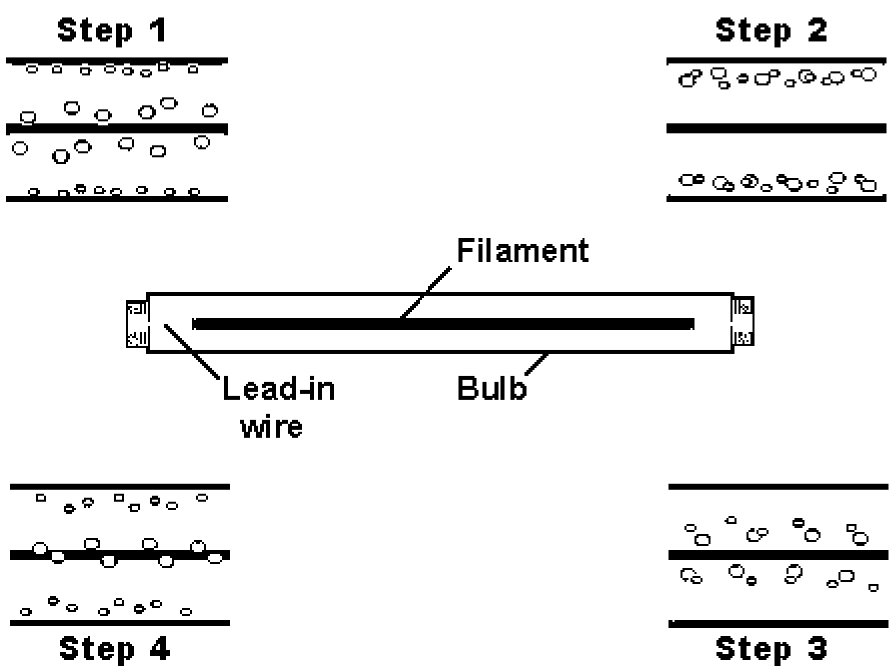

Figure-2.9: Tungsten halogen lamp and halogen cycle.

The halogen cycle describes a complex chemical interaction between tungsten, oxygen and a halide that makes tungsten halogen lamps. The steps below describe this physical phenomenon [11].

Tungsten atoms evaporate from the hot filament and diffuse toward the cooler bulb wall. The filament temperature is about 3030º Celsius (or about 5480º Fahrenheit). The temperature at the bulb wall is about 730º C (or about 1340º F).

Tungsten, oxygen and halogen atoms combine on or near the bulb-wall to form tungsten oxyhalide molecules.

Tungsten oxyhalides remain in a vapor phase at the bulb-wall temperatures and this vapor moves toward the hot filament. A combination of diffusion and convection currents is responsible for the movement.

High temperatures near the filament break the tungsten oxyhalide molecules apart. The oxygen and halogen atoms move back toward the bulb wall and the tungsten atoms are re-deposited on the filament. The cycle then repeats.

CHAPTER 3

DESIGN AND CONSTRUCTION

3.1. System Overview

The basic parts of overall laser can be listed as:

1. Resonator,
2. Power Unit,
3. Cooling Unit. T

the block diagram of a typical laser is shown in fig-3.1.

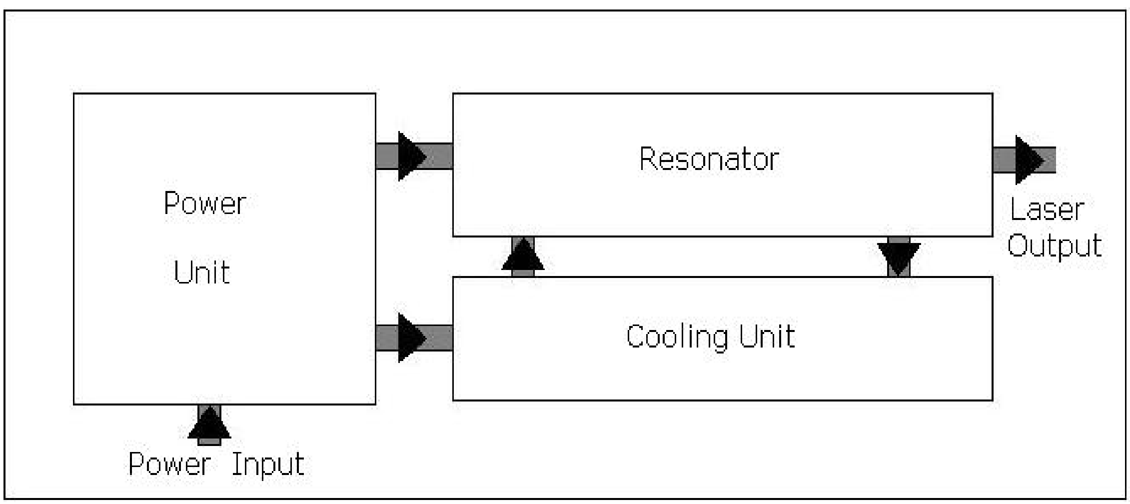

Figure-3.10: Block diagram showing a typical laser

The power unit of the laser is responsible for delivering optical power to the resonator. This power must be meaningful for the Nd:YAG rod in the resonator. The type of the optical pumping tool that is quartz-halogen lamp in this system or xenon flash lamp for pulsed system and its spectral emission is important. The power unit must be able to supply enough electrical power to the lamps. Other responsibility of the power unit is that it should feed the cooling unit.

In CW operation, the power unit is composed of two power supplies. One is a variable DC supply for the quartz halogen lamp and the second one is an AC supply for the cooling unit.

In pulsed operation the cooling system supply is the same as in the CW operation, but flash lamp requires a special supply unit and intense care in design.

The resonator is a basic two mirrored stable one with an elliptical reflective cavity. Elliptical geometry is used to increase optical pumping efficiency which will be discussed later.

The cooling unit is a part of the system in which special care is needed in its design. The coolant in this laser is de-ionized water because it contains no residues, impurities that can harm the rod and light source. Water cooling is necessary since the power dissipated as heat is high. This heat must be removed from the system in order to have stable laser output and long life time.

3.2. Resonator

In the laser a classical two mirrored, stable, hemispherical resonator is used. The back reflector is a concave mirror with a radius of 2 meters while the output coupler is a plane mirror; fig-3.2. Such cavities are the most commonly used in commercial lasers as they yield an excellent combination of good power, ease of adjustment, stability once aligned and good mode control.

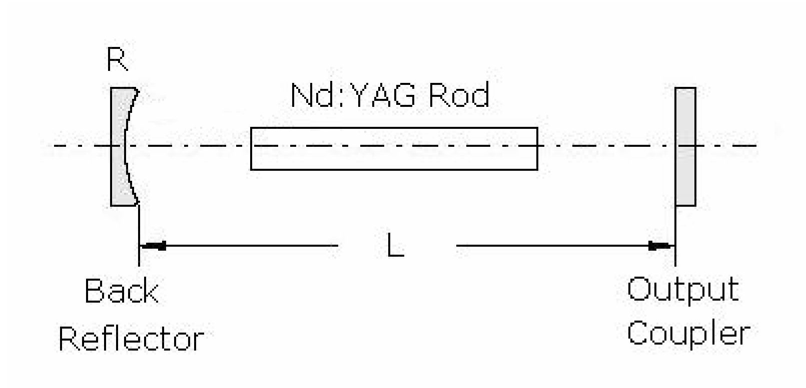

Figure-3.11: Hemispherical resonator. R= 2.0 m.

When flat mirror is placed approximately at the center of the curvature of the sphere, the resultant mode has a relatively large diameter at the spherical mirror and focuses to a diffraction-limited point at the plane mirror. In practice if the mirror separation L is slightly less than R the resultant diffraction losses becomes small [9].

3.2.1. Mirrors

The mirrors used in the resonator are a high reflective, 2 meters of radius concave back reflector and a flat output coupler. The mirrors are responsible for sustaining oscillations.

3.2.1.1. Back Reflector

The back reflector is Laser Components GmbH HR1064 SM1-2.00C high reflective mirror. It is concave with radius of 2.00 meters. The diameter of the mirror is 1.0”. Its reflectivity is almost %100.

3.2.1.2. Output Coupler

The output coupler is Laser Components GmbH PR1064/95/AR PW0537C mirror. This mirror is flat in both sides. The outer side has an antireflective coating. The inner side has a coating which makes the whole mirror 5% transparent. The diameter of the mirror is 0.5”.

3.2.2. Elliptical Cavity

One important parameter that affects the efficiency of the laser is the optical pumping efficiency. Optical pumping efficiency is the ratio of light targeting the laser rod to the light emitted from the light source. In order to increase the optical pumping efficiency the cavity must have an optimum geometrical design. There are various designs which depend on the rod, lamp geometries and cooling requirements fig-3.3.

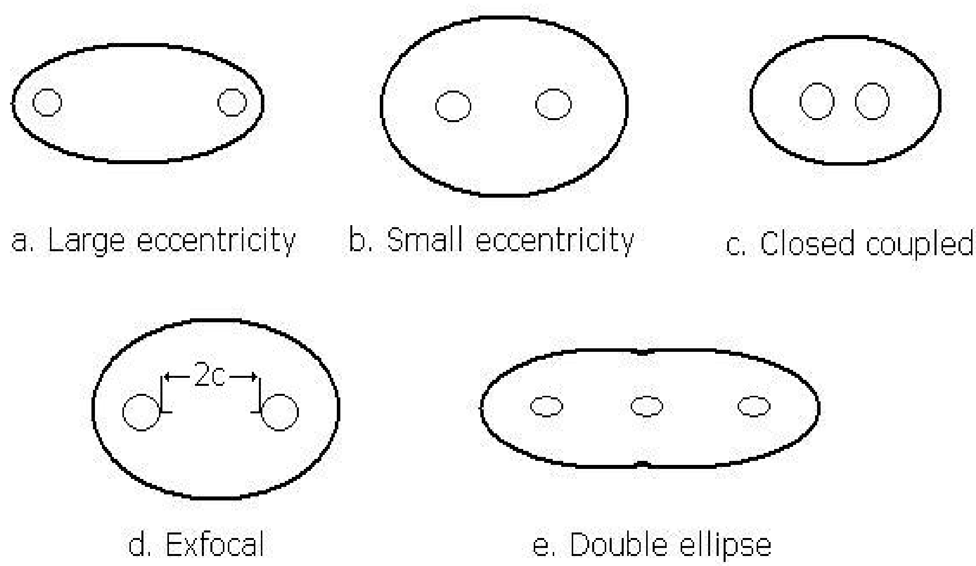

Figure-3.12: Elliptical pump cavities.

The reason to choose elliptical pump cavities is because an ellipse has two focal points. Any ray passing through one focal point also passes from the other focal point fig-3.4.

