CHARACTERIZATION OF HIGH POWER LASER DIODE AS A SOLID STATE PUMPING SOURCE

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Dedication to my beloved father Md Jani b Zainal, my mother

Rahimah@Hendon bt Daud, my siblings and friends...

Thank you for your unforgettable supports

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ABSTRACT

Laser diode is popular to be used as an optical pumping source, taking an advantage because it is small in size and light in weight. On the other hand, the laser diode creates a lot of heat dissipation because it was injected by a current. Due to the cuteness of active medium, it will generate a large beam divergence. In attempt to demonstrate the issue and overcome these problems, two laser diodes were characterized and an investigation is carried out to stabilize the output. The first laser diode bar was purposely employed to highlight the issue of beam divergence. The second laser diode is highly collimated and capable to be focused. However, both lasers are not stable, meaning no cooling is provided. Two collimators model FLA40B and FLA15 were used to reduce the beam divergence of laser diodes. The stability of laser diode is identified by operating the laser in free running mode. Knowing that the output turn out to be very small, the result indicates that the laser required stabilizer. Fan extractor and heat sink were introduced in the system. Realizing that the output is still not stable, a Thermoelectric Cooler (TEC) was designed and constructed. After stabilizing the lasers system, they were utilized to pump orthovanadate Nd:YVO_4 crystal disk. The fluorescence beams were detected via spectrum analyzer. The pumping by using collimated high power laser diode was further enhanced by focusing the beam into an active medium and filtering the emission radiation using IR filter. The result obtained shows that, the laser diode produce output power of 1.8 W without cooling system with differential responsivity of 0.21 W/A and an efficiency of 8%. With TEC provided the laser power increased up to 4.6 W with power conversion of 12%. The output power of collimated beam achieved up to 8.6 W with differential responsivity of 0.54 W/A and an efficiency of 27%. Both laser diodes produced fundamental wavelength center at 808 nm. This is a suitable absorption band for orthovanadate crystal. However, the spectrum gain of the laser diodes is kept on broadening at higher pumping current. Changes in refractive index and the increase in active zone were the cause to the spectrum gain's broadening. The emission spectrum comprised of 878 nm, 917 nm with majority line of 1064 nm. It is also noticed that by focusing the high power laser diode and filtering the output, the emission radiation becomes more pronounce and significant.

ABSTRAK

Diod laser sangat popular digunakan sebagai sumber pengepaman optik disebabkan saiznya yang kecil dan ringan. Sebaliknya diod laser ini menghasilkan pembebasan haba yang tinggi disebabkan ianya dipam menggunakan arus elektrik. Menarik tentang medium aktif ini ialah ianya dapat menghasilkan cahaya yang mencapah. Dalam percubaan untuk melakukan demonstrasi ini dan mencari penyelesaiannya, dua diod laser telah dicirikan dan siasatan telah dijalankan untuk menstabilkan keluaran. Diod laser yang pertama telah digunakan untuk tujuan memahami isu pencapahan cahaya. Diod laser yang kedua pula adalah daripada jenis yang terarah dan boleh difokuskan. Walaubagaimanapun kedua-duanya tidak stabil. Bermaksud tiada sistem penyejukan disediakan. Dua jenis penjajar iaitu FL40B dan FLA15 telah digunakan untuk mengurangkan kecapahan cahaya daripada diod laser. Kestabilan diod laser ini dikenalpasti dengan mengoperasikannya dalam mod bebas. Diketahui keluarannya terlalu kecil, menunjukkan laser tersebut memerlukan penstabil. Kipas dan penyerap haba telah diperkenalkan dalam sistem ini. Disedari keluaran laser masih lagi tidak stabil, penyejuk elektriktermo (TEC) telah direka dan dibina. Setelah sistem laser distabilkan, ia seterusnya digunakan untuk mengepam cakera kristal $Nd:YVO_4$. Cahaya pendafluor telah dikesan menggunakan penganalisis spektrum. Pengepaman menggunakan diod laser berkuasa tinggi yang terarah seterusnya ditingkatkan dengan memfokuskan cahaya tersebut ke dalam medium aktif dan menapis sinaran keluaran menggunakan penapis infra merah. Keputusan yang diperolehi menunjukkan diod laser menghasilkan kuasa keluaran sebanyak 1.8 W tanpa sistem penyejukan dengan pembezaan responsiviti sebanyak 0.21 W/A dan kecekapan 8%. Kuasa keluaran telah ditingkatkan sebanyak 4.6 W dengan kecekapan 12% apabila menggunakan TEC. Kuasa keluaran daripada cahaya yang terarah mencapai sehingga 8.6 W dengan pembezaan responsiviti sebanyak 0.54 W/A dan kecekapan 27%. Kedua-dua diod laser menghasilkan panjang gelombang asas pada 808 nm. Ia adalah jalur penyerapan yang sangat bagus untuk cakera orthovanadat. Walaubagaimanapun spektrum gandaan diod laser semakin melebar pada pengepaman arus yang tinggi. Perubahan indeks biasan dan peningkatan dalam zon aktif adalah punca kepada pelebaran spektrum gandaan ini. Spektrum keluaran panjang gelombang 808 nm, 917 nm dengan 1064 nm adalah majoriti garis tersebut. Didapati dengan memfokuskan diod laser dan menapis keluarannya, sinaran keluaran menjadi lebih jelas dan signifikan.

