STUDIES OF DIODE-PUMPED SOLID-STATE
LASERS BASED ON Nd:KGW AND Nd:YAG.

BY

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To my parents, brothers, and sisters.
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ABSTRACT

The experimental part of the thesis was dedicated to the studies of diode-pumped solid-state lasers. It includes experiments with end-pumped continuous wave (CW) Nd-doped crystals. In particular, we have concentrated on Nd.KGW, a relatively new and not studied in the literature about the laser materials. We have performed some basic measurements of this material. A fibre-bundle coupled laser diode array was used as a pump source. We have investigated two main optical arrangements for the pump, allowing operation in two regimes:

1- Low pump power operation using selected output power from a single fibre of the fibre bundle.

2- High pump power operation using the total output power from the bundle.

The main parameters of the cavities we use (e.g. the cavity mode and the pumping spot size), were determined using the matrix approach and the equations for propagation of the Gaussian beam.

The highest output power obtained in this work for Nd.KGW with a transverse electromagnetic (TEM\textsubscript{00}) single-mode, continuous (CW) operation, was 400 mW for 1700 mW pumping power from the diode laser. We present also data about the performance of a diode pumped Nd.YAG crystal.

Our experiment shows that Nd.KGW is a promising material for low and medium pumping power levels.
CHAPTER ONE

INTRODUCTION
1. INTRODUCTION

Nearly ten years ago when the technique of diode-pumped solid-state lasers (DPSS) was discovered.

At that time the technique was very expensive and not affordable, this is because of the limited serious research work in this area. But nowadays, the development of reliable high power diode laser arrays, the reduction of the expenses, and the compactness of such systems make it the most promising one among the other pumping techniques.

Beside the above mentioned advantages of this technique, the generation of the heat in the diode-pumped crystals is low compared to the other methods of pumping. This is because of the good matching between the emission wavelength and the absorption band of the crystal, that will result in total absorption for the pump beam in the absorption band of the crystal.

The interest in optical pump of solid-state lasers, and in particular DPSS technique, has dramatically increased because of the development of a large number of new solid-state materials in the last few years.

The rapid progress in the development of the DPSS leads to the searching and investigation for more efficient solid state materials for various applications in material processing, remote-sensing, medical and optical communications. [22]

One of those materials is Neodymium-doped potassium gadolinium tungstate, NdKGW, which is the most promising crystal with the following advantages: broad pump band centred at 810 nm, high anisotropy and efficient direct pump geometry.
The research reported on this thesis is about studying the DPSS based on Nd:KGW and Nd:YAG crystals. The experimental set-up was built at the Laser, Atomic and Molecular Physics (LAMP) laboratory at the International Centre for Theoretical Physics (ICTP).

During this research, the conditions and parameters that lead to high efficiencies and low thresholds in the end-pumped solid-state cavities, were studied.

Firstly, the pumping beam parameters, conditions and the spectral characteristics were determined.

Secondly, the characteristics and features of the active materials used in this work (Nd:KGW and Nd:YAG) were studied also. These conditions are the absorption, emission and the temperature dependence.

Thirdly, the studies and calculations of the cavity parameters and their optimisation were performed.

The optimisation of all the above mentioned items results in an efficient output lasers from the solid material.

The performance and the parameters of the laser output from each of the two crystals were studied by determining the slope efficiency and the threshold pumping power for each of them.

The results and data obtained in this research confirm the fact that the Nd:KGW crystal is a promising one.

The description of the theory relevant to our experiment was put in chapter two and the experimental set-up, results and discussion in chapter three. In chapter four, the conclusion and the aspects were put.
CHAPTER TWO

THEORY
2. THEORY

2.1 Generalities in laser physics:

Transition occurring between discrete energy levels in any atomic system is associated with either emission or absorption of photons. The governing equation being:

\[ E_2 - E_1 = h\nu_{21} \quad (2.1) \]

Where \( E_1 \) and \( E_2 \) are discrete energy levels, \( \nu_{21} \) is the frequency of the encountered photon and \( h \) is Planck's constant.

An electromagnetic wave whose frequency \( \nu_{21} \) corresponding to an energy gap of such atomic system can interact with it. In thermal equilibrium the population of the atomic system is larger in the lower levels of the system than that of the higher levels. When an electromagnetic wave of appropriate wavelength interacts with such system raising its atoms or molecules to higher levels, and hence absorption takes place.

The lasing process requires that energy equilibrium of the laser material be changed in such a way that the energy becomes stored in the atoms of this material. This change is achieved by an external pump source which transfers electrons from the lower energy levels to the higher levels. Thus the pump source produce a situation in which the higher energy levels are more populated than the lower energy levels, this is called "Population Inversion". And the material possess such inversion is called "Inverted Material". An electromagnetic wave of appropriate frequency, incident on this "inverted" laser material will be amplified; in fact the incident photon induces the atoms in the higher levels to drop to lower levels and hence emit new photons in phase of the incident photons. The energy is extracted from the atomic system and transferred to the radiation field. In general the atoms of the laser undergo repeated quantum jumps and so acts as microscopic transducers. As a result of the pumping process, atoms absorb energy, thus jumping to a higher energy level. On descending back to the lower energy level it releases a photon. [18].

In the laser cavity which consists of two reflecting mirrors with the inverted amplifying material and the pump source. The amplification of the signal inside the
cavity is achieved by the laser inverted material, this amplified signal is usually enclosed by the high reflecting cavity mirrors that hold this light and redirecting it through the inverted material (the active medium) for repeated amplification. To extract the amplified beam from the cavity, the reflectivity of the output mirror is reduced to allow part of this light to emerge from the cavity[16].

This outgoing amplified light is the laser beam, the word laser itself is an acronym for Light Amplification by Stimulated Emission of Radiation.

At the same time each atom should deal with the photons that have been emitted earlier and reflected back by the mirrors.

The stimulated emission is completely indistinguishable from the stimulating radiation field. This necessarily implies that the stimulated radiation will have the same phase and the same spectral characteristics as the stimulating emission. Thus a high degree of coherence is obtained in the beam [9].

2.2 Interaction of Radiation with Matter:

Consider, for simplification, an idealised material with just two non-degenerate energy levels, 1 and 2, level 2 being the higher, with population $N_1$ for level 1 and $N_2$ for level 2, the total number of atoms $N_{\text{tot}}$ is:

$$N_{\text{tot}} = N_1 + N_2 \quad (2.2)$$

The atom can descend from state $E_2$ to $E_1$ by emitting energy or from $E_1$ to $E_2$ by absorbing energy. This energy is added or removed from the atom appears as quanta of energy $h\nu_{21}$ of definite frequency.

Let us first give a word about the three types of interaction of electromagnetic radiation with matter, they are:

2.2.1 Absorption:

If a quasimonochromatic wave of frequency $\nu_{21}$ passes through a material with energy gap $h\nu_{21}$, then population of the lower energy level is depleted at a rate given by the following equation:

$$\frac{dN_1}{dt} = -B_{12}p(\nu)N_1 \quad (2.3)$$

Where: $p(\nu)$ is the radiation density, $B_{12}$ is a constant of proportionality with dimension cm$^3$/s$^2$ J. The product $p(\nu)B_{12}$ is the
probability per unit frequency that the transitions are induced by the effect of the field [9]

2.2.2 Spontaneous Emission:

The population of the excited level \( N_2 \) of an atom decays spontaneously to the lower level at a rate proportional to the population of the upper level:

\[
\frac{dN_2}{dt} = -A_{21}N_2 \tag{2.4}
\]

\( A_{21} \) is a constant of proportionality with a dimension \( s^{-1} \) and being a characteristic frequency of the upper level and is often called spontaneous transition probability. The atoms emitted spontaneously are incoherent. A characteristic physical parameter is the life-time of the electron in the excited state. The atom will return back spontaneously to the lower state and radiating away the energy. This process can occur without a presence of an electromagnetic field [9].

2.2.3 Stimulated Emission:

In this process the atom gives up a quantum to the radiation field by "induced emission" according to the following equation:

\[
\frac{dN_1}{dt} = -B_{12} \rho(\nu_{21})N_2 \tag{2.5}
\]

\( B_{21} \) is a constant of proportionality.

We remark that the probability of the induced transition is proportional to the energy density of the external radiation.

The net change in population of the lower and the upper levels, can be derived on using equations (2.3), (2.4) and (2.6):

\[
\frac{dN_1}{dt} = -\frac{dN_2}{dt} = B_{21} \rho(\nu)N_2 - B_{13} \rho(\nu)N_1 + A_{21}N_2 \tag{2.6}
\]

And then we obtained the following relation:

\[
\frac{dN_1}{dt} = -\frac{dN_2}{dt} \tag{2.7}
\]

\( N_1 + N_2 = N_{\text{tot}}, = \text{constant} \).

In thermal equilibrium transitions from \( E_1 \) to \( E_2 \) equal to the transitions from \( E_2 \) to \( E_1 \), then,

\[
\frac{dN_1}{dt} = \frac{dN_1}{dt} = 0 \tag{2.8}
\]
We can write

$$N, A_{21} + N, f(v) B_{21} = N, f(v) B_{12} \quad (2.9)$$

The first term in the above equation represents spontaneous emission, the second is the stimulated emission, and the term on the right hand side represents the absorption.

From Boltzmann distribution one can deduce the following:

$$\frac{N_2}{N_1} = \exp \left( \frac{(E_2 - E_1)}{KT} \right) \quad (2.10)$$

On using (2.10) with (2.9) we get:

$$\rho(v_{21}) = \frac{(A_{21} / B_{21})}{\left( \frac{g_2}{g_1} \right) \left( \frac{B_{12}}{B_{21}} \right) \exp(h\nu_{21} / KT) - 1} \quad (2.11)$$

Where $g_1, g_2$ denote the degeneracies of level 1 and 2 respectively. From the Black-body radiation theory, for the distribution of radiation density $\rho(v) dv$ contained in a bandwidth $dv'$ for an electromagnetic radiation contained in an isothermal enclosure in thermal equilibrium temperature $T$:

$$\rho(v) dv = \frac{8\pi \nu^3}{C^3} \frac{h\nu}{\exp(h\nu / KT) - 1} \quad (2.12)$$

Comparing equations (2.12) and (2.13) we can readily get:

$$\frac{A_{21}}{B_{21}} = \frac{8\pi \nu^3 h\nu}{C^3} \quad \text{and} \quad B_{21} = \frac{g_1}{g_2} B_{12} \quad (2.13)$$

These relations between the $A$'s and the $B$'s are called Einstein's relations [9].

**2.3 Population Inversion:**

In thermal equilibrium, the population of the low energy levels of an atomic system is generally larger than the population of the high energy levels. We note that the absorption coefficient is positive, and the incident radiation will be absorbed.

In atomic systems where population is larger for high energy levels, so the population difference will be negative and the absorption coefficient also will become negative. This means that there is a stimulated emission or amplification of the applied signal.

Thus it is customary to write the equation for the photon density rate as given below:

$$-\frac{\partial \rho(v)}{\partial x} = \rho(v) B_{21} g(v, v_0) \left( \frac{g_2}{g_1} n_1 - n_2 \right) \frac{1}{c} \quad (2.14)$$
g(ν_s, ν_o) is the lineshape factor.

\( c \) is the velocity of the light.

So when \( n_2 > n_1 \), this implies that \( \frac{\partial n}{\partial x} > 0 \).

It follows that an essential condition for the amplification process is the population inversion. We can summarize that as follows:

\[ N_2 > N_1 \quad \text{if} \quad E_2 > E_1 \]

We note that this condition can not be observed in thermal equilibrium.

When the populations of both energy levels are equal we speak of "inversion threshold".

In order to achieve population inversion we must have a source of energy to populate a specified energy level, this energy is called the pump energy.

To explain the pump process we treat the following two models:

(1) In case of the three level optically pumped systems, such as ruby, illustrated in Fig(2.1),

![Fig(2.1)](image)

All the atoms are initially in the lowest energy level \( E_1 \). Excitations are supplied to the solid by radiation with frequencies that will produce absorption into the broad band \( E_3 \).

The majority of the excited atoms undergo radiationless transition into an intermediate sharp level \( E_2 \). The energy lost by the atoms when it returns back to the ground state by emitting a photon. This transition is the one responsible for the laser action. Atoms in level \( E_2 \) will return to the ground state by spontaneous emission transition below threshold. When pump radiation is extinguished, level \( E_2 \) is emptied by
fluorescence. When pump intensity exceeds threshold then the decay from the fluorescent level consists of stimulated and spontaneous radiation, the stimulated emission produces the laser beam. Since the terminal laser level is highly populated ground state, $E_2$ must be populated with high population before the transition from $E_2$ to $E_1$ be inverted.

One of the important features of a three level system is that transition from the pump level to the upper laser level must be fast relative to the spontaneous transition.

Hence the life-time of the atoms in $E_2$ level should be large in comparison with the relaxation time of the transition from $E_1$ to $E_2$, which means

$$\tau_{32} \ll \tau_{21}$$

\(\tau\) is the relaxation time for a certain transition.

then $N_3$ in level $E_3$ is very small and can be neglected compared with $N_1$ and $N_2$, i.e.

$$N_3 \ll N_1, N_2$$

then we can write:

$$N_{\text{tot}} = N_1 + N_2 \quad (2.15)$$

An other feature in the three level system is that atoms are pumped directly from level $E_1$ to level $E_2$ with a momentary pause in level $E_1$, as if there were two energy levels $E_1$ and $E_2$. To have equal population in $E_1$ and $E_2$ then one half of the atoms must be raised to the upper level $E_2$.

$$N_2 - N_1 = N_{\text{in}}/2 \quad (2.16)$$

To preserve amplification, then the population of the second level should be greater than of the first one, and in many cases with practical importance, the number of the population inversion ($N_2 - N_1$) is less than the total number of atoms and so the pumping power necessary for maintaining this inversion is also small compared with the inversion power necessary for equal population of the level.