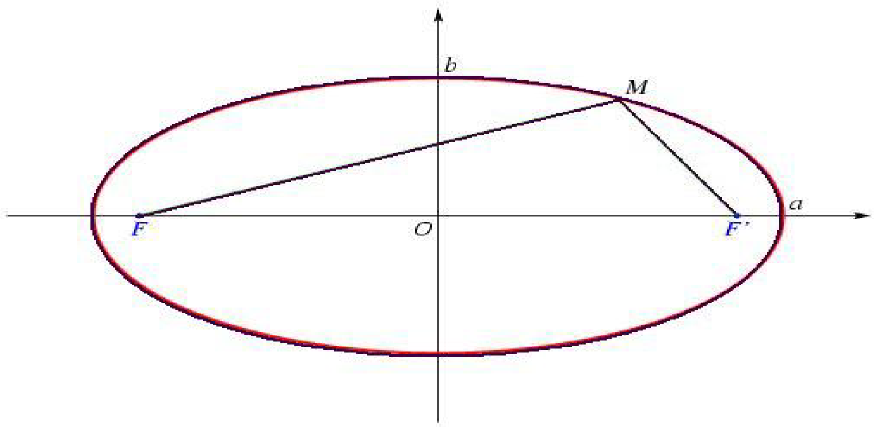

Figure-3.13: Ray trace between focal points of an ellipse.

Using this fact it is possible to increase pumping efficiency by citing light source to one focal point and laser rod to the other one. This statement is valid unless the source and the target are both points but the light source and the laser rod is not points. In practice the source or the rod is shifted a little towards the center. In cavity design of the laser an ellipse with small eccentricity is used fig-3.5.

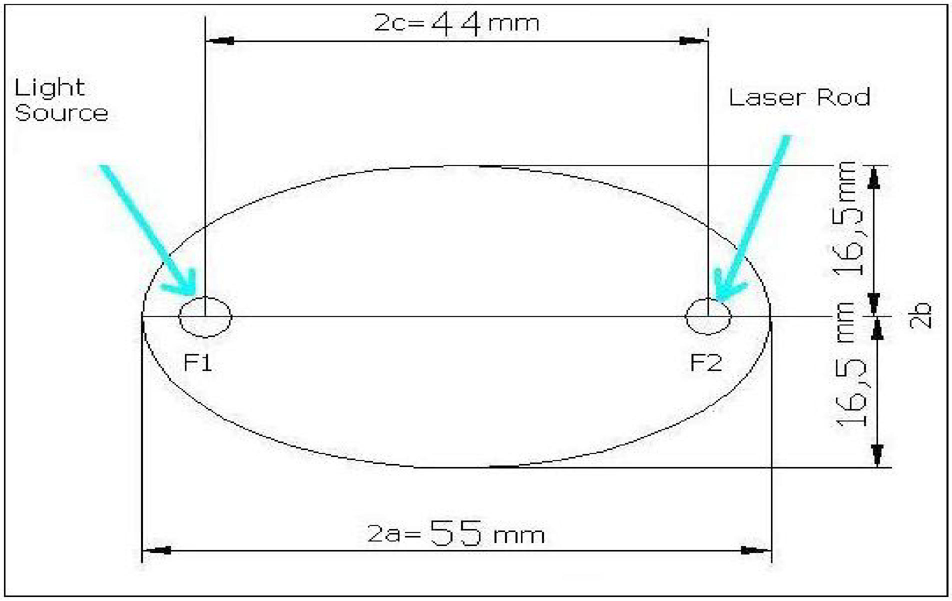

Figure-3.14: Cross section of elliptical cavity with small eccentricity. The cover is aluminum with dimensions: 91x102x85 in mm.

The inner surface is gold coated in order to increase reflections from the side wall. The whole cavity is shown In fig-3.6.

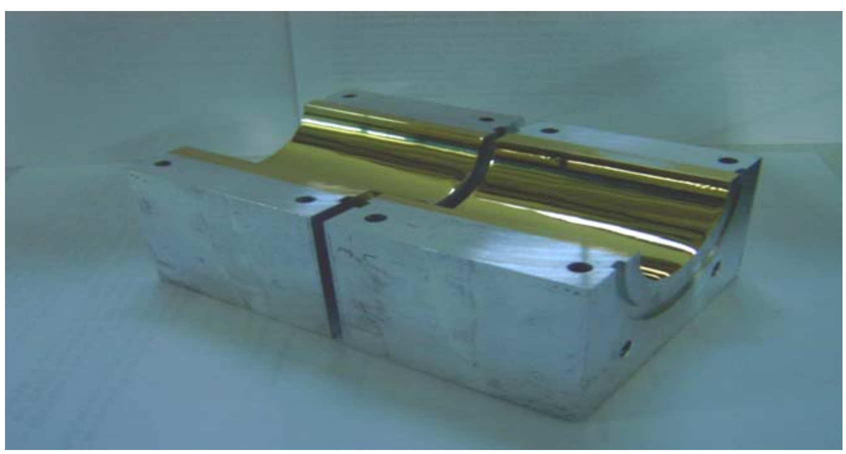

Figure-3.15: Elliptical cylinder cavity; upper and lower sides together.

The substrate material of the cylinder is aluminum. The spectral reflectance of both Al and Au are given in fig-3.7. [10].

In the figure the graphs shows that the reflectance of gold is higher than that of aluminum for wavelengths between 700nm and 900nm. This range corresponds to the maximum absorption of the Nd:YAG rod. Nd:YAG rod has maximum absorption at wavelength 800nm. At this wavelength the reflectance of gold is 97% while the reflectance of aluminum is 85%. It is obvious that coating the cavity with gold increases the optical pumping efficiency.

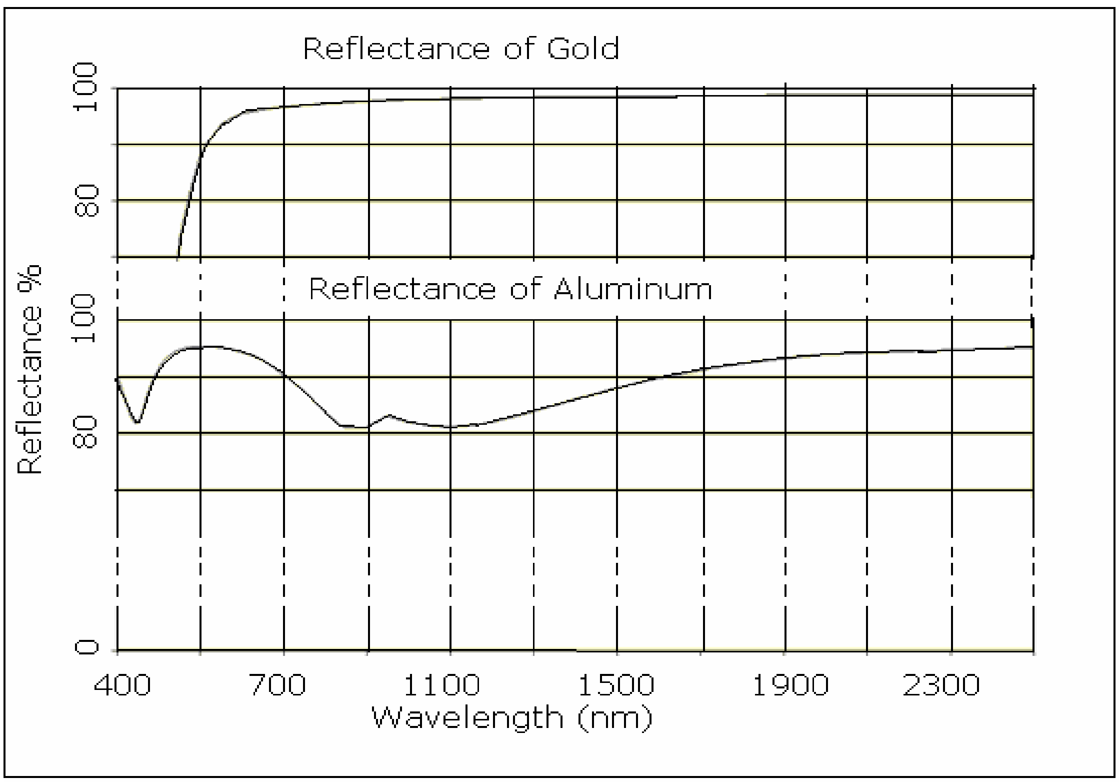

Figure-3.16: Spectral reflectance of gold and aluminum.

3.2.3. Flash Lamp

The flash lamp used in the laser was xenon filled, line shaped one. It was an old one and no specifications were available. This was a handicap that it makes supply design more difficult. The supply was astable so that no experimental emission spectrum was retrieved. The spectrums taken from [12] are shown in fig-3.8.

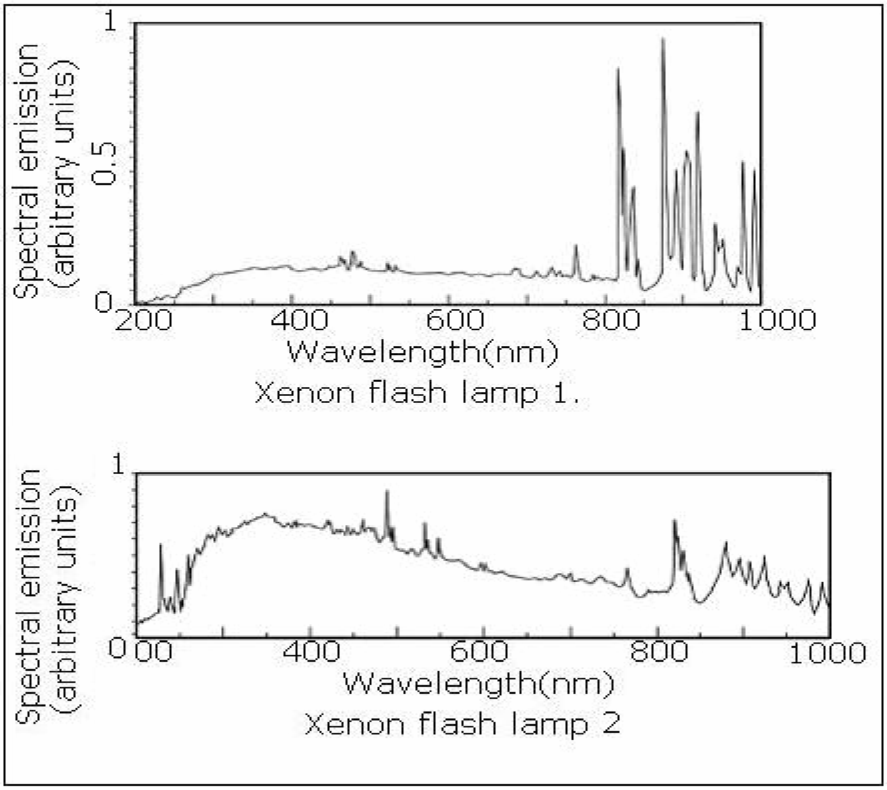

Figure-3.17: 1. Spectral emission from xenon flashlamp filled to a pressure of 390 torr at low electrical loading (100-microfarad capacitor charged to 500 V). 2. Spectral emission from xenon flashlamp filled to a pressure of 390 torr at high electrical loading (200-microfarad capacitor charged to 1000 V).