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LIST OF SYMBOLS

c	-	Speed of light [m / s]
C_L	-	Loop stability capacitance
d	-	Depth of active region in semiconductor
D_n	-	Diffusion constant for electron
h	-	Planck constant [J · s]
i		Electric current [A]
i_t	-	Threshold current of a laser diode [A]
I_S	-	Sink current [A]
n_p		Electron concentration in *p*-region
P	-	Optical power [W]
R_C	-	Current limit resistor
R_L	-	Loop stability resistance
R_S	-	Temperature set resistor
$\Re_d$		Differential responsivity
V	-	Voltage [V]
η		Quantum efficiency or efficiency of power transfer
η_d		External differential quantum efficiency
η_e		Emission efficiency
η_i		Internal quantum efficiency
λ_o	-	Free space wavelength [m]
v		Frequency [Hz]
Φ_o		Output photon flux
Ω	-	Electric resistance [R]

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CHAPTER I

INTRODUCTION

1.1 Overview

Semiconductor laser, first discovered in 1962 was thought to be a breakthrough invention that would revolutionize industry (Welch, 2000). July 1962 Keyes and Quist presented a paper, “Recombination Radiation Emitted by Gallium Arsenide Diodes,” at the Solid State Device Research Conference (SSDRC) in Durham, NH. This paper described intense luminescence with a quantum efficiency of approximately 85 % from GaAs junctions at 77 ^{o}K. These results were so startling that they energized a number of research group to consider the question of semiconductor laser.

The paper announcing the first semiconductor laser operation was the General Electric paper submitted in September 1962 and appearing in the November 1, 1962, edition of *Physical Review Letters* (Hall *et al*, 1962). The resulting diodes were cooled to 77 ^{o}K and operated in pulsed mode.

Laser research then began to diverge into number of separate areas. The idea of using heterosturctures in semiconductor diode laser was a very powerful idea and was proposed by Kroemer (1963), resulting in reduce threshold continuous wave, cw emission. Such a structure requires two interfaces of different indexes of refraction, one on top and one below the active region formed two junctions so called heterostructure or double heterostructure. However the heterostructure concept required the development of appropriate materials processing technologies, such as liquid phase epitaxy (LPE), metal-organic chemical vapor deposition (MOCVD), and molecular beam epitaxy (MBE) (Hecht). Therefore the original proposal of Kroemer went relatively unnoticed.

Nelson (1963) first demonstrated the liquid phase epitaxy growth of GaAs on GaAs. Distributed feedback lasers (DFB lasers) were another another major track in laser development. DFB lasers incorporate an intrinsic grating to force single longitudinal mode operation. Kolgenik and Shank (1971) first developed the experimental and theoretical ideas behind DFB lasers.