The disadvantage of the such systems is that greater than half of the total atoms in ground state must be transferred to the metastable level $E_2$, which provides large number of atoms for spontaneous emission. In addition each of the atoms in the pump cycle will transfer their energy into the lattice from $E_3$ to $E_2$ by radiationless transition. We note one of the drawbacks of the three level laser system which is that lasing takes place between the energy level $E_2$ and the ground state $E_1$, the lowest energy level of the system. This leads to a low efficiency.
(2) In case of the four level system, the pump transition starts from the ground state $E_0$ to the absorption band $E_1$. See Fig.(2.2),

![Diagram](image)

The atoms which are excited will continue rapidly to the metastable level $E_2$, lasing takes place between the metastable level $E_2$ and an other level $E_1$ above the ground state level $E_0$, called lower laser level, from which atoms undergo fast raditionless transition to the ground state.

Solid-state materials suitable for use in the four level system should have,

$$\tau_{10} << \tau_{21}$$

In addition the lower laser level should be far from the ground state to reduce population in the thermal equilibrium. The equilibrium population of the terminal laser level $E_1$ is given by

$$\frac{N_1}{N_0} = \exp\left(-\frac{\Delta E}{kT}\right)$$

(2.17)

$\Delta E$ is the energy difference between the lower laser level and the ground state and it is obvious if $\Delta E >> KT$, then $\frac{N_1}{N_0} < 1$, which means that $N_1 < N_0$. In this case inversion between level 2 and level 1 takes place with a very small pumping power.

Also in four laser systems the relaxation times $\tau_{32}$ and $\tau_{10}$ are small compared with $\tau_{21}$ [9].

2.4 The Metastable Level:

The metastable level is of great importance for the laser action to occur. It has relatively long life-time which enables the population inversion to occur.
In good laser materials the frequencies of the transition from level $E_1$ to level $E_2$ and from level $E_1$ to level $E_0$ fall within the frequency range of the vibration spectrum of the host crystal lattice, therefore all these transitions will relax directly through the non-radiative decay, for example by emitting phonons to the lattice vibrations. On the other hand the transitions $E_3$ to $E_0$, $E_3$ to $E_1$, $E_2$ to $E_0$ and $E_2$ to $E_1$ are of frequencies higher than the highest frequency of vibration of the crystal lattice. Atoms making such transition can relax through simple single-photon spontaneous emission. Since these transitions are not possible within the lattice, so these transitions will relax either by a radiative emission or multiple photon processes. So these high frequency transitions will have the much slower relaxation time. The pump level $E_3$ will relax directly into the metastable level $E_2$, while level $E_2$ itself is metastable and long lived because there is no other levels located close below it into which it can decay directly.

Selection rules state that the atom may get into the excited state and from it will have some difficulties to go back to the ground state. A state from which all dipole transitions are forbidden to decay to lower energy states is called metastable. An atom stay in such state much longer time than it would do in any other ordinary state, then from which can escape easily.

To increase the population in the metastable level, several conditions should be met, let us consider the four level system, energy is transferred from the pump band to the upper laser level by fast radiative transitions. Also the energy is removed from the lower laser level to the ground state by radiationless transitions. So for an electron in the pump band to decay to the upper laser level rather than decaying to the ground state, we must have $\tau_{32} \ll \tau_{30}$ for population to build up, also relaxation out of the lower laser level should be fast so $\tau_{10} \ll \tau_{21}$. In conclusion, if there is a good relaxation time ratio between any two energy levels, then population inversion is possible between them. So for a successful lasing, sufficient population inversion is a matter of pumping. Since the optical gain for a given population inversion is inversely proportional to the line width, so the metastable level should have a sufficiently narrow line width [9].
2.5 The Laser Rate Equations:

They consist of a pair of differential equations that describe the dynamic behaviour, population inversion, and radiation density within a laser medium. Considering the previous three and four level systems in Fig.(2.1) and (2.2), and by ignoring longitudinal and radial variation of radiation within the laser medium, we can derive the rate equations.

The threshold conditions for obtaining a laser and a first order approximation to the relaxation oscillations can readily be deduced from the rate equation. They are also useful in predicting the efficiencies and the general performance of the laser.

In applying the rate equations to various applications, the expression for the probability for stimulated emission $\rho(v)$ $B_{21}$ is replaced by the photon density $\phi$ and the stimulated emission cross section $\sigma$.

Einstein coefficient for stimulated emission $B_{21}$ can be written in term of stimulated emission cross section as:

$$B_{21} = \frac{c}{h \nu g(v)} \sigma_{21}(\nu). \quad (2.18)$$

$C$ is the speed of light in the medium $c = \frac{c_0}{n}$.

Since:

$$\rho(v) = h \nu g(v) \phi \quad (2.19)$$

Where:

$\rho(v)$ is the energy density per unit frequency.
$g(v)$ is lineshape factor.
$\phi$ photon density.

Then:

$$B_{21} \rho(v) = c \sigma_{21}(v) \phi \quad (2.20)$$

Considering the two systems of lasers, a discussion of the rate equation is below.

The three level systems: Assuming the transition from the upper pump band 3 to the upper laser level 2 is so fast so that $N_3 \approx 0$. In solid state lasers the ratio $\tau_{23}/\tau_{21} = 0$.

The spontaneous losses from the pump band to the ground state are expressed by us the efficiency factor $\eta_0$ which defines as

$$\eta_0 = (1+\tau_{23}/\tau_{31})^t \leq 1.$$
which determines what fraction of the atoms that falls from level 3 to be potentially useful in the laser action.

The change of the photon density in the three level system by assuming that all atoms are existing in either level 1 or 2.

\[
\frac{\partial n_1}{\partial t} = \left( n_z - n_1 \frac{g_2}{g_1} \right) \gamma_\sigma + n_1 \frac{1}{\tau_{21}} - W_p n_1 \quad (2.21)
\]

and

\[
\frac{\partial n_2}{\partial t} = - \frac{\partial n_1}{\partial t} \quad (2.22)
\]

Since:

\[n_1 + n_2 = n_{\text{tot}}.\]

Where \(W_p\) is the pumping rate with dimension \(s^{-1}\), \(n_1\) and \(n_2\) are the population densities of level \(E_1\) and \(E_2\) respectively.

The terms in the equation (2.21) represent the net stimulated, spontaneous emission and the optical pumping (can be thought of as the rate at which atoms are supplied to the metastable level) then we can write:

\[W_p = n_0 W_{13} \quad (2.23)\]

Where \(W_p\) is the pumping rate and \(W_{13}\) is the pumping parameter. We can define the inversion population density as:

\[n = n_z - n_1 \frac{g_2}{g_1} \quad (2.24)\]

Equations (2.21), (2.22) and (2.24) lead to,

\[
\frac{\partial n}{\partial t} - n \gamma_\sigma \frac{\partial n}{\partial t} - n + n_{\text{tot}} (\gamma - 1) + W_p (n_{\text{tot}} - n) \quad (2.25)
\]

Where \(\gamma = 1 + \frac{g_2}{g_1}\) and \(\tau_r = \tau_{21}\) (2.26)

and \(n_1 = \frac{n_{\text{tot}} - n}{1 + \left( \frac{g_2}{g_1} \right)}\) and \(n_2 = \frac{n + \left( \frac{g_2}{g_1} \right) n_{\text{tot}}}{1 + \left( \frac{g_2}{g_1} \right)} \quad (2.27)\)

The rate of change of the photon density is:

\[
\frac{\partial \varphi}{\partial t} = \sigma n \varphi - \frac{\varphi}{\tau_c} + S \quad (2.28)
\]

Where : \(\tau_c\) = is decay time of photon in the laser resonator.
S is the rate at which spontaneous emission contributes to the laser emission [9].

**The four level systems:** Here we assume that the transition from the pump band \((E_3)\) to the laser upper level \((E_2)\) occurs rapidly, so that \(n_3 \approx 0\), hence one can write for the rate of change of the population of the two levels \(E_1\) and \(E_2\):

\[
\frac{dn_1}{dt} = W_p n_0 - \left( n_2 - n_1 \frac{g_2}{g_1} \right) \sigma \varphi - \frac{n_2}{\tau_{20} + \tau_{21}}
\]

(2.29)

And:

\[
\frac{dn_2}{dt} = \left( n_2 - n_1 \frac{g_2}{g_1} \right) \sigma \varphi + \frac{n_1}{\tau_{21}} - \frac{n_2}{\tau_{10}}
\]

(2.30)

We note that:

\[
n_{tot} = n_0 + n_1 + n_2
\]

(2.31)

In an ideal four level system, we shall steadily fast empty level \(E_1\) in favour of \(E_0\). As if the system seems to be pumped from a large source independent of the lower laser level, For an ideal four level system having the inversion population density \(n\) we have:

\[
n = n_2,
\]

\[
n_{tot} = n_0 + n_2.
\]

So we can write:

\[
\frac{dn}{dt} = -n \sigma \varphi - \frac{n}{\tau_f} + W_p (n_{tot} - n)
\]

(2.32)

Where:

\[
\frac{1}{\tau_f} = \frac{1}{\tau_{21}} + \frac{1}{\tau_{20}}
\]

(2.33)

\(\tau_f\) is the fluorescence decay time.

\(\tau_{21} = 1/A_{21}\) is defined as the effective radiative lifetime associated with the laser line.

If we take into account that not all atoms are excited to the pump band and will end up in the upper laser level, then

\[
W_p = \eta_0 W_{03}
\]

(2.34)

where:

\[
\eta_0 = \left( 1 + \frac{\tau_{32}}{\tau_{31}} + \frac{\tau_{31}}{\tau_{30}} \right)^{-1} \leq 1
\]

(2.35)
2.6 Laser Basic Components:

A laser consists essentially of three main components:

2.6.1 The active medium:

This can be solid, gas or liquid. Its principal function is to amplify the incident electromagnetic waves.

This work is mainly devoted to solid-state active media.

2.6.2 The Pumping sources:

This component selectively pumps the energy into the active medium and hence selectively to populate certain energy levels. Consequently population inversion will be achieved [3]. The pumping schemes can be classified as:

(i) Optical Pumping:

A laser is said to be optically pumped when the population inversion is obtained by the absorption of radiation incident on the laser medium [18].

As examples of method employed in pumping, we give: Flash lamp pumping for pulsed, arc lamp for continuous pumping, exploding wire, an other laser, the sunlight and the diode laser. Also chemical reaction in gases and high voltage electron beam pumping in gases and solids [3].

(ii) Electrical Pumping:

This method is also called the gas discharge pumping. We get pulses at high pressure while at low pressure we get a continuous wave. Here the electron collides or makes an impact with atoms and then energy transfers by collision between different atoms.

In this work the optical pumping was used, in particular the diode laser pumping [3].

2.6.3 The optical resonator:

This component consists of two opposite mirrors, which stores part of the induced emission concentrated within a few resonator modes [1].

Resonators fall into two main categories:

(1) Stable resonators:

Here the beam inside the resonator bounces forth and back almost paraxially to the stem, as shown in the Fig(2.3) [1].
A simple resonator usually consists of two curved mirrors of radii $R_1$ and $R_2$. Details concerning this resonator are in a later part of the thesis.

**2) unstable resonators:**

Here the beam bounces forth and back spreading away from the axis of the resonator, as shown in Fig. (2.4) [1].

In general for an efficient laser action, a good active medium and optimum condition for both pumping and resonator construction must be observed.

The Fig. (2.5a) shows the general basic components of the laser, two mirrors are assumed for the construction of the optical resonator together with the side-pumping by a flash lamp [1].
2.7 Types of lasers:

The laser is named after its active medium, accordingly, there are three main categories of lasers: Gas state, liquid state and solid state lasers [7].

2.7.1 Gas state lasers:

In gases the broadening of energy levels is rather smaller than in solids. For gases at low pressures optical pumping is not used since collision induced broadening is very small, and the line width is mainly determined by Doppler broadening. The optical pumping will be inefficient since the emission spectrum of these lamps is more or less continuous, where as there is no absorption band in the active material (gas). The gas lasers are usually pumped by electrical means i.e. excitation is achieved by passing sufficiently large current (continuous or pulsed) through the gas. Others mechanisms for pumping gas lasers are: Gas dynamic expansion, chemical pumping and optical pumping by means of an other laser [7].

2.7.2 The liquid-state lasers:

The liquid lasers of an active medium of a certain organic dye compound in liquid solvents, such as ethyl alcohol, methyl alcohol, or water. The laser dyes usually belong to one of the following classes:

(i) Ploymethine dyes: \( \lambda = 0.7-1.5 \ \mu \text{m} \).
(ii) Xanthene dyes: \( \lambda = 0.5-0.7 \ \mu \text{m} \).
(iii) coumarin dyes: \( \lambda = 450 \ \text{nm} \).
(iv) Scintillator dyes: they oscillate in the UV region.

The organic dyes usually have their strong absorption band in the UV or visible region of spectrum. So when they are excited by a light of an appropriate wavelength they display intense and broad band fluorescence spectra [7].

2.7.3 Solid State Lasers:

By solid state lasers we mean those lasers having their active medium either an isolating crystal or glass. The ions used in doping usually belong to the series of the transition elements such as metal ions Cr\(^{3+}\) or rare earth Nd\(^{3+}\). The active transitions used for the laser action involve states arising from the inner unfilled shells. As a consequence atoms tend to have longer decay time.

One can observe the following in solid-state materials that suit the lasers.
(1) Non-radiative decays are fairly weak, so that the upper state life time $\tau$ is nearly equal to the spontaneous life time (millisecond range). Since for three level laser the critical pump rate $W_{cp}$ is equal to $1/\tau$, this means that the value of $W_{cp}$ is low enough to permit laser action.

(2) The transition line width $\Delta v_0$ is relatively small, since broadening mechanisms are relatively ineffective. For four laser systems (like Nd$^{3+}$) the threshold pump rate is proportional to $1/\sigma_T \geq 1/\sigma_T_{cp}$, we have $\Delta v_0 \propto 1/\sigma_T_{cp}$. So small line width of the laser implies that low threshold pumping rate $W_{cp}$.

Examples of solid state lasers are:

(1) **Ruby laser:**

It is Al$_2$O$_3$ crystal in which small percentage of Al$^{3+}$ ions are replaced by Cr$^{3+}$ ions. It follows the three level system scheme [7].