From fig-3.8 it is seen that lamp 1 is more suitable than the other one when spectral emissions are compared with the spectral absorption of Nd:YAG.

Lamp 1 gives most of its energy at wavelengths above 800nm. 800nm is the wavelength at which the absorption of Nd:YAG is highest.

Lamp 2 is also suitable but the energy emitted at wavelengths lower than 700nm results in radiationless transfers from the upper pumping bands. This adds extra heat to be removed from the system.

Besides xenon filled flash lamps, krypton filled flash lamps can also be used. The spectral emissions of these lamps show that they suit better to the absorption spectra of Nd:YAG fig-3.9. [12]. But these lamps are much more expensive than the xenon filled ones.

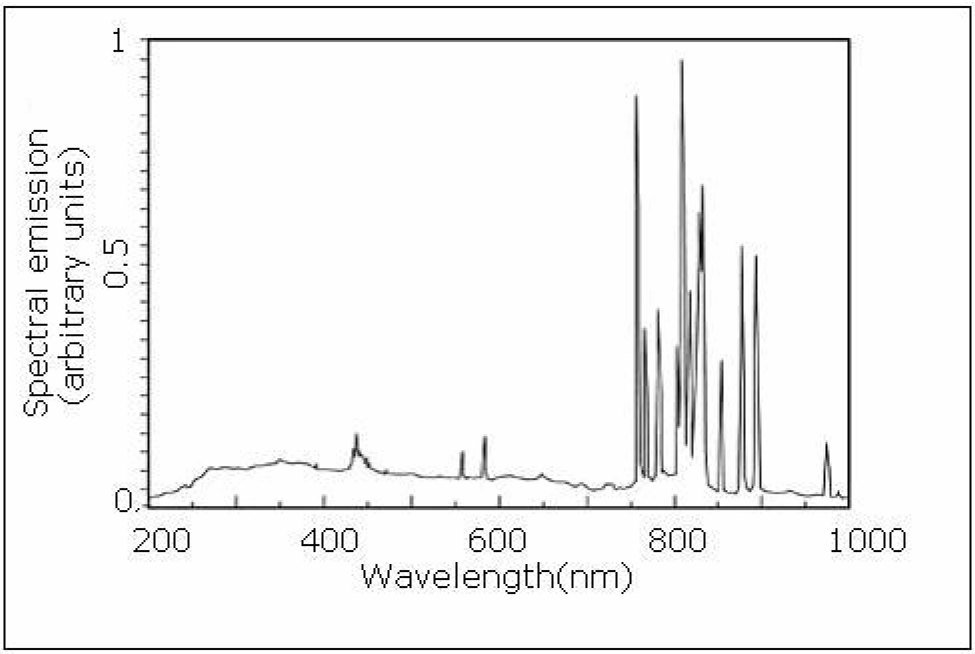

Figure-3.18: Spectral emission of krypton filled flash lamp pressure of 700 torr at low electrical loading (100-microfarad capacitor charged to 500 V).

3.2.4. Tungsten Halogen Lamp

Tungsten halogen lamps are the cheapest light sources that can be used in CW mode Nd:YAG lasers. Their spectral emissions are suitable for Nd:YAG. The spectral emission of a 500W, 220V tungsten halogen lamp taken with Ocean Optics HR2000 Series Fiber Optic Spectrometer is shown in fig-3.10.

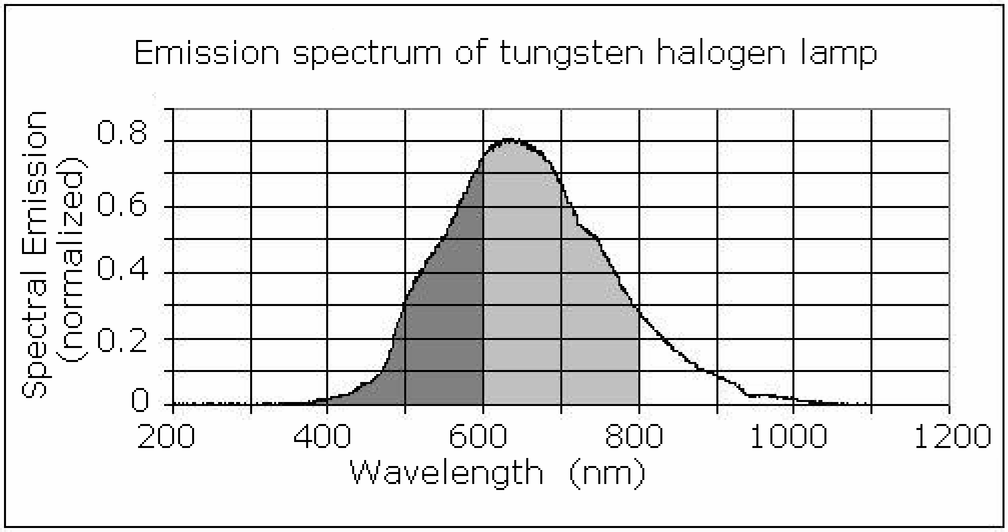

Figure-3.19: Spectral emission of tungsten halogen lamp 5 minutes later after it is initiated.

The emission spectrum of tungsten halogen lamps shows that it is quite suitable for optical pumping. The light gray area at the graph shows the most efficient emission for the Nd:YAG. The dark gray area is also suitable but it leads extra heat to be removed.

3.3. Power Design

The power design is a job which is time consuming especially for pulsed mode operation.

3.3.1. Flash Lamp Deriver Electronics

For pulsed mode operation a pulsed light source which is a flash lamp must be driven. There are various supply designs for flash lamps. The power supply for a pulsed flash lamp performs a number of functions:

Charging a capacitor that stores electrical charge until the flash lamp is ready to fire.

Providing a trigger pulse that initiates the pulse.

Controlling the flow of current during the pulse to control the pulse shape.

A circuit example that performs all these functions is shown in fig-3.11. The charging power supply charges a capacitor *C*, which holds the charge until the pulse is desired. Then the trigger circuit delivers a high-voltage pulse that breaks down the flashlamp and initiates the current flow. The capacitor discharges through the flashlamp, with the pulse characteristics controlled by the values of *C*, inductance L, and resistance of the flashlamp.

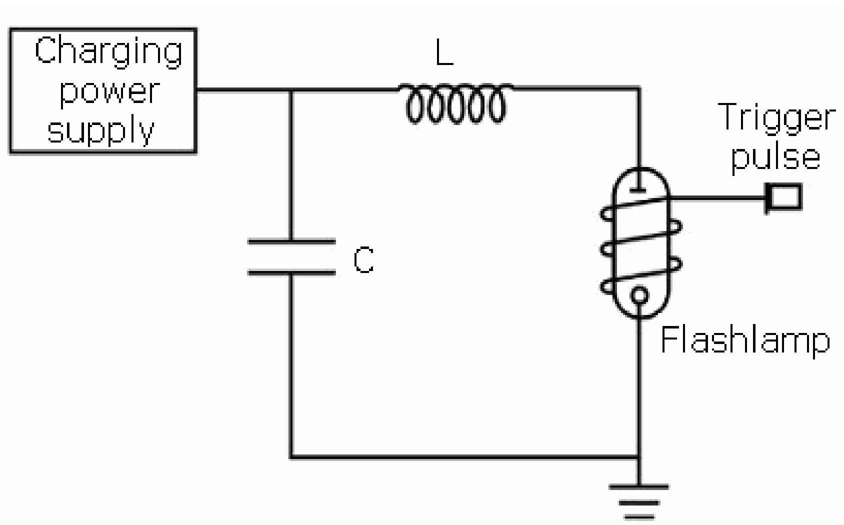

Figure-3.20: A prototype supply for flash lamp operation.

3.3.1.1. Charging Power Supply

The function of the charging power supply is to charge the energy-discharge capacitor. The charging must be completed within the interpulse time of the laser.

In most cases the charging power supply contains a transformer and a rectifier bridge. These elements supply the required DC voltage to charge the capacitor to a preset high voltage from an AC line. In fig-3.12 a charging supply with a semiconductor (SCR) switch to turn off the charging voltage when it reaches the selected value.

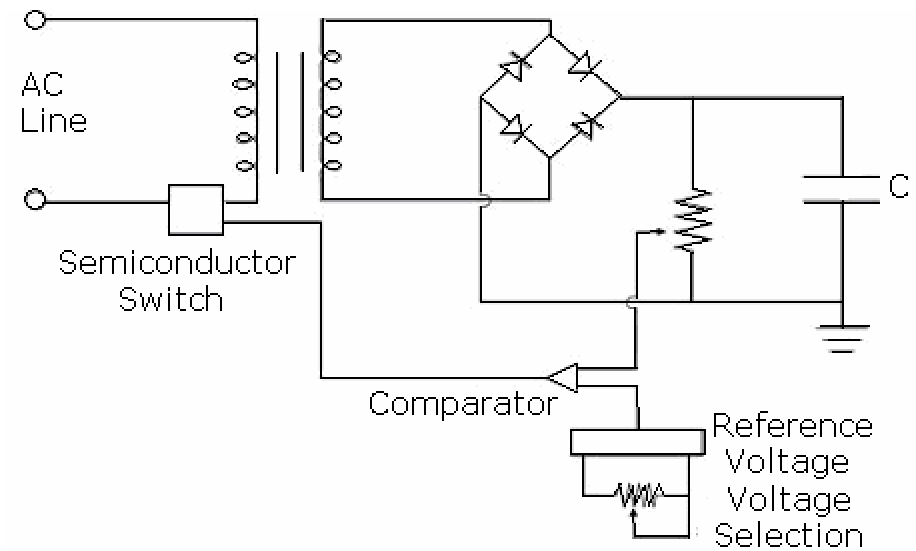

Figure-3.21: Charging supply with SCR control.

The circuit as shown in the figure contains no provision for limiting the current that charges the capacitor. When the charging begins, the capacitor is discharged and appears to be a short circuit. To protect the diodes, transformers, and other circuit components, the current must be limited. This is frequently done with a resistor as the current-limiting component, as illustrated in fig-3.13.

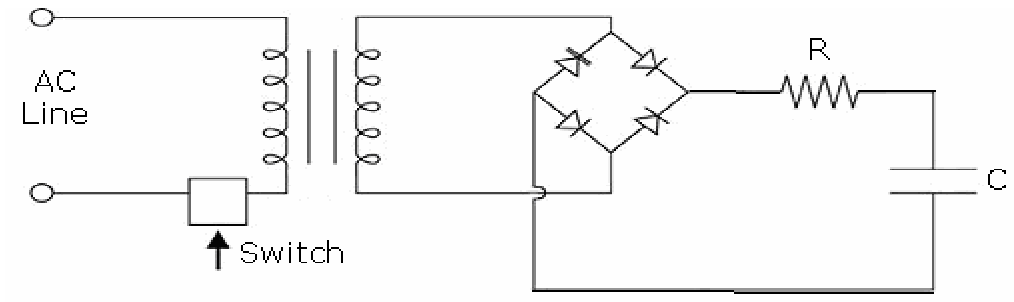

Figure-3.22: Charging supply with current limiting resistor.