Vertical-cavity surface-emitting lasers (VCSEL) were later developments in semiconductor laser technology. In this type of laser, lights not emitted from the edge of the device but rather through the entire top layer of the semiconductor crystal itself. Soda *et al*. (1979) demonstrated the first VCSEL. This was a double heterostructure InGaAsP device operating at 1.3 µm. It used metal mirrors and lased at 77 ^{o}K.

1.1.1 Semiconductor Materials

The next major technology breakthrough for semiconductor lasers and specifically high-powered lasers was the conceptual development and experimental realization of psuedomorphic material, otherwise referred to as strained layer materials. Up to this time crystal growth was limited to the material systems that were lattice matched to a common substrate. In mid-1980s, layers that were on the order of 10 nm could be grown in the midst of a lattice match layer structure where the lattice mismatch could be significant.

For AlGaAs lasers grown on GaAs subtrates, emission wavelengths could be extended from less than 780 nm to longer than 1100 nm, easily reaching the emission wavelengths necessary for pumping of Er doped fiber amplifiers (Welch, 2000). It was further shown that the incorporation of In in the active region of an AlGaAs laser inhibited the migration of defects in the material thus improving the reliability of the material. From these developments came high-power lasers operating at 980 nm and the first short wavelength laser could meet a 20-year lifetime required for communication systems.

Pseudomorphic materials were critical to the development of another class of high power lasers, which is GaAsP lasers for the emission of 810 nm. Meanwhile AlGaInP lasers could produce emission between 630 and 680 nm. Pseudomorphic concepts have since been applied to AlGaInN laser for efficient operation in the 380 to 470 nm region and in the AsSb-based materials, the lasing properties is in the mid-IR.

1.1.2 Laser Diode Application

The first use of MOCVD and MBE was in the fabrication of AlGaAs lasers operating between 780 and 860 nm. From this material system came the first application of high power semiconductor laser, that of pumping Nd:YAG lasers at wavelength around 810 nm. The use of diode pumping Nd:YAG lasers enabled a dramatic reduction in size and a significant increase in operating efficiency as compared to flashlamps pumped solid-state laser. High power semiconductor laser used for pumping Nd:YAG lasers were first commercially introduced in 1984 at output powers of 100 mW. Today monolithic laser arrays have been demonstrated at output powers approaching 200 W cw where reliable opration of 60 W is commercially available.

Second application that has been impacted by high-power semiconductor lasers has been optical storage. Read-only applications within optical data storage have existed for a number of years at 830 and 780 nm. It has been the advances in high power laser technology that have pushed the reliable output powers to greater than 30 mW that has enabled the ability to write on optical discs. Initially, this was introduced to that market at 830 nm, followed closely behind by 780 nm and more recently 650-680 nm lasers, the movement to shorter wavelength for benefits of higher storage capacities.

Other applications that have benefited from higher power semiconductor lasers in the early years of their development include free-space/satellite communications, where extensive work and a number of demonstration were successful at secure free-space optical links, direct diode material processing applications including heat treatment of metal surfaces, medical applications such as photodynamic therapy, hair removal and other therapeutic applications.

1.1.3 Diode Pumped Solid State Material

Studies of diode pumped solid state was done by several researcher. The active feedback control in Q-switched diode pumped Nd:YVO_4 laser by monitoring the fluorescence intensity from laser crystal was presented by Wenjie *et al.* (1999). The Q-switched pulse energy is stable with proposed feedback scheme based on the fluorescence intensity. Chen (1999) reported a high-power diode-end-pumped Nd:YVO_4 laser at 1.34 μm in influence of Auger upconversion. The strong dependence of the slope efficiency on the dopant concentration is attributed to an Auger upconversion process..