(2) **Neodymium Lasers:**

They are the most common and popular solid state lasers. The active medium is the crystal Y$_2$Al$_5$O$_{12}$ (Called YAG, an acronym for yttrium aluminium garnet).

In this laser material some of Y$^{3+}$ ions are replaced by Nd$^{3+}$ ions. Also phosphate or Silicate glasses are doped with Nd$^{3+}$ ions. The typical doping of Nd$^{3+}$ in YAG is 1%. Higher doping leads to fluorescence quenching and results in strained crystal, since the radius of Nd$^{3+}$ is 14% larger than that of Y$^{3+}$. This doping level makes the YAG crystal appear pale purple since the absorption band of the Nd$^{3+}$ are in the red region of spectrum.

The common Nd lasers are:

(i) Nd: YAG and (ii) Nd Glass.

In this work some details are given about Nd:YAG laser as an example, since it is typical one for solid state lasers, and similar to Nd:KGW laser, also both of them were used [7].

(i) **Nd:YAG:**

The two main pump band occur at wavelengths 0.73$\mu$m and 0.8 $\mu$m, these two pumping band are coupled to the upper laser level ($^4F_{3/2}$) by fast non radiative decay from where the decay to the I levels occurs (notably $^4f_{9/2}$, $^4f_{11/2}$ and $^4f_{13/2}$). The rate of this decay is much slower (0.23 sec) since the transition is forbidden by the electric dipole...
interaction and because of the weakness of nonradiative decay because of the large energy gap between $^4F_{3/2}$ and the nearest level below it. See Fig (2.5 b).

![Energy Level Diagram](image)

This means that level $^4F_{3/2}$ accumulates the large fraction of the pump energy and therefore acts as an upper laser level. There are several transitions between $^4F_{3/2}$ and the lower lying levels, but the strongest one is between $^4F_{3/2}$ and $^4I_{11/2}$. The level $^4I_{11/2}$ is coupled to $^4I_{9/2}$ by fast nonradiative decay, since the energy difference between the $^4I_{11/2}$ and the ground state is about the order of magnitude of $KT$, then thermal equilibrium is rapidly established between them. $^4I_{11/2}$ in a good approximation is always considered empty, so it is considered as a favourable candidate as lower laser level.

The laser action of Nd:YAG takes place between $^4F_{3/2}$ and $^4I_{11/2}$ transition via four level scheme. It is worthy to mention that Nd:YAG at 1.06 is homogeneously broadened at room temperature due to interaction with lattice phonon. The corresponding line width $\Delta \nu_0=6.5$ cm$^{-1}$ = 195 Ghz at $T=300$ K. This makes YAG a good one for mode-locking operation, also the long life time of the upper laser level ($\tau$ =0.23 sec) makes it good for Q-switched operation.

Nd:YAG can operate either in CW or pulsed mode of operations [7]

About its output characteristics:

(1) Output power up to 200 W.
Average output power of 500 W for pulsed operation of repetition rate (50 Hz).

The slope efficiency about 1% to 3% for both pulsed and CW operation [7].

Nd:YAG laser is used in variety of applications among which:

1. Ranging (in military laser range-finders and target designator).
2. Scientific application (Q-switched Nd:YAG laser).
3. Material processing (cutting, drilling, and welding).
4. Medical applications (Photocoagulation).

2.8 Properties of Solid State Lasers:

A good solid state material for efficient lasers usually shows the following: they must possess sharp fluorescence lines, strong absorption band and relatively high efficiency for the fluorescent transition of interest. Doped crystals invariably exhibit these characteristics [10].

The ions of transition metals, rare earth (lanthanide and actinide series) are of interest as active ions in this connection.

In addition to the sharp fluorescence line of emission, a solid laser material should possess also broad-band pump transition [17].

2.9 Solid State Host Materials:

They are grouped into crystalline solids and glasses. Their selection is based on the following criteria:

1. The axial variation of index of refraction usually leads to inhomogeneous propagation of light through the crystal and consequently to a poorer laser beam.
2. The crystal should possess chemical and thermal properties that is not influenced by the heat generated during the pump process, thus avoiding excessive stress under thermal load.
3. During doping optimum conditions must be observed [9].

2.10 Calculation of the parameters of the Laser Resonator:

In this work two approaches were used to calculate the resonator parameters, they are:

(i) Gaussian beam formula
(ii) Matrix approach formulae.
The first one is fast and easy if the parameters of the resonator are determined, the second also is easy but not fast also, it is used in some computer's software.

2.11 Gaussian Beams:

When the laser is oscillating in TEM$_{00}$ mode, it emits a beam with a Gaussian intensity distribution, also other modes exhibit Gaussian intensity distribution multiplied by a certain polynomials. Thus beams emitted by any laser are called Gaussian beams [6].

2.11.1 Calculation of the parameters of the resonator using the propagation equations of the Gaussian beam:

The intensity distribution in any curved mirror cavity is characterised by a beam waist such as that shown in Fig.(2.7).

\[ I(r) = \exp\left(-\frac{r^2}{\omega_0^2}\right) \]  

(2.36)

where $r$ is the distance from the centre of the beam.

The intensity is normalised to unity at the centre of the beam. When $r = \omega_0$, the intensity is $1/e^2$ times that of the centre.

The beam propagates inside and outside the cavity in such away that it remains its Gaussian profile.
At a distance \( Z \) from the beam waist the intensity distribution is given by the equation (2.36) with replacing \( W_0 \) with \( W(Z) \) which is given by:

\[
W(Z) = W_0 \left[ 1 + \left( \frac{Z\lambda}{W_0^2 \pi} \right)^2 \right]^{\frac{1}{2}} \tag{2.37}
\]

at large distances from the beam waist, the Gaussian beam diverges with an angle \( \theta \) such that:

\[
\theta = \frac{\lambda}{\pi W_0} \tag{2.38}
\]

The wave-front at the beam waist is that of a plane wave.

At a distance \( Z \) from the waist the radius of curvature of the wave front \( R(Z) \) will be given by:

\[
R(Z) = z \left[ 1 + \left( \frac{\pi W_0^2}{Z\lambda} \right)^2 \right]^{\frac{1}{2}} \tag{2.39}
\]

To apply the above equations to the laser cavity we must know the size and position of the beam waist.

In the confocal cavities where mirrors are separated by a distance ‘\( d \)’, the size of the beam waist \( W_0 \) at \( Z=0 \) will be given by

\[
W_0 = \left( \frac{d \lambda}{2 \pi} \right)^{\frac{1}{2}} \tag{2.40}
\]

When the cavity is not confocal then it is customary to define a stability parameters (\( g \)-parameter) of the two mirrors used in the cavity [9]:

\[
g_1 = 1 - \frac{d}{R_1} \tag{2.41}
\]

And

\[
g_2 = 1 - \frac{d}{R_2} \tag{2.42}
\]

Where \( R_1 \) and \( R_2 \) are the radii of curvature of the mirrors. Then the size and the position of the waist are found by the matching the radii of curvatures of the wave front and the mirror. If this matching does not exist then the stable electric field distribution also will not exist i.e. the rays would not follow a closed path. Then the radius of curvature of the wavefront of the beam must be known at two different locations \( Z_i \) (the
distance of the mirror 1 from the waist) and \( Z_2 \) (the distance of the mirror 2 from the waist) [6].

We have:

\[
R(Z_1) = R_1 \quad (2.43)
\]

\[
R(Z_2) = R_2 \quad (2.44)
\]

We can write \( Z_1 \) and \( Z_2 \) in terms of the stability parameters:

\[
Z_1 = \frac{g_1(1 - g_1)}{g_1 + g_2 - 2g_1g_2} \quad (2.45)
\]

And

\[
Z_2 = \frac{g_1(1 - g_1)}{g_1 + g_2 - 2g_1g_2} \quad (2.46)
\]

Also we can write for the beam waist size \( W_0 \):

\[
W_0 = \left( \frac{d\lambda}{\pi} \right)^2 \left[ \frac{g_1g_2(1 - g_1g_2)}{(g_1 + g_2 - 2g_1g_2)^2} \right]^\frac{1}{4} \quad (2.47)
\]

Now the spot size of the beam at any location, in particular for mirror 1:

\[
W(Z_1) = \left( \frac{d\lambda}{\pi} \right)^2 \left[ \frac{g_2}{g_1(1 - g_1g_2)} \right]^\frac{1}{4} \quad (2.48)
\]

Similarly for mirror 2:

\[
W(Z_2) = \left( \frac{g_1}{g_3} \right)^\frac{1}{2} W(Z_1) \quad (2.49)
\]
2.12 Stability of the Resonators:

The equation for the spot size of the beam, contains a negative root \((1-g_1g_2)\), if the product \(g_1g_2\) is greater than unity then the spot size will be imaginary.

The cavities for which the product \(g_1g_2\) greater than unity are called Unstable, and for which the product is less than the unity are called Stable Resonators [6].

One can write for the stability criterion for the laser cavities, as follows:

\[
g_1g_2 = (1 - \frac{d}{R_1})(1 - \frac{d}{R_2}) < 1
\]  \hspace{1cm} (2.51)

When \(g_1g_2 = 1\) we get a hyperbola, shown in Fig(2.8).

Stable resonators are located between the two branches of the hyperbola, outside these branches are the unstable ones.

In figure (2.8), CC stands for concentric, CF for confocal, PP for plane parallel, and h for hemispherical resonators. The dashed line indicates the sensitive resonators of \(g_1g_2 = 1/2\).

2.13 Optical Resonator:

As mentioned before the optical resonator consists of two reflectors facing each other, e.g. Fabry-Perot interferometer. It is not necessary that the two reflectors be plane, but should be well aligned so that multiple reflections can take place [6].
Consider a Fabry-Perot resonator with a wave travelling inside it, normal to the mirrors, with amplitude $A_0$. After many reflections the field inside the cavity will be:

$$E = A_0 (1 + r^2 e^{i\phi} + r^4 e^{2i\phi} + \ldots) \quad (2.52)$$

Travelling to the right.

$r$: is the amplitude reflection coefficient of both mirrors.

$\phi$: is the phase change, associated with one round trip.

d: distance between the two mirrors.

The intensity inside the cavity will be:

$$I = I_0 \frac{1}{1 + F \sin^2 \frac{\phi}{2}} \quad (2.53)$$

Where

$$F = \frac{4R}{(1 - R)^2} \quad (2.54)$$

$R$ is the reflectance.

The above expression of the intensity (2.53) is the transmittance of Fabry-Perot interferometer.

The condition of equality of $I$ and $I_0$ is that:

$$m\lambda = 2d \quad (2.55)$$

Which the famous constructive condition.

For all values of $\lambda$ the intensity inside the resonator is smaller indicating that the wave either absorbed or transmitted by the mirrors, so oscillation can not take place.

It is convenient to think of an output mirror having an effective reflectance $R_{\text{eff}}$ equal to $R$ when $m\lambda = 2d$.

We write

$$R_{\text{eff}} = \frac{R}{1 + F \sin^2 \frac{\phi}{2}} \quad (2.56)$$
Commonly the second mirror of the cavity is 100% reflectance.

The interferometer will transmit fully at a series of wavelengths separated by free spectral range:

$$\Delta \lambda = \frac{\lambda^2}{2d}$$  \hspace{2cm} (2.57)

Or in terms of the frequency:

$$\Delta \nu = \frac{C}{2d}$$  \hspace{2cm} (2.58)

Generally, in a laser the effective reflectance is equal to \( R \) only at a discrete frequencies separated by \( \Delta \nu \).

The spectral modes of the laser resonator can be understood through the following set of diagrams. The mode of the laser resonator can be defined as self-consistent field configuration i.e. optical field distribution reproduces itself after each round trip in the resonator. Usually the modes of the resonator written as TEM\(_{xy}^{m,n}\), where TEM stands for Transverse Electromagnetic Field, and \( x \) and \( y \) are the numbers of the bright spot in the \( x \) and \( y \) directions respectively.

The TEM\(_{00}\) is the lowest mode with the least diffraction losses[14].

### 2.14 Types of optical Resonators:

As mentioned previously, there are two main categories of resonators stable and unstable resonators. See Table (2.1) for more details:

<table>
<thead>
<tr>
<th>No.</th>
<th>Type of the Resonator</th>
<th>The Resonator’s Parameters</th>
<th>Remarks</th>
</tr>
</thead>
</table>
| 1-  | Symmetric.             | i) Radii of curvature: \( R_1 = R_2 = R \).  
    | Fig (2.9)              | ii) The \( g \)-parameter: \( g_1 = g_2 \). | The waist of the Gaussian beam lies at the centre of the resonator |
| 2-  | Half-symmetric.        | i) Radii of curvature: \( R_1 = \infty \) & \( R_2 = a \). | The allowed range for \( g_2 \) is from +1 to 0 in the \( g \)-plane |
| 3- | Symmetric confocal. Fig.(2.11) | i) Radii of curvature: $R_1 = R_2 = d$.  
ii) The g-parameter:  
$g_1 = 1 \& g_2 \cdot g = 1 - d/R_2$.  
| 4- | Long radius. Fig.(2.12) | i) Radii of curvature: $R_1 = R_2 = \infty$.  
ii) The g-parameter:  
$g_1 = g_2 = 0$.  
| 5- | Hemispherical. Fig.(2.14) | i) Radii of curvature: $R_1 = \infty \& R_2 = a$ value.  
ii) The g-parameter:  
$g_1 = 1 \& g_2 \approx \Delta d/d \approx 0$.  
iii) The spot size at the plane mirror:  
$W_0^2 = W_1^2 = \frac{d \Delta}{\pi \sqrt{d}}$.  
|  |  | This type is useful in obtaining the laser oscillation from laser medium whose gain is very small. Here due to the small mode size there is a small diffraction losses.  
|  |  | This type is avoided in practical although it has large volume mode, because it is difficult to align.  
|  |  | They are the most common used ones in the practical laser, especially in the low and medium power gas lasers. The advantage of this type of resonators is that the mode alignment difficulties can be eliminated completely.  


iv) The spot size at the curved mirror:

\[ W' = \frac{d\lambda}{\pi} \sqrt{\frac{d}{\lambda d}} \]

Table (2.1)
2.15 Matrix approach in calculating the parameters of the resonator:

The trajectory of any ray passing any refracting medium will be determined by (i) Co-ordinates of one point on it, and (ii) the angle it makes with the z-axis. Let them be y and v respectively. Also the angle is usually replaced by what is called optical direction cosine \( V = nv \), where \( n \) is the refractive index. It is also important to determine the input and output reference planes, assume they are RP\(_1\) and RP\(_2\) respectively [2].