The circuit shown in this figure is simple and straightforward, and is adequate when the pulse-repetition rate is low and the time available to charge the capacitor is relatively long. Then the current is relatively low and the losses in the resistor will not be too high.

At higher pulse-repetition rates, the time available to charge the capacitor is short and the current must be higher. Then losses in the resistor become unacceptably high and other current-limiting methods are required. One such method is shown in Fig-3.14, which uses an inductor in the primary of the transformer to limit the current. When the capacitor is discharged and the current would otherwise be large, the current is limited by the inductive reactance.

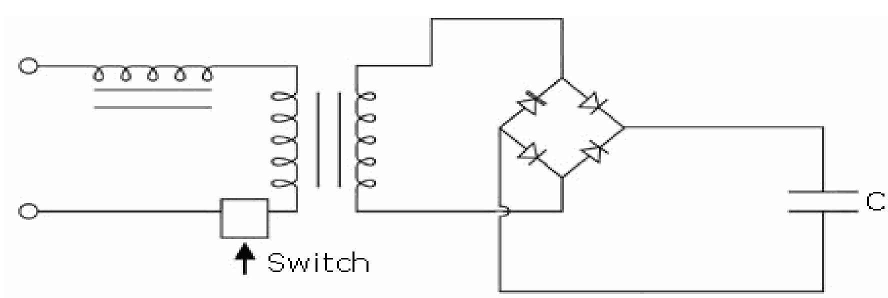

Figure-3.23: Charging supply with current limiting inductor.

When the pulse-repetition rate becomes still higher and approaches the frequency of the power line, few cycles of the power line fall within the charging period. The charging current comes in surges, one surge for each half cycle of the power line. This makes the charging erratic and irreproducible, because of fluctuations in the relationship of the charging surges and the temporal window available to complete the charging. A resonant charging circuit to counter this problem is shown in fig-3.15. The capacitor C_1 is much larger, perhaps ten times larger, than the discharge capacitor C, and acts as a filter. The current flows during the first half cycle of the resonant frequency and charges the discharge capacitor to a voltage two times the source voltage.

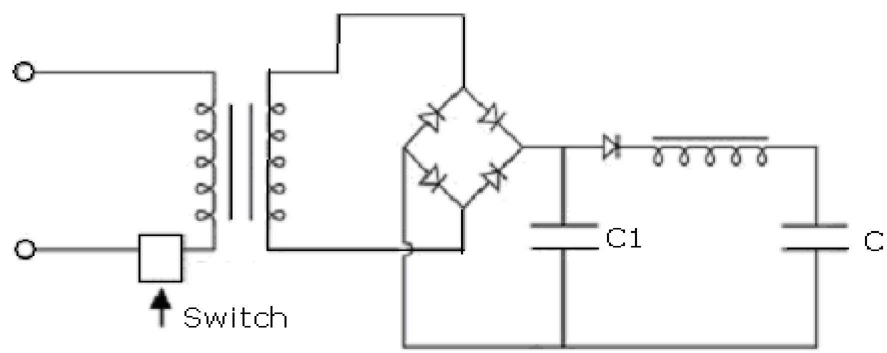

Figure-3.24: Charging supply with resonant charging unit.

3.3.1.2. Triggering

Four types of triggering circuits have commonly been used as circuitry to trigger the flashlamp:

Overvoltage,

External,

Series,

Parallel.

The last three are used most often with solid-state lasers. The advantages and disadvantages of the triggering mechanisms will be discussed.

An overvoltage trigger circuit is shown in fig-3.16. In this figure and the three that follow, the emphasis is on the triggering portion of the circuit. The circuit diagram for the power supply itself is simplified; this will be described in more detail later. In overvoltage triggering, the initial bias voltage across the lamp is sufficient to break down the gas in the lamp and begin the discharge. The voltage is applied to the lamp when the switch is closed. The type of switch used is usually a hydrogen thyratron, a triggered spark gap, a mercury ignitron, or a silicon-controlled rectifier (SCR). A modern circuit may have a single 1000-volt MOSFET or VFET transistor switch stage. In cases where a few thousand volts need to be switched, isolated stages of MOSFETs or VFETs can be cascaded to meet the voltage requirements [13]. Overvoltage triggering provides a relatively simple approach to triggering, but it does require the use of a relatively expensive high-voltage switch.

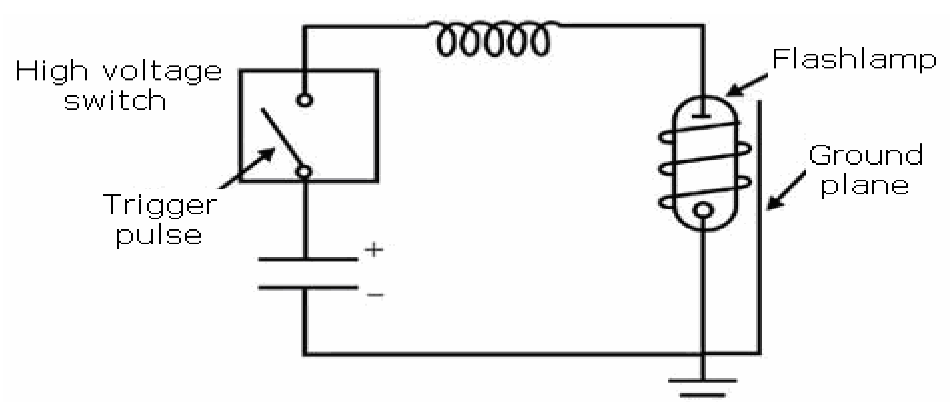

Figure-3.25: Overvoltage trigger circuit.

In external triggering, the high-voltage trigger signal is applied directly to a trigger wire outside the lamp envelope, as illustrated in fig-3.17. This type of circuit can use small, lightweight, and inexpensive transformers. The main advantage of external triggering is that the energy-discharge circuit is independent of the trigger circuit. The inductor in the pulse-forming network (to be discussed later) is not affected by the trigger pulse. A major disadvantage of external triggering circuits is that the trigger voltage is exposed. Therefore, this method of triggering is not recommended for use at high altitudes or in humid environments.

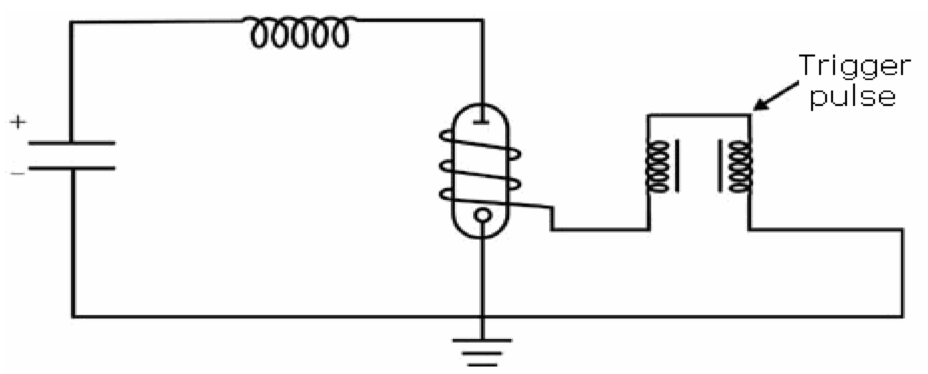

Figure-3.26: External trigger circuit

In series triggering, the secondary winding of the trigger transformer is in series with the energy-storage capacitor and the flashlamp. This circuit is shown in fig-3.18. When the lamp is ignited, current flowing in the circuit saturates the transformer core. This means that the saturated inductance of the transformer serves as the pulse-forming inductor. This reduces the overall component count in the circuit. Series triggering offers reliable and reproducible triggering[13]. Another advantage of series triggering is trigger reliability at low capacitor-charging voltages. Also, this method yields safe and reliable operation in severe environments because all high-voltage sources can be encapsulated[13]. Disadvantages of series triggering include large size, heavy weight, and high cost of the trigger transformer and large saturated secondary inductance.

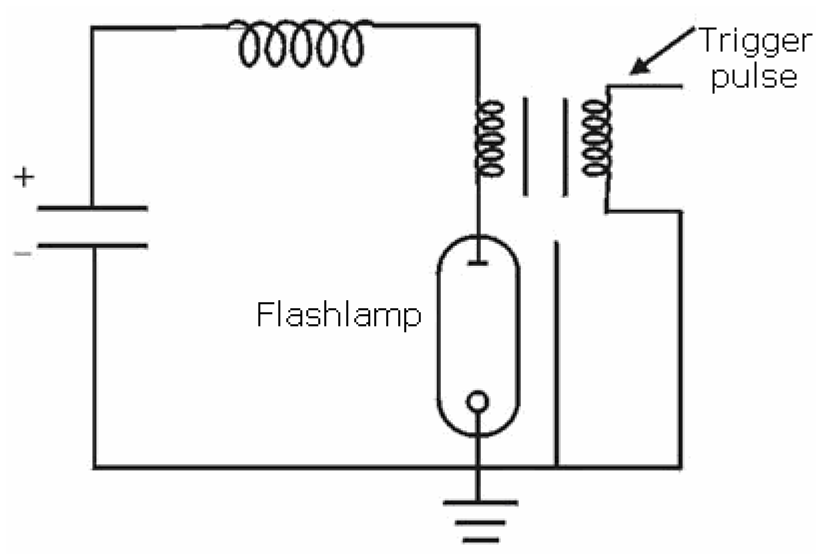

Figure-3.27: Series trigger circuit

In parallel triggering, the secondary of the trigger transformer is connected to the lamp in parallel. A circuit is shown in Fig-3.19. A capacitor or a diode is needed to isolate the secondary winding of the transformer from the energy-storage capacitor. Parallel triggering retains the advantages of series triggering and has an additional attractive feature of requiring only a small external triggering transformer. The disadvantages of this circuit involve the requirements of the isolating element. If a capacitor is used, as is illustrated in the figure, the trigger circuit needs a large pulse-forming inductor. If a diode or train of diodes is used, it adds parasitic losses to the circuit[13]. The requirements placed on the diode are very exacting. It may not be possible to obtain a suitable diode, and if one is available, it will be very expensive.

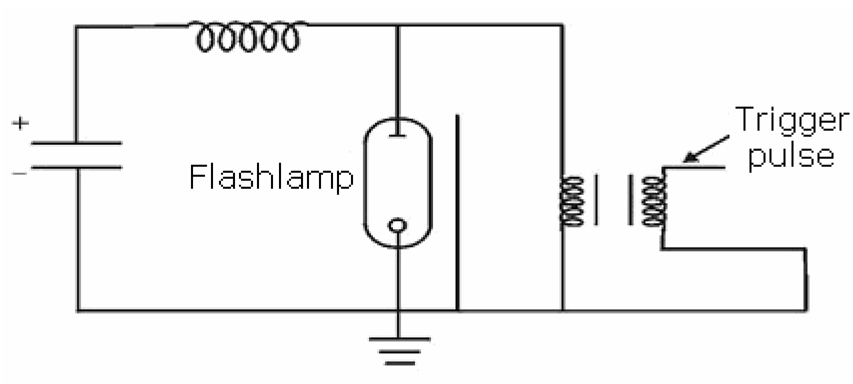

Figure-3.28: Parallel trigger circuit

The exact value of the trigger voltage is difficult to specify. Typically, it is in the kilovolt range and decreases as the bias voltage (the main-capacitor voltage) on the lamp increases. But there are variations even among lamps of nominally identical manufacture. The manufacturer usually specifies nominal trigger conditions for specific models of flashlamps. In our case since the flash lamp we use is old no specifications were available. Also, in addition to having the appropriate values of trigger and bias voltage, the relation of the polarities of the voltages must be correct.