A research about an inexpensive diode-pumped mode-locked Nd:YVO_4 laser for nonlinear optical microscopy was done by Yang in year 2000. The resulting self-defocusing lens couples with an aperture appearing in the gain medium and then produces a cavity loss modulation. The laser was shown to be useful for probing polar structures of nonlinear optical materials with second harmonic microscopy. The effective stimulated emission cross-section in a diode pumped Nd:YVO_4 micro-laser at 1064 nm with various doping concentrations was presented by Mukhopadhyay (2002). In this method a micro-laser is formed by keeping a small piece of the sample in a plane resonator under semi-monolithic configuration and a fiber coupled diode laser was used for pumping. The overlap integrals in this method were estimated by measuring the thermal lens focal length at the threshold.

A design of diode-pumped high efficiency Nd:YVO_4/LBO red laser is reported by Zheng (2002). With an incident pump laser of 800 mW, using type-I and type-II CPM LBO, 97 and 52 mW TEM_{00} mode red laser outputs were obtained. A laser diode directly end-pumped, passively Q-switched Nd:YVO_4/CR: YAG laser was presented by Zheng (2001). From this paper a KTP crystal was inserted into the cavity, Q-switched 532 nm with an average power of 56 mW, pulse width of 28.4 ns, repetition rate of 118.2 kHz and peak power of 16.7W was obtained at last. A fiber-coupled diode-single-end-pumped Nd:YVO_4 laser with an Nd:YVO_4 crystal of 0.3 at% doping concentration and 3 X 3 X 10 mm^3 dimensions was reported by Zhang (2003).

A high-power Q-switched Nd:YAG/Cr:YAG laser mounted in a silicon microbench was presented by Evekull (2003). The use of microstructure silicon carriers provides efficient thermal control, compact integration and alignment of active and passive optical components Lee (2003) analyzed a linear cavity for intracavity frequency doubling of a diode-pumped acousto-optic Q-switched Nd:YAG rod laser, and showed that a green laser beam with a short pulse width can be generated efficiently. Minimum laser pulse width of approximately 32 ns was obtained around 1 kHz repetition rate for both green and IR laser beams.

Cheng (2000) demonstrated diode-pumped CW and passively Q-switched Nd:YVO4 laser using an ultra-thin (100 lm) crystal as the gain medium. diode-pumped normal Nd:YVO4 laser using thick (e.g. 1 mm) crystal as the gain medium often operates in multiple modes and is difficult to realize Cr4.:YAG passively Q switched laser in such a cavity. A diode-pumped Nd : YVO4 laser passively Q switched with GaAs is studied theoretically and experimentally by Ping Li (2001). The experimental results show reasonable agreement with the theoretical results on the whole. Minassian (2003) reported that the first operation of a diode-side-pumped Nd:YVO4 laser in a bounce geometry at 1342 nm. A master oscillator power amplifier (MOPA) version of the bounce-geometry produces 20 W of output power. These results represent the highest power at 1342 nm from a Nd:YVO4 oscillator and oscillator-single-amplifier MOPA system.

The thermal lensing effect induced by high-power diode pumping in the grazing incidence side-pumped Nd:YVO4 laser geometry is numerically modeled and analyzed by Bermudez G (2002). The 3D temperature distributions and the correspondent thermally induced lens in Nd:YVO4 crystal are calculated for the straight and zig-zag paths of the laser beam. A practical method is described and used for determination of the effective stimulated emission cross-section (e) in an operating diode pumped Nd:YVO4 micro-laser at 1064 nm with various doping concentrations Waichman (2002) have used diode arrays in a linear configuration to side-pump passively Q-switched and free-running Nd:YAG and Nd:YVO4 lasers. The gain distribution found was used to evaluate the pump power density, which in turn, was used to calculate the dependence of the laser pulse width on the pumping power.