Assume that the co-ordinates of the ray on RP\(_1\) are \( y_1 \) and \( V_1 \), and on RP\(_2\) are \( y_2 \) and \( V_2 \).

To analyse the passage of the ray from RP\(_1\) to RP\(_2\), we need to express \( y_2 \), \( V_2 \) in terms of \( y_1 \), \( V_1 \), i.e. to know the properties of the ray coming from RP\(_1\) at RP\(_2\).

These equations for both types of elements are found linear and therefore can be written in the form of a matrix like:

\[
\begin{bmatrix}
  y_2 \\
  V_2
\end{bmatrix} =
\begin{bmatrix}
  A & B \\
  C & D
\end{bmatrix}
\begin{bmatrix}
  y_1 \\
  V_1
\end{bmatrix} \tag{2.61}
\]

And the matrix element is being that its determinant is unity, i.e. \( AD - BC = 1 \). Where \( A, B, C \) and \( D \) are symbols indicating parameters of the ray [2].

2.15.1 The Ray transfer matrix:

Consider the beam propagating as shown in Fig (16.2).

![Figure 16.2](image)

originating from S (RP\(_1\)) at co-ordinates \( y_1 \) and \( V_1 \), going to a certain reference plane (RP\(_2\)) with co-ordinates \( y_2 \), \( V_2 \). In this case, the angle \( v_1 \) will not change, but the distance from the axis will change:

\[ y_2 = \text{RP} = PQ + QR. \]
Then $y_2$ could be written as:

$$y_2 = y_1 + \frac{t}{n} (n v_1) = 1y_1 + TV_1.$$ 

And

$$V_2 = V_1 = 0y_1 + 1V_1$$

Therefore we can write:

$$\begin{bmatrix} y_2 \\ V_2 \end{bmatrix} = \begin{bmatrix} 1 & T \\ 0 & 1 \end{bmatrix} \begin{bmatrix} y_1 \\ V_1 \end{bmatrix}$$

(2.62)

So the ray transfer matrix of the transition can be obtained as:

$$\tau = \begin{bmatrix} 1 & T \\ 0 & 1 \end{bmatrix}$$

(2.63)

$T$ is called the reduced thickness $= t/n$.

Also, we can by the same procedure obtain the refraction matrix, it is then:

$$\Re = \begin{bmatrix} 1 \\ \frac{-(n_2 - n_1)}{r} \\ 0 \end{bmatrix}$$

(2.64)

Where $r$ is the radius of curvature of the curved surface, $n_2$ and $n_1$ are the refraction indices of the two media separated by the curved surface. The quantity $(n_2-n_1)/r$ is called the refracting power of the surface [2].

The reflection matrix can be obtained also, as:

$$\Re_f = \begin{bmatrix} 1 \\ 0 \\ -P \end{bmatrix}$$

(2.65)

Where $P$ is the reflection power of the surface.

The above discussion can be applied to the resonator to get its ray transfer matrix from which one can determine the resonator mode parameters and properties.

The construction of the ray transfer matrix is made through a chain of multiplication of translation, reflection and refraction matrices going from the output reference plane to the input reference plane and return back again to the same point on the output plane (round trip) [2].

Assume the production of the chain of these matrices is (The ray transfer matrix):

$$\quad$$

33
Ray transfer matrix representing the round trip:
\[
\begin{bmatrix}
A & B \\
C & D
\end{bmatrix}
\]
(2.66)

Where \(AD-BC = 1\).

Then the resonator parameters can be calculated as follows:

The trace of ray transfer matrix is calculated:
\[\Lambda + D\]

The eigenvalues:
\(\epsilon_1\) and \(\epsilon_2\)

And the corresponding eigenratios:
\((\epsilon_1-D)/C\) and \((\epsilon_2-D)/C\)

If \(\Lambda+D\) is between +2 and -2, then \(\epsilon_1\) and \(\epsilon_2\) can be written as:
\[\epsilon_1 = e^{i\theta}\] and \[\epsilon_2 = e^{\pm\theta}\]

Where \(\theta\) specified within the range \(0 < \theta < \pi\).

Outside the above range of the \(\Lambda+D\):
\[\epsilon_1 = e^{\pm\theta}\] and \[\epsilon_2 = e^{\pm\theta}\]

These eigenvalues are important in calculation of the parameters of the resonator.

The method to determine these parameters using the matrix approach is as follows:

First we have to determine the following parameters:

The stability condition:
\[1 > (\Lambda + D)/2 > -1\]

The eigenvalues:
\(\epsilon_1\) and \(\epsilon_2\).

Cos\(\theta\) :
\[\cos\theta = (\Lambda + D)/2\]

Radius of curvature measured at the output plane:
\[R = 2B/(D-A)\]

Divergence of the wave front measured at the output plane:
\[1/R = (D-A)/2B\]

Beam radius:
\[W = [(\lambda B)/\pi \sin\theta)]^{1/2}\]

Waist location:
\[Z = (A-D)/2C\]

Waist radius:
\[W_0 = [(-\lambda \sin\theta)/\pi C]^{1/2}\]

Where \(\lambda\) above is the wavelength [2].

The last approach was used to calculate the parameters of the resonators which were used throughout this work. These calculated parameters were compared with those given by the Gaussian formulae, the agreement was found good.

The matrix approach is faster and handy. There is a computer programme with the same approach that was used to determine and to compare these resonator parameters [2].
2.16 Optical Pumping:

In our experimental work a diode laser was used to pump the radiation into the solid material so as to get the laser. In optical pumping the source is chosen to provide maximum possible light in the absorption region of the laser active medium. The electrical current which is supplied to the pump source is converted to optical radiation with high fluxes in given spectral bands.

The efficient pump source will emit maximum radiation at wavelengths that excite atoms in laser materials and produce minimal emission in all spectral region out of this useful absorption bands.

The various sources of optical pumping for solid state lasers can be grouped into:
(i) Noble gas and metal vapour discharge lamps, (ii) filament lamps, (iii) non electrical sources such as the sun, (iv) the chemical flash bulbs, (v) the radiation obtained from the detonations and (vi) the laser diode [9].

The application of a particular pump source depends on the desired output power, the mode of the operation, high or low repetition rate, and on the laser material which has to be pumped. For example pulse operation can be obtained either from noble gas flash lamps or laser diodes, the other pump sources provide CW or quasi-CW pumping.

In high gain media such as Nd:YAG and Nd:KGW all the above sources can be utilised.

2.17 Laser Diodes as a pump source:

It is the most promising pumping method for solid state laser materials. In the past serious application of this method was not achieved due to the low output power, low packing density and high cost of the diode laser components. But nowadays there is a continuous interest in this technique, the reason of this stems from the increase in the system efficiency and component life time and the reduction of the thermal load of solid state laser materials. The latter leads to the reduction of the thermo-optic effects and therefore better beam quality. Also it enables an increase in the pulse repetition frequency[8].

This method of pumping has higher efficiency than the flash lamps, in pumping the Nd:YAG and Nd:KGW lasers. And since Nd-doped crystals have strong and broad
absorption line e.g. NdKGW which is an excellent candidate for efficient diode pumping [21].

This stems from the good spectral match between the laser diode emission and the absorption bands of the of Nd materials. The output radiation to the electrical input efficiency is higher in flash lamps than laser diodes, but small fraction of the blackbody spectrum is usefully absorbed by the Nd bands [9].

The good match between the diode laser emission and the long wavelengths absorption bands of Nd leads to reduction in the amount of heat deposited in laser material. So all the pumping power will be absorbed in the absorption band.

Also the life-time and the reliability of the system will be higher in the laser diode pumped solid state lasers. These advantages make the diode pumping is the most preferable than the lamp pumping.

In flash lamps pumping at higher pumping fluxes there is substantial amount of UV content which causes material degradation in the pump cavity and in the coolant, this is avoided by using laser diode pumping. So the absence of the high-voltage pulses, high temperatures, and UV radiation in laser diode pumped systems lead to much more benign operating features in this field.

The first laser diode action was in GaAs. Improvements were made so as to get reduced threshold current, higher slope efficiency, life-time and output power. To achieve this some devices such as double-heterostructures, multiple-quantum-well structures, gradient-index single quantum-well-structures, monolithic phased arrays and multiple-stripe lasers were used. The production of diode arrays follows two different ways, multiple strips on single GaAs with small stripe to stripe spacing. So by this way an array which phase-locked can be obtained from which a beam can be focused with diffraction-limited spot.

Also higher power levels and more stripes on a single chip can be obtained with the phase-locking technique [9].

The building blocks of solid state laser pumps are the incoherent arrays.

2.17.1 Single Diode:

The first diode laser was a homojunction, which is made entirely from one semiconductor material (e.g. gallium arsenide) The different portions of this diode have
different concentrations of doping. The junction was of the same material. Such laser diode has threshold current of 40,000 A/cm² and quantum efficiency of 20% [9].

More developed single laser diode with decreased threshold current 8000 A/cm² and increased quantum efficiency 40%, is a GaAlAs-GaAs single heterojunction laser diode. In this type the active medium is sandwiched between two different chemical components, typically GaAlAs. Further developments lead to reduction of the threshold current (1000-3000 A/cm²), this was obtained by the double heterojunction laser which is consist of multiple layer of GaAlAs-GaAs-GaAlAs, 0.5 μm GaAs sandwiched as an active medium.

The most advanced and with high efficiency CW pumped laser diode are the quantum-well structures (QW), where the active layer is less than 30 nm (the order of de Broglie wavelength of an electron). The QW laser diodes allow better utilisation of carriers for radiative transitions as a result their threshold current decreases several times than that of the normal double-heterostructure (DH). The common types of the QW diodes are:

The diode based on the single quantum well and graded index is better than MQW from efficiency, output power and damage threshold point of view [9]. Single-quantum well double-heterostructure (SQW-DH), the graded-index separate confinement heterostructure (GRINSCH) and the multiple quantum well (MQW) structures.

The peak power of the laser diode is limited by the catastrophic optical damage. The output power can be increased by spreading the beam over a large area of the output facet.

Increasing the thickness of the active region lead to some extent to increasing of the output power. This output power increases linearly with the stripe width, but they lase at a multimode of incoherent filament.

In order to achieve more stable laser diode operation, the broad active stripe is divided into single-mode stripes, which gives multistripe structures or linear arrays, which the main constitute of the laser diode pumping [9].

2.17.2 Linear Array:

Here the stripes are formed by a spatial variation of induced current (gain-guided) or material composition (index-guided). The stripe geometry has the ability to limit the
number of modes of the laser, with an aim to obtain a single mode and better output than multimode produced by wide-stripe diode [9].

There are two multistripe systems: coherent and incoherent. In the first design each stripe operates in the fundamental transverse mode and coupled to the adjacent stripes. The arrays, of optical field are phase-locked. In solid state lasers pumping, incoherent arrays are used because the radiation pattern does not have to be tightly imaged into a small spot. In incoherent arrays there is optically insulating layer between the active stripes, and so each stripe represents an independent layer, this leads to the advantage that a very large number of stripes can be built on a monolithic substrate. In the advanced class of structures the catastrophic optical damage results from absorption of active region at the facet, can be avoided by making the facet non-absorbing [9].

2.17.3 Planner or 2-dimensional arrays:

These are made by subassembling extended linear arrays or bars of individual stripe laser, and then stacking these linear arrays to form a 2-dimensional array. This process is done by growing a sequence of layer of AlGaAs on the GaAs substrate using MOCVD technique. The layers act to supply carrier and optical confinement to achieve good lasing efficiency [9].

2.18 The performance of the laser diode arrays:

Here the discussion about the performance of the laser diode arrays suitable for solid state laser pumping is provided into the following points:

2.18.1 The output power:

Because of the improved device technology and integration of an increasing number of devices into arrays, laser diodes achieved the highest optical output power recently. The discussion here based on quasi-CW laser diode( those of pulses longer than few microseconds).

The pumping of Nd: YAG and Nd: KGW requires a pulse of width approximately 200 microseconds, so the quasi-CW pumping system is suitable for pumping of these materials.

As the pulse width for typical laser diode(GaAlAs) increased the output peak power decreased, this is because of the catastrophic facet degradation(absorption of the optical
energy near the facet), starting a thermal runaway condition which raises the temperature of the facet to melting point.

By forming the laterally isolated regions, high power laser diodes arrays can be obtained by adding more stripes, otherwise as the width of the laser approaches and exceeds the cavity length, transverse lasing and amplified spontaneous emission compete for the carriers and so the laser action is diminished [9].

2.18.2 Efficiency:

The conversion of the electrical input energy to optical output efficiency of a laser diode depends on:

(i) Internal quantum efficiency.

(ii) Electrical series resistance.

(iii) Threshold current.

(iv) Operating point of the laser relative to the threshold current.

The first three items can be improved through optimisation of the internal structure of the diode, like layer thickness, and doping concentration, the fourth one requires laser to work at a very high output power densities.

The performance of the commercially available laser diodes usually expressed in terms of the slope efficiency, the usual values of these slope efficiencies are on the order of 25%.

The index-guided, single-quantum-well structures have efficiencies 40%-50% on the average. The conversion efficiency is one of the key parameters in the design of the laser diodes. One of the major limiting factor with regard to the average power in the laser diodes is the heat dissipation in 2D array, researches in graded-index single quantum well structure show that conversion efficiency of 40% and higher, this implies that 1.5 W dissipated for each watt emitted. Also further improvements lead to increasing the emitted power without increasing the total dissipated power of the array [9].

2.18.3 Life-time:

One of the features of the laser diodes is their long life-time, $10^5$ hours at room temperature, CW output power of few miliwatts per stripe.