3.3.1.3. Control of Pulse Shape

The flashlamp operates in an RLC circuit, as shown in Fig-3.20. The resistance, *R,* is provided by the flashlamp; the inductance, *L*, by the series inductance; and the capacitance, *C*, by the discharge capacitor. The influence of the triggering circuit components is minimal and can be ignored. The circuit constitutes a pulse-forming network, and the shape of the current pulse depends on the values of *R*, *L*, and *C*.

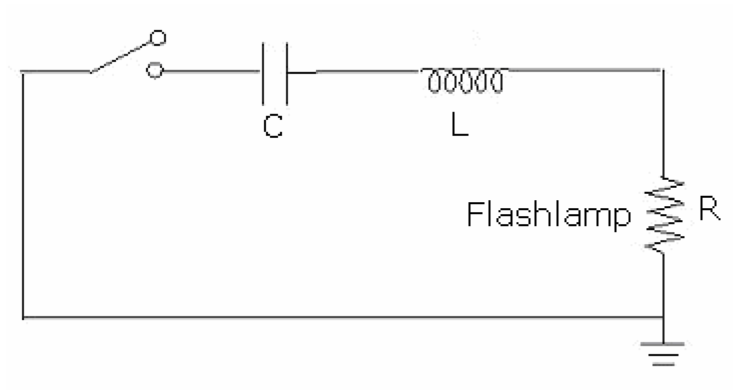

Figure-3.29: RLC discharge circuit

The analysis of an RLC circuit with a constant resistor is relatively simple. But as we have seen, the resistance of the flashlamp is not constant, but changes through the duration of the pulse. For the moment, however, we will discuss the current waveforms that are available in the context of a constant resistance *L*. If the relationship of *R*, *L*, and *C* is such that

$$R < 2\,(L/C)^{1/2,} \qquad 3.1$$

then the circuit is said to be underdamped and the current waveform will be as shown in Fig-3.21. There will be oscillations in the current, with the current reversing and swinging negative at some times. This is highly undesirable. The flashlamps are designed for current flow in one direction and can be damaged by current reversals. Also, the current will pass through several nulls during the discharge. This will make the pumping of the laser erratic[13].

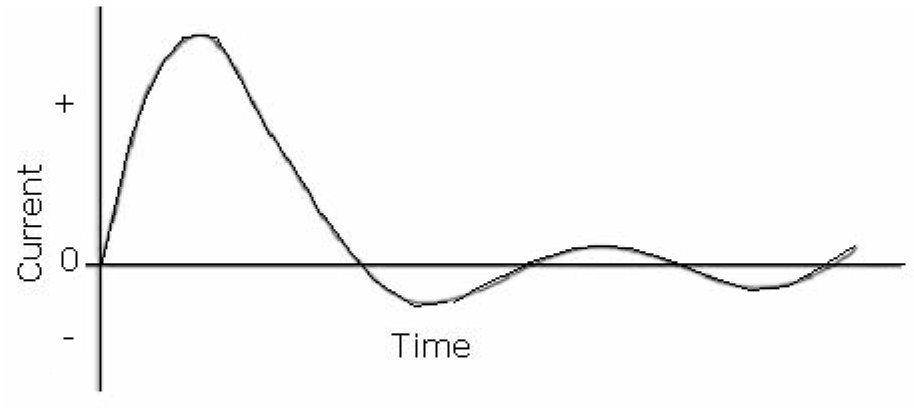

Figure-3.30: Underdamped current waveform from a flashlamp discharge circuit.

If we have

$$R > 2\ (L/C)^{1/2,} \qquad 3.2$$

the circuit is said to be overdamped and the current waveform will be as shown in fig-3.22. There are no current reversals, but the peak value of the current is limited and the pulse is stretched out, usually to a value longer than desired.

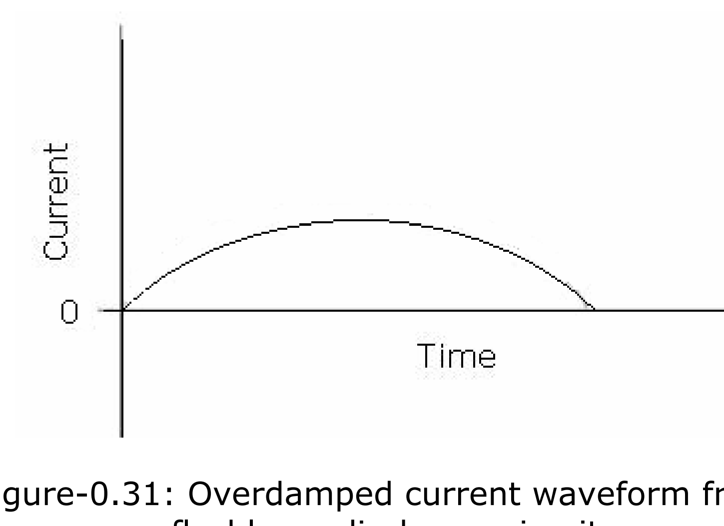

Figure-0.31: Overdamped current waveform from a flashlamp discharge circuit.

If we have

$$R = 2\ (L/C)^{1/2} \qquad 3.3$$

the circuit is critically damped and the current waveform will be as shown in Fig-3.23. This is the desirable case. There are no current reversals. The current rises with a reasonably short rise time to its peak value and then falls over a somewhat longer period to zero and ceases. One obtains desired high peak values of current in this case.

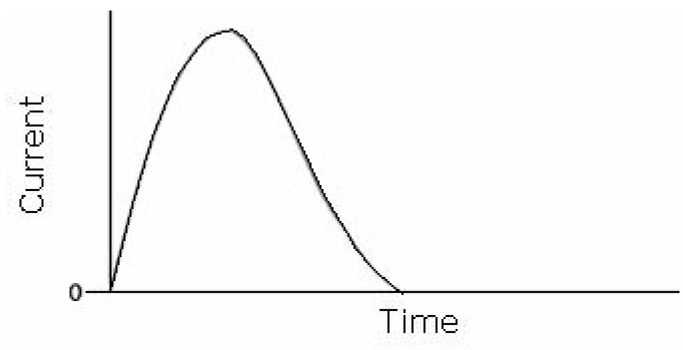

Figure-3.32: Critically damped current waveform from a flashlamp discharge circuit.

The time-varying resistance of the flashlamp during the pulse complicates the analysis so that it is not possible to use the expressions above. But it is still possible to adjust the circuit components to avoid the undesirable cases of underdamped and overdamped behavior and to obtain the desirable case of critically damped behavior.

Given that the energy E_0 is to be discharged, and the pulse duration, t_p, is specified as the time between the points on the leading and trailing edges of the pulse at 10% of the peak amplitude. With these inputs, one desires to know the values of capacitance C, inductance L, and charging voltage V, to yield a critically damped pulse with these characteristics.

These values may be obtained from the following equations [13]:

$$C = (0.09 \times E_0 \times t_p^2/K_0^4)^{1/3} \quad 3.4$$

$$L = t_p^2/9C \quad 3.5$$

$$V = (2E_0/C)^{1/2} \quad 3.6$$

Here K_0 is the lamp-impedance parameter. Its value should be known for the specified flashlamp, but in our case we do not know this parameter. Use of the above three equations will then allows one to solve for the proper circuit parameters.

Under these considerations the final design of flash lamp electronics is shown in fig-3.24.

In figure the whole electronics of a pulsed Nd:YAG laser is shown. This electronics is responsible for delivering electrical power to the flash lamp and triggering it in desired way.

In the figure, the charging supply is a classical DC supply which converts AC line to 2500V DC. A step up transformer and a full bridge rectifier is used. This supply charges the capacitors which have an equivalent capacitance of 25μF. Since the desired repetition rate is small a current limiting resistor is connected in series which is 25 Kohm.

The triggering circuit is composed of an oscillator a SCR switch and a flyback transformer. The triggering mechanism is parallel triggering.

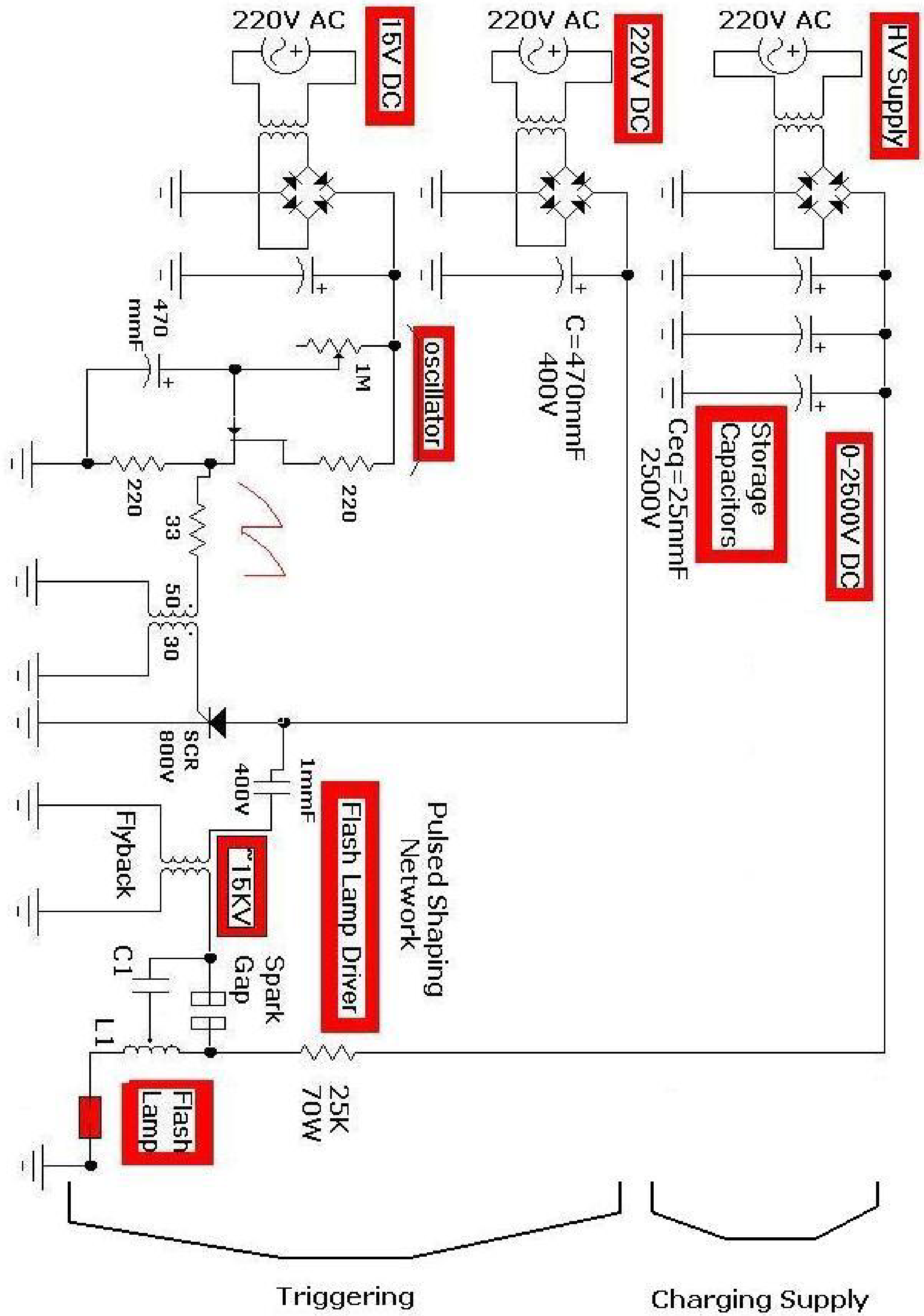

Figure-3.33: Designed and constructed pulsed Nd:YAG Laser flash lamp electronics. Charging supply, triggering and pulse shaping circuits.