Bernal presented an ABCD transfer matrix spatial mode analysis of a diode-side-pumped Nd:YVO_4 laser resonator. The mode spot size behavior of the oscillating Gaussian beam in the sagittal and tangential planes is used to determine the best configuration for the diode-sidepumped Nd:YVO4 laser resonator. Yang reported an inexpensive diode-pumped Nd:YVO4 laser mode-locked with combined effects of nonlinear mirror (NLM) and cascaded second-order optical nonlinearities (CSON) in a KTP crystal. The laser was shown to be useful for probing polar structures of nonlinear optical materials with second harmonic microscopy. Wenjie (1999) implemented active feedback control in a Q-switched diode-pumped Nd:YVO4 laser by monitoring the fluorescence intensity from the laser crystal. The Q-switched pulse energy is stabler with his feedback scheme based on the fluorescence intensity than that with the conventional Q-switching when pumping source is not stable.

Martin was done a research about a Nd:YAG laser having a ring configuration, with a Faraday rotator to provide unidirectional operation has been end-pumped by a single 20 W diode bar equipped with a beam-shaper. Using a thin intracavity etalon for wavelength selection, a single-frequency output of 4.2 W is obtained on the 1061.4 nm transition. Hailin Wang (2003) reports on the characterization of a diode-side-pumped CW Nd:YAG laser. A side-pumped configuration with 9 laser diodes is used for the laser. Output power of the laser under different output couplers, resonator lengths and temperatures of the cooling water has been studied.

Yu (2002) reports on the characterization of a side-pumped 40 W CW Nd:YAG laser. A side-pumping con4guration with six laser diodes is used for the laser. Output power and beam quality of the laser under di6erent output couplings, cavity lengths, types of cavity and di6erent temperatures of the cooling water have been experimentally studied. Chen (2004) studied about a high-power diode-pumped Nd:YAG laser at 1123 nm is acousto-optically Q-switched at a pulse repetition rate range of 5–20 kHz. The general agreement indicates that the simple model is adequate for a first order prediction of the low-gain laser characteristics. High efficiency laser performance of 2mm diameter and 20mm long Nd:YAG crystal rod transversely pumped by laser diode array was presented by Kundu (2001). The complete solid-state Nd:YAG laser was described to be simple, compact and highly efficient.

1.2 Problem Statement

Laser diodes have widely application because of it compactness and high power. However because of divergence, it might reduce a lot of its power. As a result, the power may not enough to excite a solid state material. Furthermore because lasers have been pumped by forward-bias current, a lot of energy have been dissipated into heat which also contribute in stability of the laser output power. Hence this project was carried out to investigate the stability of laser diode. In additional the spectrum of high power laser diode might be broaden and overlap with emission spectrum. This will cause the difficulty in analyzing the emission spectrum. The way to reduce or eliminate this problem needs to be found.

1.3 Research Objective

The main objective of this project is to investigate the performance of high power laser diode used to pump solid state material. In attempt to achieve these goals, we carried out some of these following works:

1. To characterize laser diode bar

2. To develop thermoelectric cooler as a stabilizer
3. To collimate the divergence mode laser diode bar
4. To estimate laser diode efficiency
5. To analyze the absorption spectrum
6. To analyze the emission spectrum

1.4 Research Scope

In this project two types of laser diode were employed; diverged laser diode and collimated laser diode. Thermoelectric cooler was developed to stabilize the laser diode. Neodymium orthovanadate ($Nd:YVO_4$) crystal was employed as a laser medium. The characterization of laser beam was carried out by using spectrum analyzer, powermeter, CCD profiler and oscilloscope.

1.5 Thesis outline

The thesis is divided into five chapters. In the first chapter, it reviews some of previous research on development of laser diode, and its application in various field of research.

Chapter II reviews the theory of the diode-pumped solid-state laser including properties of semiconductor laser, laser diode working principal, efficiency and solid-state material including the energy level.

Chapter III described about the experimental methods and techniques used in laser diode. This will include the calibration the laser diode, development of cooling system and setup on pumping of the gain material.

Chapter IV discussed the experimental results gained from the Chapter III. It will discussed the development of the cooling system, characterized the divergence and collimated laser diode and also characterized the fluorescence of the $Nd:YVO_4$ crystal after been pumping by laser diode.

Finally, the conclusions of the project are noted in chapter V. These provide with the summarization of the whole project and also problems arisen during the period of study. Finally, a few suggestions are recommended for future study.

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