Generally life-time increases as the threshold is lower for the diode current. Individual laser diode in an array can fail for several different reasons, some of them mentioned below:
(1) Damage of the laser mirrors (facets) leads to decrease their reflectivities, or increasing of the non-radiative carrier recombination at the facets.

(2) Ohmic contact degradation which increases the thermal and resistance effects in the laser diode.

(3) Internal damage results from movement of the lattice defects into the active region, so decreasing the quantum efficiency.

Some researches show that mean life-time to failure up to $10^5$ hours, also the failure of an individual diode does not short out the whole array since of the bulk resistance which is enough to distribute the current. Life-time for arrays working at proper temperature limits can be estimated as of order of five to ten years continuous operation [9].

2.18.4 Spectral properties:

The most critical spectral properties and features of laser diodes for pumping solid state materials are: the centre wavelength of the emission, the spectral width and the shift of the wavelength with the temperature.

The wavelength of the laser diode depends on the band gap of the material in which the electrons and holes recombine, in binary materials like gallium arsenide, the gap band has only one value.

Range of possible wavelengths can be obtained in ternary compound (like GaAlAs) and quaternary (like InGaAsP).

In many host materials like YAG, YLF and KGW the Nd ions have absorption bands corresponding to 0.807 µm and this corresponds to the emission band of the laser diodes of active medium Ga$_{0.01}$Al$_{0.99}$As. For Nd ions pumping, the output wavelength can be tailored to the absorption peak by changing the concentration of Al in the active medium, typical change of concentration of 1% corresponds 10 Å change in the output wavelengths.

The narrow spectral width, which is desired, is very difficult to be achieved. For Nd YAG a width of the spectral emission line at 808 nm is 20 Å, for absorption coefficient larger than 3.8 cm$^{-1}$. Individual laser diodes have spectral line width of 20-40 Å.
The change of the composition and temperature gradient in the laser array lead to broader spectral emission of the whole array. For example, in GaAlAs structure the peak emission changes 3 Å/°C, so in order to keep the spectral emission within the absorption bands of Nd:YAG the composition of the diode should be controlled within 1% of Al, and the temperature variation within the array should be kept under 20°C.

The tunability of the GaAlAs laser diode output wavelengths in the range (λ = 770-900 nm) can be achieved by varying the composition of Ga1-xAlxAs diode. So as long as the active solid state material has absorption band within the above range, the laser diode can be used to pump such material [9].

### 2.19 Threshold conditions of the laser oscillator:

Referring to Fig. (2.5) it can be seen that the falling beam on the laser material will be amplified inside the laser cavity.

The mirror R2 will reflect back the beam to be amplified again on passing through the laser material, and then proceeds to strike the mirror R1. Thus oscillation sets in. The above cavity is called the regenerative oscillator.

Consider an active medium with a length l, assume the gain per unit length of the inverted material is (g). At each passage through the active medium the intensity increases by a factor of $\exp(gd)$, while at each reflection at the mirrors. There are energy losses of $1-R_1$ and $1-R_2$. The condition for the threshold is that the photon density after a round trip equals the initial photon density, thus a necessary threshold condition can be summarised by:

$$R_1 R_2 \exp(2g l) = 1$$  \hspace{1cm} (2.67)

Define the gain loop as:

$$G = R_1 R_2 \exp(2g l)$$  \hspace{1cm} (2.68)

If G is larger than the unity, radiation of a proper frequency will oscillate rapidly till it becomes larger than the other frequencies in the oscillator.

It worth mentioning that losses encountered inside the oscillator are mainly due to (i) reflection, (ii) scattering, (iii) absorption at the mirrors or the active medium and (iv) diffraction[9].

Denoting all non-output losses by the parameter α, then one can rewrite (2.67) as follows:
\[ R_1R_2 \exp(g- \alpha)2/l = 1 \] (2.69)

Denoting
\[ \varepsilon = t_R / \tau_c \] (2.70)
for the fractional power losses per round trip.

\( t_R \) is the round trip time = \( 2l/C \).
\( l \) is the optical length.
\( \tau_c \) is the photon life-time in the cavity.

Equation (2.69) can be written as:
\[ 2g/l = (\ln(R_1R_2))^{-1} + 2\alpha/l \] (2.71)
The R.H.S of (2.71) is the fractional power loss per round trip. Since \( \varepsilon = 2g/l = t_R / \tau_c \) we can write
\[ \tau_c = 2l/C [\ln(R_1R_2)]^{-1} + 2\alpha/l \] (2.72)

Internal losses in solid-state laser may be typically less than 1-2 at % per cm [20].

Introducing the other losses, and denoting for the reduced reflectivity \( R_2 = 1-L_M \) that accounts for the miscellaneous losses. \( L_M \) is a small percent.

Using the following approximation:
\[ \ln(1-L_M) = -L_M \] (2.73)
one can write for the optical losses in the cavity.
\[ L = 2\alpha/l + L_M \] (2.74)

Then
\[ \tau_c = \frac{2l}{C(1 - \ln R_1)} \] (2.75)

Using (2.73) and (2.74) one can rewrite (2.69) as.
\[ 2g/l = L - \ln R_1 \approx T + L \] (2.76)

Which is the threshold condition.
\( T \) is the transitivity of the output mirror.
\( -\ln R_1 \) is valid only when \( R_1 \) close to unity[15].
CHAPTER THREE

EXPERIMENTAL SET-UP, RESULTS AND DISCUSSION
3. EXPERIMENTAL SET-UP, RESULTS AND DISCUSSION

The performance of any laser system is determined by the efficiency and threshold conditions. A good laser performance should be of high efficiency and low threshold.

In order to obtain an efficient output laser from the solid state oscillator, many conditions should be met, particularly those of the pumping process and the cavity construction.

3.1 The pump source:

In this work the pump source is a diode array (OptoPower Corp. Mod EO15-810-FCPS) coupled to a fiber bundle that consists of nineteen multimode silica fibers. The fiber bundle is to obtain circular output beam, moreover it increases the output power and the reliability of the system [4].

The wavelength of the emitted beam can be tuned to the wavelength range 806.1-807.5 nm by changing the temperature from 20°C to 26°C, by using the temperature controller built in the system. This tuning is performed to allow the exact matching of the absorption band of several Nd-doped materials. The maximum output power can reach 7W for a current of 16 Am. of current. The output of the bundle is circular, of diameter 1.2 mm. About 90% of the energy is contained in a cone of apex 10°. The individual cores of the fibers are 150 μm apart, so care should be taken in imaging the pumping spot.

3.2 Spatial distribution of the pumping beam:

The determination of the pumping beam parameters was the first task in this work. The first parameter of the pumping parameters is the spot size of the laser diode beam in the pumped crystal. The set-up used to determine these parameters is illustrated in Fig. (3.1). It consists of the diode array, positive lenses, two pinholes of 3 mm and 25 μm in diameter, a digital powermeter and a photodetector. In this work, two procedures are adopted in pumping the crystal: the first one, pumping by the output of one of the nineteen fibers contained in the fiber-bundle, else pumping is achieved by the total output power.
from the fiber-bundle. In the former, we obtained a well defined and controllable shape of the pumping beam. The output power is relatively low compared with the second method.

In the later, much higher output power from the diode was gained, but the distribution of the pumping beam is not homogeneous over long distance inside the crystal.

The set-up in Fig (3.1) was used for pumping by the first procedure. The small positive lens of 2 cm focal length is used to magnify the output of the fiber bundle. The imaging of the light from the fiber-bundle was in 1:6 ratio. The magnification enabled us to spatially filter the most bright output of the fibers through a pinhole of 3 mm. To demagnify the image of the filtered output of a single fiber, a doublet lens with high numerical aperture (NA = 0.5) is used. The imaging ratio was 6:1. Then the image is focused on the pinhole (25 μm). The photodetector and the powermeter are used to register the readings of the intensities when the position of the pinhole was varied.

Fig (3.1)

The pumping spot size achieved by using this system was determined by scanning the pump spot of the diode beam by a large area silicon photodetector (Model 818 series, Newport) placed on a movable mount perpendicular to the optical axis of the beam. The photodetector was apertured by a 25μm pinhole and was connected to a digital powermeter (Model 815, Newport). In this way the beam intensity was measured as a
The function of the position. Table (3.1a) illustrates the experimental data obtained during horizontal scanning.

<table>
<thead>
<tr>
<th>No.</th>
<th>Positions of the pinhole µm</th>
<th>Intensities mW</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>2</td>
<td>20</td>
<td>0.002</td>
</tr>
<tr>
<td>3</td>
<td>40</td>
<td>0.005</td>
</tr>
<tr>
<td>4</td>
<td>60</td>
<td>0.017</td>
</tr>
<tr>
<td>5</td>
<td>80</td>
<td>0.016</td>
</tr>
<tr>
<td>6</td>
<td>100</td>
<td>0.063</td>
</tr>
<tr>
<td>7</td>
<td>120</td>
<td>0.129</td>
</tr>
<tr>
<td>8</td>
<td>140</td>
<td>0.229</td>
</tr>
<tr>
<td>9</td>
<td>160</td>
<td>0.321</td>
</tr>
<tr>
<td>10</td>
<td>180</td>
<td>0.413</td>
</tr>
<tr>
<td>11</td>
<td>200</td>
<td>0.471</td>
</tr>
<tr>
<td>12</td>
<td>220</td>
<td>0.503</td>
</tr>
<tr>
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<td>240</td>
<td>0.89</td>
</tr>
<tr>
<td>14</td>
<td>260</td>
<td>0.5</td>
</tr>
<tr>
<td>15</td>
<td>280</td>
<td>0.438</td>
</tr>
<tr>
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<td>0.336</td>
</tr>
<tr>
<td>17</td>
<td>320</td>
<td>0.218</td>
</tr>
<tr>
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<td>340</td>
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<tr>
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<td>360</td>
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<tr>
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<td>380</td>
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<tr>
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<td>0.001</td>
</tr>
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</table>

Table (3.1a)

These data of the intensities and positions are plotted in Fig. (3.2a).

From the resulting curve, the full width at half maximum (FWHM) of the pump beam was determined to be 180 µm.
The same scanning was done vertically to ensure that the pumping spot is not astigmatic. The experimental results and data in Table(3.1b).
<table>
<thead>
<tr>
<th>No.</th>
<th>Positions of the pinhole μm</th>
<th>Intensities mW</th>
</tr>
</thead>
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<td>0</td>
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<td>0.017</td>
</tr>
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<td>80</td>
<td>0.016</td>
</tr>
<tr>
<td>7</td>
<td>100</td>
<td>0.063</td>
</tr>
<tr>
<td>8</td>
<td>120</td>
<td>0.129</td>
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<td>0.229</td>
</tr>
<tr>
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<td>160</td>
<td>0.321</td>
</tr>
<tr>
<td>11</td>
<td>180</td>
<td>0.413</td>
</tr>
<tr>
<td>12</td>
<td>200</td>
<td>0.471</td>
</tr>
<tr>
<td>13</td>
<td>220</td>
<td>0.503</td>
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<tr>
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<td>240</td>
<td>0.489</td>
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<tr>
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<td>260</td>
<td>0.500</td>
</tr>
<tr>
<td>16</td>
<td>280</td>
<td>0.438</td>
</tr>
<tr>
<td>17</td>
<td>300</td>
<td>0.336</td>
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<tr>
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<td>320</td>
<td>0.218</td>
</tr>
<tr>
<td>19</td>
<td>340</td>
<td>0.13</td>
</tr>
<tr>
<td>20</td>
<td>360</td>
<td>0.035</td>
</tr>
<tr>
<td>21</td>
<td>380</td>
<td>0.011</td>
</tr>
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</table>

Table(3.1b)

and the plot of these data are in Fig. (3.2b).
It is seen that, there is a good agreement between the horizontal and vertical measurements, in both we conclude that the diameter of the pumping spot is about 180 μm.

The small pinhole distance from the focusing lens indicated as (D) in Fig (3.1) was varied using a step of 0.5 mm in order to obtain the exact position of the beam focus.

Fig(3.2b)
The horizontal scanning of the intensity distribution presented in Figs (3.2a,b) was done before starting changing the distance $D$. But after that, the smallest pumping spot diameter was found nearly at the same position. The experimental results are presented in Table (3.1c).

<table>
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<tr>
<th>No.</th>
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<th>$D = 4$ mm</th>
<th>$D = 3.5$ mm</th>
<th>$D = 3$ mm</th>
<th>$D = 2.5$ mm</th>
<th>$D = 2$ mm</th>
<th>$D = 1.5$ mm</th>
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<td>0.042</td>
<td>0.04</td>
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<td>0.74</td>
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</table>
The curves of the intensity distributions versus longitudinal position were obtained for each distance, starting from D = 0.5 mm up to 4.5 mm and plotted in Fig. (3.3).

<p>| | | | | | |</p>
<table>
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<tr>
<td>25</td>
<td>480</td>
<td>.073</td>
<td>.03</td>
<td>.02</td>
<td></td>
</tr>
<tr>
<td>26</td>
<td>500</td>
<td>.056</td>
<td>.022</td>
<td>.01</td>
<td></td>
</tr>
<tr>
<td>27</td>
<td>520</td>
<td>.037</td>
<td>.014</td>
<td></td>
<td></td>
</tr>
<tr>
<td>28</td>
<td>540</td>
<td>.025</td>
<td>.009</td>
<td></td>
<td></td>
</tr>
<tr>
<td>29</td>
<td>560</td>
<td>.019</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>30</td>
<td>580</td>
<td>.013</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>31</td>
<td>600</td>
<td>.009</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Table (3.1c)
From the plotted data the most suitable value for D was found to be 0.5 mm, since the spot size is smaller and symmetric and has a diameter of 180 μm.

3.3 Spectrum of the pumping beam:

The study of the spectral characteristics of the pumping beam is very important. This stems from the fact that the absorption of the laser active medium depends on these characteristics e.g. the emission wavelength.

To optimise the pumping conditions and parameters, the effect of increasing the diode current on the spectral characteristics of the output radiation from the diode was studied. The set-up for this experiment is shown in Fig.(3.4).