In flash lamp electronics, fig-3.24, a UJT is used in the oscillator. The oscillator part is isolated from the high voltage with a toroid with primary 50 and secondary 30 turns. The pulses generated by the oscillator switches the 300V DC to the primary of the flyback transformer. The resultant pulse from the secondary of the flyback is approximately 20KV which is then used to trigger the flash lamp.

Since the impedance parameter of the flash lamp is unknown the impedance matching of the circuit is tried by varying the L1 value. L1 is a coil with 14 turns of 2mm bobbin. The separation between bobbins is 5 mm. The diameter of the coil is 10cm. The capacitor C1 connected to L1 is 300pF.

With these parameters the circuit was not quite successful in driving the flash lamp. The reason was unknown K_o parameter of the flash lamp.

3.3.2. Tungsten Halogen Lamp Electronics

The halogen lamp electronics is simpler than the flash lamp one. Fig-3.25. shows the schematics of the supply that is used in the laser.

No pulse shaping or impedance matching is required. Among the entire continuous light sources that can be used for CW mode solid state lasers, tungsten halogen lamp is the easiest one to fire up. If a krypton arc lamp was used special supply units were required. These would be capacitor charging supply, simmer unit and current controller unit. These three units would require impedance matching and mathematical analysis.

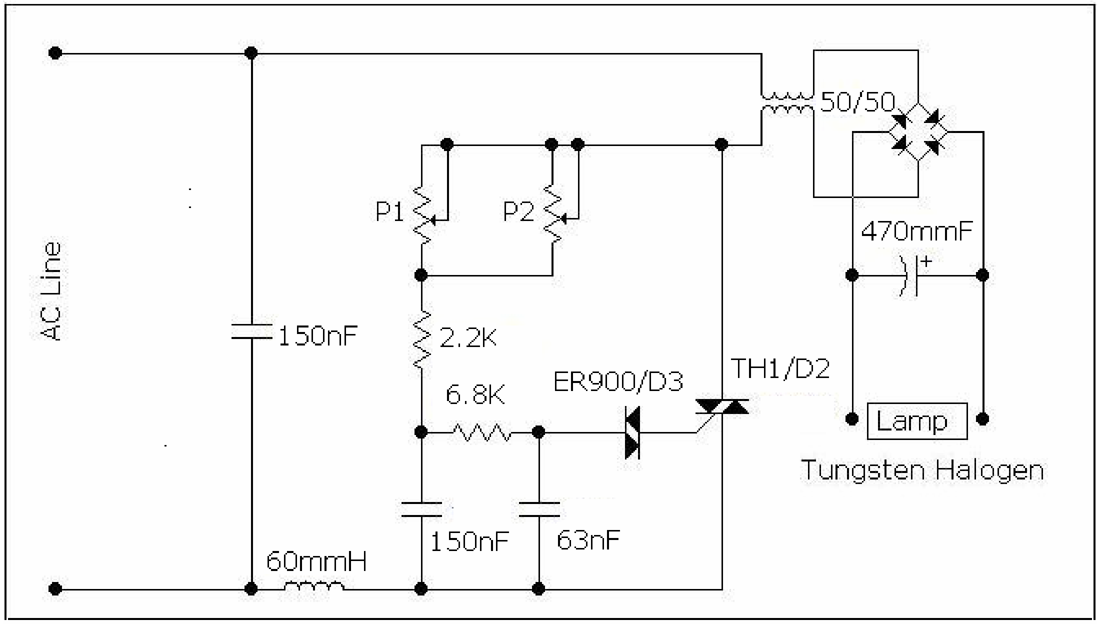

Figure-3.34: Tungsten halogen lamp power supply.

The AC line is the input of the supply. This AC voltage is controlled by the circuit. The controlling part is a dimmer circuit. P2 potentiometer controls the range while P1 varies the voltage in this range. The second part is a simple full rectifier. It converts AC voltage to DC. P1 value is 500K-ohm, the value of P2 is 1M-ohm. With given values the circuit has the ability to supply 1KW power to the lamp.

3.4. Cooling

Cooling unit is as important as the rest of the system. Without a sufficient cooling the laser will break down soon. The stability and the efficiency of the laser are quite dependent on cooling.

Smaller lasers may use open-loop cooling systems with tap water flowing across the rod. In such cases, the water should be filtered to remove any contamination or impurities. Larger systems use closed-loop cooling with water or a water-glycol solution. The coolant is usually refrigerated, but a water-to-water or water-to-air heat exchanger may also be employed. In the laser constructed de-ionized water is used. The cooling system that is used is shown in fig-3.26.

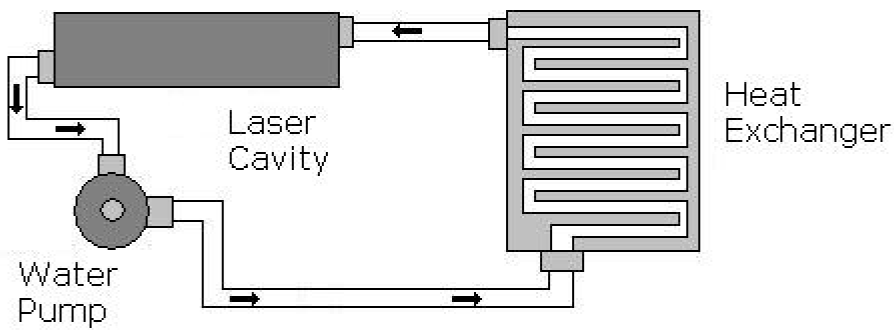

Figure-3.35: Closed loop cooling system.

The cooling system of the laser must remove most of the waste heat from the entire system. Only a small fraction of the input energy appears in the laser output. Other relatively small amounts of energy escape as fluorescence passing through the rod ends and as radiative or convective heating of the laser environment. The cooling system must be capable of removing waste heat continuously at the maximum input power level.

One way to design a cooling system for a CW YAG laser is to estimate the amount of radiant power being absorbed by the laser rod, set the desired limit on allowable temperature rise in the water after cooling the rod, and calculate the flow rate of the coolant (water).

Cooling calculations for CW mode Nd:YAG laser. Pumping power 500W. Tungsten halogen lamp is used.

Assuming the lamp is 80% efficient, rod absorbs 30 % of light power and the pumping efficiency is 60%. With these assumptions and knowing the efficiency of the rod (1%) the power absorbed by the rod (P_{abs}) can be found. Expected laser output (P_{out}) will be ignored in this calculation since it is quite low.

$$P_{abs} = 500 \times 0.80 \times 0.30 \times 0.60 = 72.00 \text{ Watts} \quad 3.7$$

Then, the laser rod heat power to be removed (H_{rm}) is:

$$H_{rm} = 72.00 \text{ Watts} \quad 3.8$$

72 Watts equal 72 Joules/second. 1 cal. is 4.18 Joules. Then,

$$H_{rm} = 72.00 / 4.18 = 17.22 \text{ cal/second} \quad 3.9$$

Limiting the rise of temperature of the coolant to 5 ^{o}C will yield a flow rate (F_R):

$$F_R = 17.22 / 5 = 3.44 \text{ cm}^3\text{/second} \quad 3.10$$

In the laser the cooling subsystem has a flow rate of 2000 cm3/minute. This value is quite high than the required one.

CHAPTER 4

EXPERIMENT

4.1. Main Room Temperature Transitions

The experimental setup that is used to measure main room temperature transitions is shown below in fig-4.1. The laser rod and tungsten lamp are inside the elliptical cavity. The cavity is an aluminum block and inside is elliptical cylinder. The rod and the lamp are at the focal points of the ellipse.

The spectrometer is fiber-optics cable coupled and its resolution is 1nm. The measurements are corrected by subtracting the background effects. First, the background radiation is measured, then transitions of Nd:YAG is measured and background is subtracted.

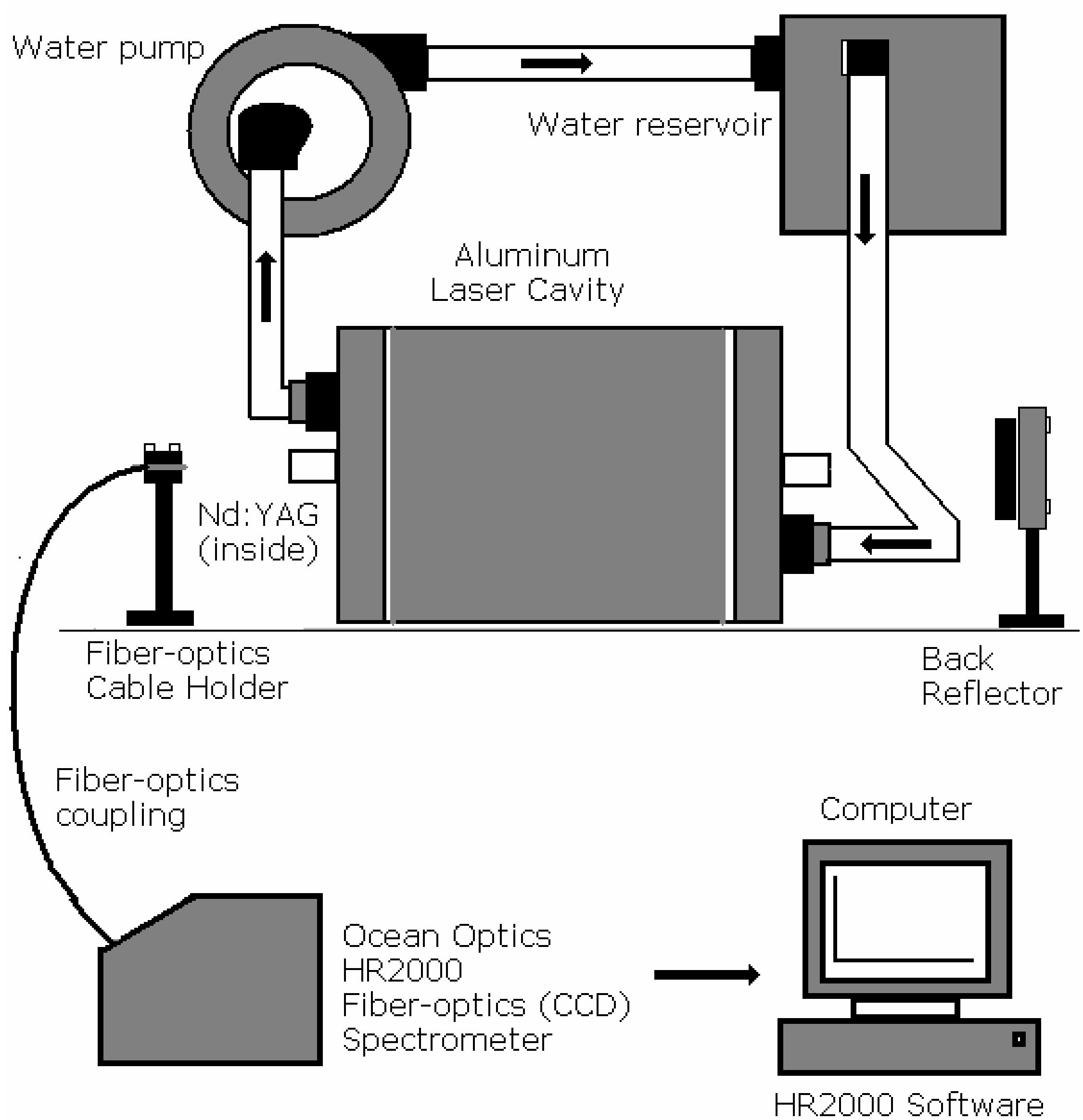

Figure-4.1: Experimental setup

In table-2.4 some main room temperature transitions of Nd:YAG were given. It was not possible to detect transitions with wavelengths below 1000nm due to the tungsten halogen lamp emission. Below 1000nm the spectrometer has been saturated by the tungsten halogen lamp. Above 1000nm tungsten halogen lamp has no spectral emission. The transitions of Nd:YAG above 1000nm which have been measured are shown in graph in fig-4.2.

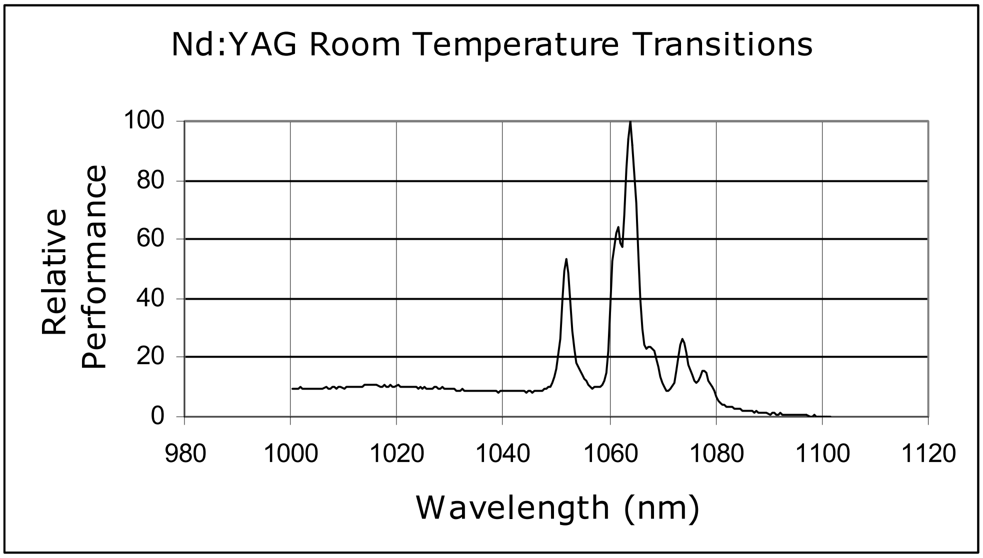

Figure-4.2: Measured Nd:YAG room temperature transitions above 1000nm.

Theoretical room temperature transitions above 1000nm [2] and experimental measurements are shown together in table-4.1.

Table 4.1: Theoretical and measured room temperature transitions of Nd:YAG.

Transition	Theoretical		Experimental	
	(nm) Wavelength	Relative Performance	(nm) Wavelength	Relative Performance
R2 ⟶ Y1	1052.05	46	1051.83	53.24
R1 ⟶ Y1	1061.52	92	1061.53	64.04
R2 ⟶ Y3	1064.14	100	1064.05	100.00
R1 ⟶ Y3	1073.80	65	1074.15	25.00
R1 ⟶ Y4	1078.00	34	1078.35	14.81

As seen in table-3 experimental room temperature transitions match with theoretical ones with small fractions of error. The error in wavelengths is because of environmental conditions, also the resolution and calibration of the spectrometer might be effective.

The relative performance is calculated with respect to the 1064.05 transition. This transition is referenced as 100 units. The error in relative performance is due to the position, type and length of the fiber-optic cable of the spectrometer. The attenuation constant of fiber-optic cable differs with wavelength. Coupling of the Nd:YAG emission to the spectrometer affects the flux of the light incident to the spectrometer. Fig-4.2 and table 4.1 shows that the Nd:YAG rod can be excited by a tungsten halogen lamp. They are the proofs to the statement that emission spectrum of tungsten halogen lamp matches with the absorption spectrum of Nd:YAG.

4.2. Power Output

The expected laser output P_{out} is quite small. With some assumptions it is possible to calculate this value. A rough calculation of output power is given below with some assumptions.

Assumptions:

a. Lamp is %80 efficient.
b. Rod absorbs %30 of the light power (typical value for tungsten halogen lamps).
c. Pumping efficiency is %60.
d. 40% of absorbed light converted to heat.
e. 30% of emission is spontaneous.
f. Coolant transmits %90 of the light.
g. Pyrex coating of the lamp transmits %90 of light.

Also the efficiency "h." of the rod is known 1% and %38 of emission is at 1064 nm "i." (calculated from table-3.1).

P_{out}= *500 x a. x b. x c. x (1-d.) x (1-e) x f. x g. x h. x i.* 4.1

Then,

P_{out}= *0.039 Watts.* 4.2

Although the emission bands are measured, the output power could not be measured because it is quite low and powermeter is calorimetric which is not suitable to measure low energy values.

A more sophisticated calculation of output power is given below [2].

$$P_{out} = A\left(\frac{1-R}{1+R}\right)I_s\left(\frac{2g_o l}{L-\ln R}-1\right) \qquad 4.3$$

In equation 4.3, I_s is a parameter of Nd:YAG and given by:

$$I_s = \frac{h\nu}{\sigma_{21}\tau_f} \qquad 4.4$$

σ_{21} is stimulated emission cross section given in table 2.1. τ_f is the life time of pumping bands its value is given in table 2.1 also can be calculated as

$$\frac{1}{\tau_f} = \frac{1}{\tau_{21}} + \frac{1}{\tau_{20}} \qquad 4.5$$

τ_{21} and τ_{20} are the life times from upper lasing level to lower lasing level and from upper lasing level to ground level respectively. Their values are given in table 2.1. τ_{20} is very small with respect to τ_{21}. Then, equation 4.5 can be approximated and solved resulting:

$$\tau_f = 230\ \mu s \qquad 4.6$$

Then,

$$I_s = 6865587\ W/m^2 \qquad 4.7$$

In equation 4.3 remaining terms: R reflectivity of output coupler 0.95, l is the length of the rod 60mm, g_o is small signal gain coefficient and L is the resonator losses . In order to solve this equation g_o and L must be known, but g_o is a value which can be found by experimentally. In order to find this parameter the output must be taken.

With some approximations equation 4.3 can be converted in to equation 4.8 [2] to eliminate g_o parameter.

$$P_{out} = \left(\frac{1-R}{1+R}\right) AI_s \left(\frac{2\eta_u \eta_B \eta_P \eta_T \eta_a P_{in}}{(L - \ln R) AI_s} - 1\right) \qquad 4.8$$

A is the cross section area of the rod and its value is 0.13 cm^2. P_{in}=500W is input electrical power to the lamp.

η_P is pump source efficiency. It includes lamp's electrical efficiency and how much of its light radiation matches with the absorption of Nd:YAG. Typical value of η_P = 0.2 – 0.6 [2]. 0.3 is assumed for the designed system.

η_T is the radiation transfer efficiency and it is a measure of radiation hitting the rod which was called optical pumping efficiency before. Typical value of η_T = 0.60–0.98 [2]. For our system 0.60 is assumed.

η_a is called absorption efficiency. η_u is upper state efficiency. They explain absorption of pump radiation by rod and transfer of energy to the upper laser level. Typical value of η_u for Nd:YAG is 0.72. η_a is given by [2];

$$\eta_a = 1 - \exp(-\alpha l) \quad 4.9$$

α is absorption coefficient and it is 0.03 cm^{-1} , l =6 cm with these values;

$$\eta_a = 0.17 \quad 4.10$$

η_B is an efficiency which relates conversion of upper state energy to laser output and its value can be approximated as 1 [2].

L is the resonator losses which results due to scatterings. Also some light which is incident to rod with small angles may not enter the rod. The approximated value of L is 0.2.

With these assumptions and calculated values the solution of equation 4.8 yields a value;

$$P_{out} = 0.036 \text{ W} \quad 4.11$$

The calculated power here is quite close to 0. The result of equation 3.8 might be negative. Negative power means the laser threshold is not achieved and no lasing occurs. Laser threshold is the minimum configuration of the system to sustain oscillations.

Threshold condition is satisfied when;

$$\left(\frac{2\eta_u\eta_B\eta_P\eta_T\eta_a}{(L-\ln R)AI_s}-1\right)=0 \qquad 4.12$$

Left hand side of equation must be positive to have a lasing.

It is possible to achieve a maximum power output by replacing the output coupler with one which has a suitable reflectivity. From equation 4.8 desired reflectivity of the output coupler can be calculated. It is difficult to solve 4.8 for R since it contains R and ln(R) terms together.

With numerical methods it is possible to calculate the optimum output coupler reflectivity. The graph of equation 4.8 is simulated numerically figure-4.3.