---

Fig.(3.4)

It consists of: the laser diode with the same focusing system as in Fig.(3.1), a monochromator(CT-6B tokamak, focal length 300 mm, relative aperture F/6, grating 1200 lines/mm, resolution ≤ 1Å°) to measure the spectrum of the diode beam, the photodetector, and the digital powermeter. Also a HeNe laser source was used to check
the alignment of the set-up and x-y plotter (Linseis, LY 1900PL) for plotting the spectrum.

The temperature of the diode was fixed at a certain value 24.3°C and the current was varied from 5.0 Amp. to 8.0 Amp. It was observed that an increase in the diode current leads to the broadening of the emission line. This is because, as the diode current increases the gain in the semiconductor material increases, and this will increase the number of the oscillating modes that unresolved [13].

The spectrum linewidth of emission was less than 0.5 nm at diode temperature 24.6°C and current 5 Amp., this is shown in Fig (3.7).

By the same experimental set-up Fig.(3.4), the dependence of the emission wavelength on the temperature of the diode was studied. Here the current of the diode was fixed to a certain value(7.5 Amp.) and the diode temperature was varied from 20°C to 26°C. A plot of the obtained results is presented in Fig.(3.5). From the plot, it is seen that the wavelength of the emission shifts to higher values when we increase the diode temperature. The explanation for this is that when the temperature is increased, the gain in the active medium will decrease, since the gain has a linear dependence on the temperature T^3 and the concentration of the medium. Decreasing the gain of the medium leads to the decreasing of the energy gap between the quasi-fermi levels, so this will reduce the energy gap between the quasi-fermi levels in the semiconductor material, and consequently the transition frequency decreases and the wavelength increases [13].

This tuning was done to choose the suitable working temperature that gives a suitable emission wavelength from the diode laser to match the absorption band of the active medium(Nd:KGW crystal) to be pumped by this diode.

In order to determine the best working temperature, a plot of the peak mission wavelengths(\(\lambda_p\)) versus the temperature of the diode was plotted. The readings are tabulated on Table (3.2). The plot of these data on Fig.(3.6).
<table>
<thead>
<tr>
<th>No.</th>
<th>Diode Temperature °C</th>
<th>Wavelength of Emission λ_{r} nm</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>20</td>
<td>806.1</td>
</tr>
<tr>
<td>2</td>
<td>20.5</td>
<td>806.3</td>
</tr>
<tr>
<td>3</td>
<td>21</td>
<td>806.4</td>
</tr>
<tr>
<td>4</td>
<td>21.5</td>
<td>806.5</td>
</tr>
<tr>
<td>5</td>
<td>22</td>
<td>806.5</td>
</tr>
<tr>
<td>6</td>
<td>22.5</td>
<td>806.6</td>
</tr>
<tr>
<td>7</td>
<td>23</td>
<td>806.6</td>
</tr>
<tr>
<td>8</td>
<td>23.5</td>
<td>806.7</td>
</tr>
<tr>
<td>9</td>
<td>24</td>
<td>806.8</td>
</tr>
<tr>
<td>10</td>
<td>24.5</td>
<td>807.2</td>
</tr>
<tr>
<td>11</td>
<td>25</td>
<td>807.3</td>
</tr>
<tr>
<td>12</td>
<td>25.5</td>
<td>807.4</td>
</tr>
<tr>
<td>13</td>
<td>26</td>
<td>807.5</td>
</tr>
</tbody>
</table>

Table (3.2)

From these experimental data we determined the range of the temperature that we can work with. It is seen from the plot that the relation between the wavelength and the diode temperature, is nearly linear in the temperature range 24.5°C to 26.0°C.
In Fig (3.6) the diode temperature 26°C corresponds to emission wavelength of 807.4 nm. Decreasing the temperature, leads to the decreasing of the emission wavelength.

We worked with emission wavelength of 807 nm, corresponds to 24.5°C.

The above discussion was concerning the pumping parameters.
Spectral Line of Pumping Beam Emission.

Fig.(3.7)
THE DEPENDANCE OF THE LASER DIODE WAVELENGTH ON TEMPERATURE

Fig. (3.5)
3.4 The properties of Nd:KGW crystal:

Now we consider the active medium, Neodymium-doped potassium gadolinium tungstate [Nd KGd(WO₄)₂; Nd KGW].

It is an isostructural compound belonging to the double potassium tungstate group which has the general formula KM(WO₄)₂. The output laser radiation from this crystal is polarised because of the anisotropy of the crystal. In this crystal Nd³⁺ ion of 0.112 nm ionic radius replaces Gd³⁺ of 0.106 nm ionic radius. Since the mismatching between atomic radii of the two ions is not great, high doping is possible without causing degradation of the quality of the crystal [3].

It is a biaxial crystal, with three orthogonal indicatrix axes nₓ, nᵧ and nₗ, where nₓ < nᵧ < nₗ. For wavelengths of about 1.067 µm the reported refractive indices are nₓ = 1.978, nᵧ = 2.014, nₗ = 2.049.

In KGW the indicatrix nₓ coincides with the crystallographic axis b [010]. The angle between the crystallographic axis a [100] and the indicatrix nₓ is 24° and the angle between the nᵧ and c [001] is 20°. The crystallographic axes a and b and b and c are orthogonal, while the angle between a and c is 94.43° [3], [12].

The crystal has the following advantages: broad absorption band centred around a wavelength of 810 nm, high anisotropy and high cross section of 1.067 nm transition. High doping level can be achieved in this crystal, about 9%, without any degradation of the optical quality. The crystal is notorious for having a low thermal conductivity, which leads to the thermal lensing effect at high pumping power rates [12].

The dimensions of Nd KGW crystal used were 5 mm diameter x 6 mm length. The concentration of the Nd³⁺ is 3.2%. It is antireflective coated at wavelengths of 1.06 µm and 1.3 µm.

According to some published literature [3], the energy extraction efficiency of Nd KGW is expected to be about twice that of the most popular solid state laser (Nd YAG). In Table (3.3) we report some selected characteristics of the Nd KGW and Nd YAG crystals [3].
<table>
<thead>
<tr>
<th>Properties</th>
<th>Nd:KGW</th>
<th>Nd:YAG</th>
</tr>
</thead>
<tbody>
<tr>
<td>Peak emission cross section</td>
<td>3.8</td>
<td>2.8</td>
</tr>
<tr>
<td>((x \times 10^{-19} \text{ Cm}^2))</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Nd concentration</td>
<td>3-10%</td>
<td>0.7-1.1%</td>
</tr>
<tr>
<td>Thermal conductivity</td>
<td>2.8[100]</td>
<td>13</td>
</tr>
<tr>
<td>(W/mK)</td>
<td>2.2[010]</td>
<td></td>
</tr>
<tr>
<td></td>
<td>3.5[001]</td>
<td></td>
</tr>
<tr>
<td>Fluorescence life-time</td>
<td>109</td>
<td>240</td>
</tr>
<tr>
<td>(\mu s)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Emission wavelength</td>
<td>1.0672</td>
<td>1.0642</td>
</tr>
<tr>
<td>( ^{3}F_{3/2} \rightarrow ^{4}I_{15/2} )</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Table(3.3)

The two crystals were continuously end-pumped by the diode laser, in a free running operation. The Nd:KGW crystal was reported to be flash lamp-pumped with Q-switched mode[11].

3.5 Absorption of the Nd:KGW crystal:

The absorption of the pump beam by the crystal was studied, using the second cavity set-up in Fig (3.14). That was as follows:

Firstly, measurements of the pumping beam power at different temperatures of the laser (ranging from 20°C-26.5°C) were obtained at a fixed diode current of 12 Amp. See Table(3.4), for the experimental data obtained in this cavity set-up.
From these data, increasing the diode temperature leads to the decreasing of the diode output power. This is due to the increase in the thermal population of the lower laser level.

<table>
<thead>
<tr>
<th>No.</th>
<th>Diode temperature °C</th>
<th>Pump power from the diode mW</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>20</td>
<td>97.2</td>
</tr>
<tr>
<td>2</td>
<td>20.5</td>
<td>96.66</td>
</tr>
<tr>
<td>3</td>
<td>21</td>
<td>96.12</td>
</tr>
<tr>
<td>4</td>
<td>21.5</td>
<td>95.85</td>
</tr>
<tr>
<td>5</td>
<td>22</td>
<td>95.58</td>
</tr>
<tr>
<td>6</td>
<td>22.5</td>
<td>95.31</td>
</tr>
<tr>
<td>7</td>
<td>23</td>
<td>95.04</td>
</tr>
<tr>
<td>8</td>
<td>23.5</td>
<td>94.5</td>
</tr>
<tr>
<td>9</td>
<td>24</td>
<td>93.96</td>
</tr>
<tr>
<td>10</td>
<td>24.5</td>
<td>93.69</td>
</tr>
<tr>
<td>11</td>
<td>25</td>
<td>93.42</td>
</tr>
<tr>
<td>12</td>
<td>25.5</td>
<td>92.88</td>
</tr>
<tr>
<td>13</td>
<td>26</td>
<td>92.61</td>
</tr>
<tr>
<td>14</td>
<td>26.5</td>
<td>92.34</td>
</tr>
</tbody>
</table>

Table(3.4)

A plot of the emitted power from the diode versus the diode temperatures is plotted in Fig.(3.8)
Secondly, measurements of the transmitted power through the crystal at the same temperature range and the same value of the diode current were obtained, see Table (3.5).
<table>
<thead>
<tr>
<th>No.</th>
<th>Diode temperature °C</th>
<th>Output power from the crystal mW</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>20</td>
<td>15.8</td>
</tr>
<tr>
<td>2</td>
<td>20.5</td>
<td>14.2</td>
</tr>
<tr>
<td>3</td>
<td>21</td>
<td>13.3</td>
</tr>
<tr>
<td>4</td>
<td>21.5</td>
<td>12.98</td>
</tr>
<tr>
<td>5</td>
<td>22</td>
<td>12.87</td>
</tr>
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<td>6</td>
<td>22.5</td>
<td>13.0</td>
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<td>7</td>
<td>23</td>
<td>13.42</td>
</tr>
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<td>8</td>
<td>23.5</td>
<td>13.97</td>
</tr>
<tr>
<td>9</td>
<td>24</td>
<td>14.19</td>
</tr>
<tr>
<td>10</td>
<td>24.5</td>
<td>14.3</td>
</tr>
<tr>
<td>11</td>
<td>25</td>
<td>14.19</td>
</tr>
<tr>
<td>12</td>
<td>25.5</td>
<td>14.08</td>
</tr>
<tr>
<td>13</td>
<td>26</td>
<td>13.86</td>
</tr>
<tr>
<td>14</td>
<td>26.5</td>
<td>13.53</td>
</tr>
</tbody>
</table>

Table (3.5)

A plot of these data is shown in Fig. (3.9).
Thirdly, the absorption of the crystal at the above mentioned conditions of the temperature and current, was calculated, that is by using the obtained experimental data in Table(3.6).
<table>
<thead>
<tr>
<th>No.</th>
<th>Diode Temperature °C</th>
<th>Absorption of the crystal</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>20</td>
<td>0.163</td>
</tr>
<tr>
<td>2</td>
<td>20.5</td>
<td>0.147</td>
</tr>
<tr>
<td>3</td>
<td>21</td>
<td>0.138</td>
</tr>
<tr>
<td>4</td>
<td>21.5</td>
<td>0.136</td>
</tr>
<tr>
<td>5</td>
<td>22</td>
<td>0.134</td>
</tr>
<tr>
<td>6</td>
<td>22.5</td>
<td>0.137</td>
</tr>
<tr>
<td>7</td>
<td>23</td>
<td>0.141</td>
</tr>
<tr>
<td>8</td>
<td>23.5</td>
<td>0.148</td>
</tr>
<tr>
<td>9</td>
<td>24</td>
<td>0.151</td>
</tr>
<tr>
<td>10</td>
<td>24.5</td>
<td>0.152</td>
</tr>
<tr>
<td>11</td>
<td>25</td>
<td>0.152</td>
</tr>
<tr>
<td>12</td>
<td>25.5</td>
<td>0.152</td>
</tr>
<tr>
<td>13</td>
<td>26</td>
<td>0.144</td>
</tr>
<tr>
<td>14</td>
<td>26.5</td>
<td>0.147</td>
</tr>
</tbody>
</table>

Table(3.6)

The results of the absorption coefficient at the different values of the temperatures were plotted in Fig (3.10).
Fig (3.10)

From the absorption graph of the crystal, it is seen that the absorption coefficient of the crystal decreases between 20°C and 22°C then it increases from 22°C upto 24.5°C, then it remains stable upto 25.5°C, where starts again to decrease.

Finally, a plot for the results of the measured emission wavelengths and the corresponding absorption coefficients of the crystal in Table (3.7) was plotted in Fig (3.11).
<table>
<thead>
<tr>
<th>No</th>
<th>Emission wavelength $\lambda_p$ nm</th>
<th>Absorption coefficient of the crystal</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>805.1</td>
<td>0.163</td>
</tr>
<tr>
<td>2</td>
<td>805.2</td>
<td>0.147</td>
</tr>
<tr>
<td>3</td>
<td>805.8</td>
<td>0.138</td>
</tr>
<tr>
<td>4</td>
<td>806.1</td>
<td>0.136</td>
</tr>
<tr>
<td>5</td>
<td>806.3</td>
<td>0.134</td>
</tr>
<tr>
<td>6</td>
<td>806.2</td>
<td>0.137</td>
</tr>
<tr>
<td>7</td>
<td>807.0</td>
<td>0.141</td>
</tr>
<tr>
<td>8</td>
<td>806.3</td>
<td>0.148</td>
</tr>
<tr>
<td>9</td>
<td>807.1</td>
<td>0.151</td>
</tr>
<tr>
<td>10</td>
<td>807.6</td>
<td>0.152</td>
</tr>
</tbody>
</table>

Table (3.7)

Fig (3.11)
It is seen that the absorption coefficient of the Nd KGW crystal decreases as the wavelength of the diode laser increases, in the range 805 nm - 806.3 nm. Then start increasing in the range 806.3 nm - 807 nm.

We conclude that for good output power from the crystal, the emission wavelength should be tuned to be within the range 806.3 nm - 807 nm.

3.6 Parameters of the cavities end-pumped by a single fiber output:

In this part we constructed several cavities to be used, that pumped by the diode laser radiation emitted by a single fiber. Pumping with part of the pumping power will of course result in low output power. This offers however a well defined spot size and controllable pumping mode, providing a homogeneous distribution for the beam inside the crystal.

3.7 Experimental Set-up - cavity (1):

In the set-up we filtered the radiation coming from the single fiber, that was done by imaging the output of the fiber bundle with high magnification by a lens L1 (f = 8 mm, NA = 0.5) onto a screen S. The fiber output in question is selected by a 3 mm aperture placed in the position of the screen S. Mirror M2 reflects the radiation of wavelength of 1.06 μm. The output of the Nd:KGW laser beam is measured by a detector in the position shown.
3.8 The performance of cavity(1):

The first cavity assembled, in this work, was a near-hemispherical one of 287 mm length, with a plane mirror M₁ of reflectivity 99%, and the curved mirror M₂ with radius of curvature of 300 mm and 100% reflectivity. The parameters of the transverse electromagnetic (TEM₀₀) mode for this cavity were determined by adopting the matrix approach— in the coming sub-section.

3.8.1 Determination of the cavity mode parameters:

Referring to section (2.15), the chain of the ray transfer matrices of the round trip of the beam inside the resonator, starting from the output plane, can be written as:

\[
\begin{bmatrix}
  1 & 0.287 & 1 & 0.287 \\
  0 & 1 & 0 & 1 \\
  0 & 1 & 0 & 1 \\
  0 & 1 & 0 & 1 \\
\end{bmatrix}
\]

\[
\begin{bmatrix}
  \frac{1}{-2} & 0 \\
  \frac{1}{-3} & 1 \\
\end{bmatrix}
\]

\[
= \begin{bmatrix}
  -2.846 & 0.574 \\
  -6.7 & 1 \\
\end{bmatrix}
\]

The overall matrix will be:

\[
\begin{bmatrix}
  -2.846 & 0.574 \\
  -6.7 & 1 \\
\end{bmatrix}
\]

The following parameters are calculated as follows:

1- The value of \( \frac{A + D}{2} \) was \( -2.846 + 1 = 0.923 \), that means the resonator is stable one.

2- \( \cos \theta = -0.923 \), then \( \theta = 174.9^\circ \).

3- \( R \) (radius of curvature of wavefront) = \( \frac{2 \times 0.574}{1 + 2.846} = 0.3 m \), which matches with the radius of curvature of the mirror.

4- \( w \) (the beam radius, at the curved mirror): \( \left( \frac{1.067 \times 10^{-6} \times 0.574}{3.14 \times \sin 174.9^\circ} \right)^{\frac{1}{2}} = 713 \mu m \).

5- \( Z \) (the location of the beam radius): \( \frac{2.846 + 1}{2 \times 6.7} = 0.287 m \).

6- \( w_0 \) (the radius of the waist of the mode): \( \left( \frac{-1.067 \times 10^{-6} \times \sin 174.9^\circ}{-3.14 \times 6.7} \right)^{\frac{1}{2}} = 140 \mu m \).

The location of the beam waist \( (Z = 0) \), in this case, lay on the flat mirror.
The above calculation was made to ensure that the cavity mode size which is 280 μm is well matched with the pumping mode size which is 180 μm. For low power lasers, the matching between these modes is very important and it is a key parameter in diode-pumped solid-state lasers in order to obtain high efficiencies and better performance [11].

If the ratio mode size to pump size is not optimised, the oscillator may not lase, or it may lase with higher undesirable modes. According to the literature, the optimum ratio between the cavity mode and the pump mode is 1.5. In this work, the optimum ratio was calculated to be 1.5 [5].

In this cavity, the Nd:KGW crystal was placed between the mirrors. The estimated pump spot size at the face of the crystal, near the flat mirror was 180 μm, the oscillating TEM_{00} mode inside the resonator has a size of 280μm as calculated above.

The optimised performance for this cavity was observed at the following parameters: cavity length 287 mm. The threshold pumping power was 88 mW.

The measured pumping power and the output power results are given in Table (3.8).

<table>
<thead>
<tr>
<th>No.</th>
<th>Diode current</th>
<th>Pumping power mW</th>
<th>Output (Nd:KGW) power mW</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>9.0</td>
<td>88</td>
<td>0.04</td>
</tr>
<tr>
<td>2</td>
<td>9.1</td>
<td>91.5</td>
<td>0.052</td>
</tr>
<tr>
<td>3</td>
<td>9.2</td>
<td>92</td>
<td>0.075</td>
</tr>
<tr>
<td>4</td>
<td>9.3</td>
<td>95</td>
<td>0.153</td>
</tr>
<tr>
<td>5</td>
<td>9.4</td>
<td>96</td>
<td>0.21</td>
</tr>
<tr>
<td>6</td>
<td>9.5</td>
<td>98</td>
<td>0.25</td>
</tr>
<tr>
<td>7</td>
<td>9.6</td>
<td>101</td>
<td>0.4</td>
</tr>
<tr>
<td>8</td>
<td>9.7</td>
<td>103</td>
<td>0.471</td>
</tr>
<tr>
<td>9</td>
<td>9.8</td>
<td>105</td>
<td>0.55</td>
</tr>
<tr>
<td>10</td>
<td>9.9</td>
<td>107</td>
<td>0.625</td>
</tr>
<tr>
<td>11</td>
<td>10.0</td>
<td>110</td>
<td>0.775</td>
</tr>
<tr>
<td>12</td>
<td>10.2</td>
<td>115</td>
<td>0.925</td>
</tr>
<tr>
<td>13</td>
<td>10.4</td>
<td>118</td>
<td>1.09</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>---</td>
<td>----</td>
<td>----</td>
<td>----</td>
</tr>
<tr>
<td>14</td>
<td>10.6</td>
<td>122</td>
<td>1.24</td>
</tr>
<tr>
<td>15</td>
<td>10.8</td>
<td>127</td>
<td>1.38</td>
</tr>
<tr>
<td>16</td>
<td>11.0</td>
<td>130</td>
<td>1.57</td>
</tr>
<tr>
<td>17</td>
<td>11.2</td>
<td>135</td>
<td>1.69</td>
</tr>
<tr>
<td>18</td>
<td>11.4</td>
<td>139</td>
<td>1.85</td>
</tr>
<tr>
<td>19</td>
<td>11.6</td>
<td>143</td>
<td>1.98</td>
</tr>
<tr>
<td>20</td>
<td>11.8</td>
<td>148</td>
<td>2.14</td>
</tr>
<tr>
<td>21</td>
<td>12.0</td>
<td>151</td>
<td>2.34</td>
</tr>
<tr>
<td>22</td>
<td>12.4</td>
<td>160</td>
<td>2.51</td>
</tr>
<tr>
<td>23</td>
<td>12.5</td>
<td>163</td>
<td>2.55</td>
</tr>
<tr>
<td>24</td>
<td>13.0</td>
<td>172</td>
<td>3.11</td>
</tr>
<tr>
<td>25</td>
<td>13.5</td>
<td>183.75</td>
<td>3.54</td>
</tr>
<tr>
<td>26</td>
<td>14.0</td>
<td>193</td>
<td>3.96</td>
</tr>
</tbody>
</table>

Table (3.8)

Fig. (3.13)
Fig (3.13) shows the Nd:KGW output power versus the absorbed pump power for this cavity.

The slope efficiency of this cavity was 3.7% which is low, that is due to the low transmittance of the output mirror. To obtain higher output power and slope efficiency, the transmittance of the output mirror had to be increased.

3.9 The performance of Cavity(2):

A second cavity assembled by using the same pumping configuration. It consists of the flat mirror of the previous cavity (reflectivity of 99%) and a curved mirror of radius of curvature 100 mm and reflectivity of 95%. The cavity length was 85.5 mm with the same estimated pump spot size (180 μm).

3.9.1 Determination of the cavity mode:

The TEM00 mode for this cavity, was calculated using the Gaussian beam formulae shown in section(2.11), as follows:

First, the g-parameter of each mirror of the cavity is calculated as follows:

\[ g_1 = 1 - \frac{0.0855}{\infty} = 1 \] \hspace{1cm} \text{and} \hspace{1cm} \[ g_2 = 1 - \frac{0.0855}{0.1} = 0.145 \]

So, by substituting in the beam waist formula, we get,

\[ W_0^2 = \frac{d\lambda}{\pi} \sqrt{\frac{g_1 g_2 (1 - g_1 g_2)}{(g_1 + g_2 - 2g_1 g_2)^2}} = \frac{0.0855 \times 1.067 \times 10^{-6}}{3.14} \sqrt{\frac{1 \times 0.145(1 - 0.145)}{(1 + 0.145 - 2 \times 0.145)^2}} = 11970\,\mu m \]

Or

\[ W_0 = 109\,\mu m. \]

So, the cavity mode diameter is determined to be 219 μm.

Using a photodetector connected to a registration device (the x-y plotter), the output powers from the crystal were measured at temperature of 25°C, and the corresponding pumping powers were measured.

Fig (3.14) shows the near-hemispherical cavity construction, used.
Reflectivity 99%

Reflectivity 95%

Nd:KGW

R=10 cm

Cavity length=855mm

Fig (3.14)

<table>
<thead>
<tr>
<th>No.</th>
<th>Pumping power (mW)</th>
<th>Output Nd:KGW power (mW)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>162</td>
<td>0.1</td>
</tr>
<tr>
<td>2</td>
<td>164</td>
<td>0.5</td>
</tr>
<tr>
<td>3</td>
<td>166</td>
<td>1.1</td>
</tr>
<tr>
<td>4</td>
<td>168</td>
<td>1.4</td>
</tr>
<tr>
<td>5</td>
<td>171</td>
<td>1.9</td>
</tr>
<tr>
<td>6</td>
<td>174</td>
<td>2.5</td>
</tr>
<tr>
<td>7</td>
<td>176.5</td>
<td>3.1</td>
</tr>
<tr>
<td>8</td>
<td>178</td>
<td>3.5</td>
</tr>
<tr>
<td>9</td>
<td>182.5</td>
<td>3.9</td>
</tr>
<tr>
<td>10</td>
<td>187</td>
<td>4.9</td>
</tr>
<tr>
<td>11</td>
<td>198.5</td>
<td>7.8</td>
</tr>
<tr>
<td>12</td>
<td>210</td>
<td>10.3</td>
</tr>
</tbody>
</table>

Table (3.9)
Table (3.9) gives the experimental data and results obtained, a plot of which is shown in Fig. (3.15)

From the plot the slope efficiency of this cavity is 21% and the threshold pumping power is 162 mW.
3.9.2 Optimisation of the cavity parameters:

Further optimisation for the conditions and parameters of the cavity was done by adjusting the position of the focusing lens. Doing this we were searching for a position where the pumping beam is focused in the crystal. For a good matching between the modes of the pumping beam and cavity, the cavity length was adjusted by changing the position of the output mirror. As a result of this optimisation we obtained a new cavity of length 89 mm. Table (3.10) gives the experimental data of the measurements of the output power from the crystal and the pumping power from the diode at a diode temperature of 25°C.

<table>
<thead>
<tr>
<th>No.</th>
<th>Pumping power mW</th>
<th>Output Nd:KGW power mW</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>151</td>
<td>0</td>
</tr>
<tr>
<td>2</td>
<td>153</td>
<td>0.533</td>
</tr>
<tr>
<td>3</td>
<td>155</td>
<td>0.984</td>
</tr>
<tr>
<td>4</td>
<td>158.5</td>
<td>1.476</td>
</tr>
<tr>
<td>5</td>
<td>160</td>
<td>2.01</td>
</tr>
<tr>
<td>6</td>
<td>163</td>
<td>2.665</td>
</tr>
<tr>
<td>7</td>
<td>166</td>
<td>3.198</td>
</tr>
<tr>
<td>8</td>
<td>167</td>
<td>3.649</td>
</tr>
<tr>
<td>9</td>
<td>170</td>
<td>4.223</td>
</tr>
<tr>
<td>10</td>
<td>172</td>
<td>5.289</td>
</tr>
<tr>
<td>11</td>
<td>183.75</td>
<td>8.405</td>
</tr>
<tr>
<td>12</td>
<td>193</td>
<td>9.574</td>
</tr>
</tbody>
</table>

Table (3.10)
Fig (3.16) is a plot of the data in Table (3.10).

From this plot the slope efficiency was calculated to be 24% and the pumping power threshold was 153 mW.

3.10 Polarization of the output of the Nd:KGW laser:

Using a Glan polarizer, the output Nd:KGW laser was found to be polarised in the [010] plane without using any intracavity polarizing optics. This is due to the strong natural birefringence of the KGW crystal.
3.11 Optimum Temperature:

In an attempt to find the best diode temperature for the cavity, measurements were taken for different diode temperatures, fixed at 13 Amp. and the corresponding output powers from the crystal were recorded in Table (3.11).

<table>
<thead>
<tr>
<th>No.</th>
<th>Diode temperature °C</th>
<th>Output Nd KGW power mW</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>20.0</td>
<td>5.53</td>
</tr>
<tr>
<td>2</td>
<td>20.5</td>
<td>6.35</td>
</tr>
<tr>
<td>3</td>
<td>21.0</td>
<td>6.27</td>
</tr>
<tr>
<td>4</td>
<td>21.5</td>
<td>6.56</td>
</tr>
<tr>
<td>5</td>
<td>22.0</td>
<td>6.35</td>
</tr>
<tr>
<td>6</td>
<td>22.5</td>
<td>6.19</td>
</tr>
<tr>
<td>7</td>
<td>23.0</td>
<td>5.78</td>
</tr>
<tr>
<td>8</td>
<td>24.0</td>
<td>5.12</td>
</tr>
<tr>
<td>9</td>
<td>25.0</td>
<td>5.12</td>
</tr>
</tbody>
</table>

Table(3.11)

From the tabulated experimental data a plot of the output Nd KGW powers versus the corresponding diode temperatures was obtained in Fig.(3.17).
From this it is seen that the best diode temperature is 21.4°C. This gives the highest emission from the diode, and consequently the highest output power from the Nd KGW crystal.