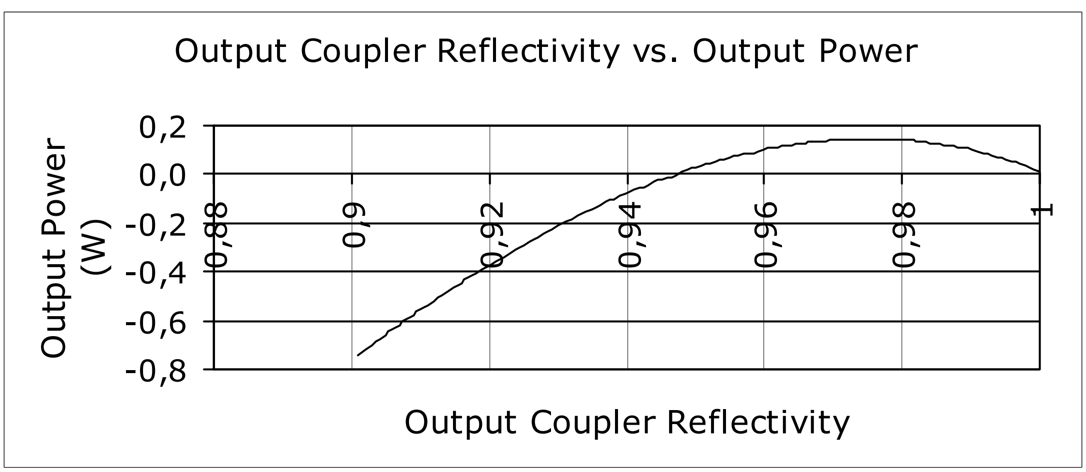

Figure-4.3: Power dependence of output coupler reflectivity.

Computer program is written in C is in Appendix. Graph shows that 95% reflectivity is a little above threshold. Graph in fig-4.3 states that the reflectivity of the output coupler must be 97.5% to have a maximum output power. With R=97.5% the maximum output power would be 0.146W.

One way to increase output power is to use more powerful tungsten lamp. The lamp power is also a parameter that affects the efficiency; the output power is not linearly dependent on input power.

In order to acquire 1.0 W of output power with R=97.5%, one may use a tungsten lamp of power 845 Watts.

With above calculations the calculated overall efficiency of the laser with 845 W input power and 97.5% coupler reflectivity is

$$\eta = 0.12\% \qquad 4.13$$

while for input power of 500 W and coupler reflectivity of 95% the overall efficiency is almost zero:

$$\eta = 0.0072\% \qquad 4.14$$

It seems as if these values are too small but the efficiency range for solid state lasers is 0.1%-4% [8]. Overall efficiency value at 4.13 is in this range.

CHAPTER 5

CONCLUSION

The output power of CW Nd:YAG lasers varies between a few milliwatts to a kilowatt. Although they vary in size and complexity of design, all have the same basic elements discussed before. The dominant transition is at 1064.05nm. The active medium is an Nd:YAG laser rod which is optically pumped by a continuous-pumping lamp and is placed between two external mirrors that form the optical cavity for the laser beam. In this work, the rod is used for CW operation. It has a diameter of 2 millimeters and has length of 60 millimeters.

The lamp is mounted with the rod inside an elliptical pumping cavity, this cavity is water cooled. The elliptical surface is gold coated. Gold is the best reflector for the pump light due to its high reflectance at the bands at which the absorption of Nd:YAG is high, but gold is not durable. Chromium plating is often used; it is not as reflective as gold but it is durable [8].

The optical cavity of the Nd:YAG laser consists of two mirrors mounted separately from the laser rod. Several cavity configurations may be used. Hemispherical cavity is used in this work. The HR mirror has a reflectivity of about 99.9% and the output coupler transmission is 5%. It is shown that 5% transmission is high for CW operation in fig-4.2.

The cooling system is a critical subsystem in the laser. Open-loop cooling systems might be used in smaller lasers with tap water flowing across the rod. In such cases, the water should be filtered to remove any contamination or impurities. Closed-loop cooling with de-ionized water is used in this work.

Lasing in ND:YAG is quite dependent on rapid transitions from the lower lasing level to the ground state by radiationless transitions in fig-2.1. These transitions occur at a high rate only if the rod temperature is low [8]. So, the overall efficiency depends very highly on the cooling. Lower operating temperature could result in higher output powers. If the cooling water is too cold, however, condensation will form on the laser head and optical surfaces. This can lead to problems and should be avoided [8].

The power losses can be traced. The input power is electrical power. Power supply will yield electrical losses. Output electrical power from the supply is the input power to the lamp. Supplied energy leaves the lamp in two ways as heat and light. In the laser, tungsten halogen lamp is used. The light is the radiation from the hot filament and has a broad, continuous wavelength spectrum. This lamp is usually less than 30% efficient for pumping neodymium lasers [8]. The efficiency of gas lamps like xenon is almost the same [8].

The light emitted from the lamps is the input to the laser rod. There exist some losses in this stage. Some fraction of this input does not reach to the rod and does not irradiate it (pumping efficiency). That is not all. Also, some of irradiating light is not absorbed by the rod (resonator loss ,L, discussed in section 4.2). Absorbed light by the rod also results in heat, fluorescence and spontaneous emissions which have nothing to do with the laser output.

With this much of loss, the overall efficiency of the CW Nd:YAG lasers is quite low. The overall efficiency of a laser is a measure of how much input electrical energy it requires to produce its laser output. Values of overall efficiency range from 0.1% to 4%, a typical value being about 1.0% [8]. These low efficiencies mean that practically all of the power that is put into a laser is lost. It is important to know how and where this power is lost, so that the losses can be kept as low as possible and the unused energy, which is practically all converted to heat, can be removed before it degrades the system performance or destroys system components.

The spectroscopy of transition bands above 1000nm in fig-4.1 and table 4.1. showed that tungsten halogen lamp satisfies pumping Nd^{3+} atoms to upper levels. Thus the statement "Tungsten halogen lamps can be used to construct a CW mode Nd:YAG laser" is verified and experimentally showed.

Other light sources like xenon filled and krypton filled arc lamps can also be used. When a comparison between tungsten halogen lamps and noble gas filled arc lamps is made, one can realize that in low power range, tungsten halogen lamps are more suitable.

Tungsten halogen lamps can be driven easily with simple electronics, but noble gas filled arc lamps require complex electronics.

An AC-DC (alternative current- direct current) converter with varying output is a sufficient supply for tungsten halogen lamps. Noble gas filled arc lamps require a constant current source and a simmer supply to initiate discharge.

Complexity of supply increases the cost of job, thus power to cost ratio is very small for noble arc lamp pumped CW mode Nd:YAG lasers.

Tungsten halogen lamps are easy to manufacture, but in arc lamps pressure of gas and electrode dimensions are very important. Gas pressure affects the spectral emission of the lamp (discussed in section 3.2.3. Spectral emission curves were given for different gas pressures). This increases the price of the source. Thus tungsten lamps are cheaper than noble filled ones.

The spectral emission fit of noble gas filled lamps is slightly better than that of tungsten lamps (in section 3.2.3 noble gas filled flash lamps were discussed). This yields higher pump source efficiency (η_P). Other advantage of arc lamps is that they are high powered. High power input increases the overall efficiency. How power input affects the efficiency is discussed in section 4.2.

The overall efficiency of the laser constructed is 0.0072% which is low but enough to show that CW mode Nd:YAG laser can be pumped by using tungsten halogen lamps. The efficiency might be increased by making changes which will decrease losses. These changes:

1. Reconstructing a more efficient cooling system; will increase the rate of rapid transitions from lasing level to ground level (radiationless transfer).

2. Choosing an output coupler with optimum reflectance; will sustain oscillations, population inversion will be reached more effectively (discussed in section 4.2: equation 4.8, fig-4.2)

3. Using smaller eccentricity elliptical cavity; more photons will satisfy to hit the rod.

4. Coating the inner wall of the cavity with durable substrate(chromium and then gold);

5. Pumping the rod with higher power light source; high power input increases overall efficiency. It is shown in section 4.2 by using equation 4.8 that overall efficiency increases to 1.12% by using an output coupler of reflectivity 97.5% and a tungsten lamp of 845 Watts.

It is not possible to find tungsten halogen lamps of power greater than 500W which are geometrically suitable to the rod that is used in this work and to the cavity that is constructed in this prototype. In order to increase pumping power a double ellipse cavity (section 3.2.2, fig-3.3.e) with two lamps can be constructed.

In this thesis Nd:YAG laser is theoretically investigated. Laser cavity, optical pumping system is examined. Tungsten halogen lamp is used as pumping source. The outcome of this work is that low power CW mode Nd:YAG lasers can be constructed easier and cheaper by using tungsten halogen lamps.

REFERENCES

[1]:Wilson and Hawkes, *Optoelectronics* (1998), Appendix 4).

[2]: Walter Koechner: Solid-*State Laser Engineering* 5^{th} *Edition* 46-54 (1999)

[3]:T.Kushida, L.E. Geusic: *Physics Review Letters* 21,1172 (1968).

[4]:T.Kushida, L.E. Geusic: *Physics Review Letters* 167,289 (1968).

[5]:H.F. Mahlein: *IEEE J. of Quant. Electr. QE-6,* 529 (1970).

[6]:C.G. Bethea: *IEEE J. of Quant. Electr. QE-4,* 254 (1973).

[7]:P.H. Klein, W.J. Croft: *J. of Appl. Physics. 38*, 1603 (1967).

[8]:http://repairfaq.ece.drexel.edu/sam/CORD/leot/course04_mod04/mod04-04.html (June, 20 2004).

[9]:Walter Koechner: Solid-*State Laser Engineering* 5^{th} *Edition* 204 (1999).

[10]:www.dentonvacuum.com/coatings/metal.html (June,26-2004)

[11]:www.goodmart.com/facts/light_bulbs/halogen_cycle.aspx (June, 24 2004).

[12]: *An Overview of Flashlamps and CW Arc Lamps*, Technical Bulletin 3, ILC Technology, Sunnyvale, CA, 1986)

[13]:http://repairfaq.ece.drexel.edu/sam/CORD/leot.html (June,30 2004)

APENDIX

Written software codes to calculate optimum out put coupler reflectivity. Codes are written in C programming language.

```
#include <stdio.h>
#include <conio.h>
#include <math.h>

float R;            //Reflectivity of output coupler
float Po;           //Output power (W)
float Pin;          //Input electrical power (W)
float r=0.002;      //Radious of the rod (m)
float l=0.06;       //Length of the rod  (m)
float Is;           //Rod's parameter
float A;            //Cross section area of the rod (m square)
float h;            //Planck's constant [J/s]
float w=1064.0;     //Wavelength [nm]
float n=1.82;       //Refractive index
float s;            //absorption cross section
float t;            //Fluoresence life time
float m=0.0257;     //Relative efficiency
float c;            //Speed of light
int i;

int main ()
```

```
{
h=6.626*pow10(-34);
w=w*pow10(-9);
s=6.5*pow10(-23);
t=115.0*pow10(-6);
c=3.0*pow10(8);
R=0.800;

A=r*r*3.14;
Is=h*c/(w*m*s*t);
printf("R     P\n");
for (i=1; R<1.0; i++)
        {
        P=((1R)/(1+R))*A*Is* ((2*m*Pin/(A*Is*(0.1-log(R))))-
1);
                R=R+0.001;
                printf("%f   %f\n",R,Po);
        }
printf ("press “q” to exit\n");
scanf ("i");
return 0;
}
```