The parameters of the laser cavity were repeated at the optimal temperature. The obtained data is presented in Table (3.12) and the corresponding graph is shown in Fig. (3.18).
<table>
<thead>
<tr>
<th>No</th>
<th>Pumping power mW</th>
<th>Output Nd:KGW power mW</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>159.84</td>
<td>1.107</td>
</tr>
<tr>
<td>2</td>
<td>162</td>
<td>1.968</td>
</tr>
<tr>
<td>3</td>
<td>166.32</td>
<td>2.952</td>
</tr>
<tr>
<td>4</td>
<td>170.64</td>
<td>4.018</td>
</tr>
<tr>
<td>5</td>
<td>176.04</td>
<td>5.125</td>
</tr>
<tr>
<td>6</td>
<td>178.2</td>
<td>6.027</td>
</tr>
<tr>
<td>7</td>
<td>182.52</td>
<td>6.847</td>
</tr>
<tr>
<td>8</td>
<td>186.84</td>
<td>9.553</td>
</tr>
<tr>
<td>9</td>
<td>198.72</td>
<td>12.22</td>
</tr>
</tbody>
</table>

Table (3.12)

From this table the output power versus the pumping power curve was plotted in
Fig. (3.18)

Fig (3.18) above from which the slope efficiency was calculated to be 29% and the threshold 159 mW.
3.12 The performance of Cavity(3):

In this cavity further optimisation was introduced. The cavity is a near-hemispherical, with a plane mirror of reflectivity of 99%. The curved mirror has a radius of curvature of 150 mm and a reflectivity of 94%. The cavity length is 143 mm. The pumping spot size was 180 μm. The actual spot size inside the crystal is bigger and position dependant.

The TEM$_{00}$ mode size has a diameter of 208 μm determined using the Gaussian beam propagation formulae and confirmed by a computer software calculation.

The experimental data and results of the pumping powers and the corresponding output powers from the crystal on the third cavity were tabulated on Table (3.13).

<table>
<thead>
<tr>
<th>No.</th>
<th>Pumping power mW</th>
<th>Output Nd:KGW power mW</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>183.0</td>
<td>0.0</td>
</tr>
<tr>
<td>2</td>
<td>185.0</td>
<td>0.041</td>
</tr>
<tr>
<td>3</td>
<td>186.0</td>
<td>0.369</td>
</tr>
<tr>
<td>4</td>
<td>188.5</td>
<td>0.779</td>
</tr>
<tr>
<td>5</td>
<td>191.0</td>
<td>1.189</td>
</tr>
<tr>
<td>6</td>
<td>193.0</td>
<td>1.681</td>
</tr>
<tr>
<td>7</td>
<td>199.0</td>
<td>2.34</td>
</tr>
<tr>
<td>8</td>
<td>202.0</td>
<td>3.403</td>
</tr>
</tbody>
</table>

Table (3.13)
A plot of the input powers versus the corresponding output powers was plotted.

![Plot](image)

**Fig. (3.19)**

From the plot of the experimental data in Fig. (3.19), the threshold pumping power was 185 mW and the slope efficiency was 18%.

It is obviously clear that the threshold of the pumping power in this case was higher than that of the two previous cavities. The reason being due to the decreasing of the reflectivity of the output mirror that leads to the decreasing of the photon life-time inside the laser cavity. This results in high threshold and low slope efficiency.

From foregoing work, it is clear that the second cavity is preferable for Nd-KGW. This is because of the higher output power, higher efficiency, and lower threshold.
3.13 Total fiber bundle output power configuration:

Thus far we used a single fiber output only. As it was already mentioned, the diode array is coupled to a bundle which consists of nineteen fibers. Below, we present some data about the construction of the cavity when the whole fiber bundle output is used.

![Diagram](image)

Fig (3.20)

Fig (3.20) shows a set up for this type of configuration. The pumping beam from the fiber bundle is imaged on the surface of the crystal in a 3:1 ratio, this is done by using a doublet lens L of focal length 6.5 cm and high NA (=0.5). This NA provides a smooth pumping spot. The diameter of the pumping spot was measured to be 400 μm. To arrange a meeting for the pumping beam and the HeNe laser -which was used for the purpose of alignment- a beam splitter BS with small losses at a wavelength of 810 nm was used. One of the advantages of this configuration is that it is simple, with minimal optics required, it finally leads to minimisation of optical losses.

The previous Nd:KGW crystal, and Nd:YAG crystal of dimensions 3x10 mm and Nd concentration of 1.1% were end-pumped in this configuration.

3.13.1 The performance of Cavity (1):

The first cavity for the Nd:YAG crystal using the new configuration, was a near-hemispherical one. The plane mirror of 100% reflectivity, the curved one is of radius of
curvature of 100 mm and reflectivity of 95%. The optimum parameters for this resonator as follows:

The cavity length was 92 mm, the threshold pumping power was 0.3W. The temperature of the diode was 24.5°C. The spot size of the pumping beam was measured to be approximately 400 µm in diameter. The TEM_{00} mode size was 420 µm at the face of the crystal. This was calculated by the Gaussian formulae and checked using the computer software.

The experimental data and results of the pumping power from the diode and the corresponding output power, were tabulated in Table (3.14).

<table>
<thead>
<tr>
<th>No</th>
<th>Pumping power mW</th>
<th>Output Nd:YAG power mW</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>290</td>
<td>0.5</td>
</tr>
<tr>
<td>2</td>
<td>413</td>
<td>23</td>
</tr>
<tr>
<td>3</td>
<td>618</td>
<td>73</td>
</tr>
<tr>
<td>4</td>
<td>810</td>
<td>128</td>
</tr>
<tr>
<td>5</td>
<td>1005</td>
<td>186</td>
</tr>
<tr>
<td>6</td>
<td>1189</td>
<td>247</td>
</tr>
<tr>
<td>7</td>
<td>1367</td>
<td>313</td>
</tr>
<tr>
<td>8</td>
<td>1539</td>
<td>376</td>
</tr>
<tr>
<td>9</td>
<td>1625</td>
<td>407</td>
</tr>
</tbody>
</table>

Table (3.14)
A plot of the power performance in Fig. (3.21).

From which the slope efficiency was found to be 31% and the threshold of the pumping power was 290 mw.
3.13.2 Nd:KGW optimised cavity(2):

The same above cavity was used to pump Nd KGW crystal in stead of Nd YAG. The optimised cavity parameters are:

The cavity length was 77 mm, the threshold pumping power was 290 mW.

The experimental data and results of the pumping powers versus the corresponding output powers for this cavity are tabulated on Table(3.15).

<table>
<thead>
<tr>
<th>No.</th>
<th>Pumping power mW</th>
<th>Output Nd:YAG power mW</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>290</td>
<td>7</td>
</tr>
<tr>
<td>2</td>
<td>413</td>
<td>56</td>
</tr>
<tr>
<td>3</td>
<td>618</td>
<td>120</td>
</tr>
<tr>
<td>4</td>
<td>810</td>
<td>188</td>
</tr>
<tr>
<td>5</td>
<td>1005</td>
<td>264</td>
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<tr>
<td>6</td>
<td>1189</td>
<td>328</td>
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<tr>
<td>7</td>
<td>1367</td>
<td>395</td>
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<tr>
<td>8</td>
<td>1539</td>
<td>432</td>
</tr>
<tr>
<td>9</td>
<td>1625</td>
<td>440</td>
</tr>
</tbody>
</table>

Table(3.15)
The plot of the performance of this cavity was in Fig. (3.22).

![Plot of Nd:KGW power vs. The pumping power]

Fig. (3.22)

It shows a slope efficiency of 34% and pumping threshold power of 290 mW.

Fig. (3.23) shows the performance of the Nd:YAG and the Nd:KGW crystals in the above cavity, this was done to facilitate the comparison between the performance of the
two crystals in the same cavity. In the plot the circular dots stand for Nd:KGW output power, while the squared dots for the Nd:YAG. It is seen that the slope efficiency is nearly the same for the two lasers.

It is expected that under the same pumping and cavity conditions, Nd:KGW will show a better performance than Nd:YAG. In our work we did not conclude to that.

A possible explanation is that the coating of Nd:KGW has a broad band. In this case the antireflection coating covers the wavelengths 1.067 µm and 1.3 µm, with 0.4% losses per reflection. While the antireflection coating of the Nd:YAG is centered at a wavelength of 1.064 µm with 0.1% losses per reflection. This difference in the passive losses is important in case of low gain system like the one we used.
Due to the birefringence of the Nd KGW, the absorption of our crystal for the depolarised light from the fiber-bundle, is less compared with that of the Nd YAG which has equal absorption for all polarisation. It is also longer in dimension than the Nd KGW crystal, so the total absorbed power is higher in the Nd YAG.

### 3.13.3 The performance of Cavity(3):

In the assembly of the third cavity for Nd YAG. It consists of plane mirrors of reflectivities 100% and 99% for the wavelength 1.064μm. The focusing lens of focal length of 50 mm. The estimated pump spot size was found to be 400 μm in diameter. The TEM$_{00}$ mode diameter as calculated by the matrix approach, was found to be 410 μm at the face of the crystal. The optimum parameters of this cavity were found to be as follows:

A cavity length of 189 mm. The diode temperature was 24.5°C. The positive lens is 42 mm from the crystal, and the front mirror to the crystal distance is 47 mm Fig.(3.24) shows the set-up of this cavity.

![Diagram of Cavity (3)](image)

Fig.(3.24)
The function of the intracavity lens in the set-up is to keep the cavity in the stable region and provide the required mode size.

The results of the pumping powers and the corresponding output powers of the Nd:YAG obtained from this cavity were tabulated on Table (3.16).

<table>
<thead>
<tr>
<th>No</th>
<th>Pumping power W</th>
<th>Output Nd:YAG power W</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>0.617</td>
<td>0.012</td>
</tr>
<tr>
<td>2</td>
<td>0.809</td>
<td>0.06</td>
</tr>
<tr>
<td>3</td>
<td>1.005</td>
<td>0.12</td>
</tr>
<tr>
<td>4</td>
<td>1.188</td>
<td>0.18</td>
</tr>
<tr>
<td>5</td>
<td>1.366</td>
<td>0.24</td>
</tr>
<tr>
<td>6</td>
<td>1.539</td>
<td>0.31</td>
</tr>
<tr>
<td>7</td>
<td>1.625</td>
<td>0.34</td>
</tr>
<tr>
<td>8</td>
<td>1.698</td>
<td>0.38</td>
</tr>
</tbody>
</table>

Table (3.16)

A plot of the data of this cavity in Fig (3.25)
From this plot it is found that the slope efficiency of the cavity was 34\% and the pumping threshold was 617 mW.

3.13.4 The performance of cavity(4):

The fourth cavity was for the Nd:KGW crystal. It consists of two plane parallel mirrors and an intracavity lens of focal length of 50 mm. The optimum parameters are as follows:

The cavity length was 192 mm, the diode temperature being 21.4°C. The back mirror has a reflectivity of 100\% for the wavelength 1.067 μm and the front one, 90\%. The pumping beam spot size was found to be 400 μm, the cavity mode diameter being 418 μm.
at the face of the crystal. The intracavity lens was located at 115 mm from the back mirror. The distance of the crystal from the front mirror of the cavity was 42 mm. Fig (3.27) illustrates the set-up of this cavity.

![Diagram of cavity](image)

**Fig (3.26)**

The experimental data and results of the pumping power from the diode and the corresponding output Nd:KGW power were tabulated in Table (3.17).

<table>
<thead>
<tr>
<th>No.</th>
<th>Pumping power mW</th>
<th>Output Nd:KGW power mW</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>1630</td>
<td>237</td>
</tr>
<tr>
<td>2</td>
<td>1559</td>
<td>214.5</td>
</tr>
<tr>
<td>3</td>
<td>1477</td>
<td>190</td>
</tr>
<tr>
<td>4</td>
<td>1311</td>
<td>137.5</td>
</tr>
<tr>
<td>5</td>
<td>1140</td>
<td>83.5</td>
</tr>
<tr>
<td>6</td>
<td>964.8</td>
<td>30.5</td>
</tr>
</tbody>
</table>

**Table (3.17)**
From the plotted experimental data it is seen that the slope efficiency is 32% and the threshold pumping power is nearly 850 mW.

The high threshold value, in this case, is due to the low reflectivity of the output mirror at wavelength 1.067 \( \mu \text{m} \) (Reflectivity = 90\%). To get low threshold pumping power and higher value of the slope efficiency, one needs to use optimal output mirrors. In this work the only available ones are of reflectivities of 90\% and 99\%.
CHAPTER FOUR

CONCLUSION
4. CONCLUSION

In this research, literature about lasers was collected and put in the chapter of the theory. More attention is paid for solid-state lasers and diode laser.

The experimental part includes determination of pumping parameters and constructing of cavities for CW diode end-pumping of Nd:KGW crystal.

We present measurements of:

i- Pumping parameters: e.g. spot size, spectral properties, temperature behaviour of the pump beam.

ii- The absorption of the active medium and its dependence on the wavelength.

iii- The output power and pump threshold power for several different cavity configurations, the main resonator parameters e.g. the mode size.

This work has demonstrated the performance of the TEM$_{00}$ single-mode of Nd:KGW at 1.067 µm and Nd:YAG at 1.064 µm lasers that end-pumped by diode laser coupled by a fiber-bundle, in two different optical arrangements:

(1) Single fiber output power.

(2) The output power of the nineteen fibers contained in the fiber-bundle.

It has been shown that Nd:KGW crystal is well suited for CW operation. The output power obtained was 400 mW and the corresponding pumping power was 1600 mW. This level of output power is higher than the recently published data in the literature[3].

Scaling of the output power to higher levels may be restricted by the thermal lensing.
This problem requires further studies. We expect that also other features of \text{Nd:KGW} may attract attention in the future, e.g. its high non-linear coefficient and strong stimulated Raman scattering lines.
References

12- Data sheet about Nd:KGW crystal, Optron Technology Company, Bulgaria.


22- K. A. Stanko, G. Marowsky, CLEO/Europe’94.