DESIGN AND CHARACTERIZATION OF A FLEXIBLE DIODE PUMPED SOLID STATE LASER NEODYMIUM ORTHOVANADATE

GANESAN A/L KRISHNAN

A thesis submitted in fulfillment of the
requirements for the award of the degree of
Doctor of Philosophy (Physics)

Faculty of Science
Universiti Teknologi Malaysia

NOVEMBER 2014

Dedicated to my family and friends

ACKNOWLEDGEMENT

First of all, my sincere thanks to Professor Dr. Noriah Bidin who had performed her duty as my supervisor excellently. Also, I’m extremely grateful to her for providing continual supports from every possible aspect throughout my research. I am always impressed by her diligence and determination which had been a source of motivation for me.

I also would like to express acknowledgement to Mrs. Norhasimah Yaacob who is the science officer of Laser laboratory. She had provided her supports for this research in term of technical and documentation aspects. Thanks are also address to all kind cooperation throughout the research works. This acknowledgement section would not complete without names of my Laser laboratory colleagues because they had been my second family throughout this study. Therefore, I thank Mohamad Fakaruddin Sidi Ahmad, Nur Athirah Taib, Nurul Nadia, Lau Pik Suan, Ebrahim Pourmand, Syafiq Affandi, Nur Ezzaan Khamsan and many more.

Finally, I am ever grateful to my family and Suganthi Murthy for their supports and encouragements in term of psychological and financial aspect in the times of need.

ABSTRACT

The main goal of this research is to determine temperature variation of stimulated emission cross section of laser crystal through alternative method. Neodymium-doped yttrium vanadate ($Nd:YVO_4$) laser crystal has been utilized as the gain medium. A 808 nm laser diode was employed as the pumping source. A laser system was designed and then a prototype was created. Performance of the laser system was quantified with 97 % reflective at 1064 nm output coupler. It was found that slope efficiency and threshold power of the system were 46.9 % and 0.109 W respectively. The focal power of the laser crystal was varied with absorbed pump power at a rate of 0.228 D/W. From output fluorescence spectrums recorded at various crystal temperatures, variation of linewidth, wavelength and intensity of 1064 nm emission were determined. The rate of change of linewidth, wavelength and intensity with temperature were 5.4 pm/^{o}C, 3.7 pm/^{o}C and 0.075 arb. unit/^{o}C respectively. Through spectroscopic method, stimulated emission cross section variation with temperature was found to be -0.462 %/^{o}C with respect to stimulated emission cross section at 20 ^{o}C. For stimulated emission cross section determination through performance method, larger pump beam radius and 70 % reflectivity at 1064 nm output coupler were used. To obtain linear graph, a graph of P_{out}/f_l against P_{abs} was drawn. At 30 ^{o}C, gradient of the graph, threshold power and cavity loss were found to be 46.6 %, 0.760 W and 6.6 % respectively. Through performance method, stimulated emission cross section variation with temperature was found to be -0.447 %/^{o}C with respect to stimulated emission cross section at 20 ^{o}C. The change of stimulated emission cross section with temperature obtained through performance method is in good agreement with spectroscopic method.

ABSTRAK

Matlamat utama kajian ini adalah untuk menentukan perubahan keratan rentas pemancaran terangsang terhadap suhu kristal laser melalui kaedah alternatif. Kristal Itrium vanadat didop neodimium (Nd:YVO_4) telah digunakan sebagai medium aktif. Diod laser dengan panjang gelombang 808 nm telah digunakan sebagai sumber mengepam. Satu sistem laser telah direka dan kemudian prototaip telah dicipta. Prestasi sistem laser itu diukur dengan penganding keluaran 97% reflektif pada panjang gelombang 1064 nm. Hasil kajian telah mendapati bahawa kecekapan cerun dan kuasa ambang sistem masing-masing ialah 46.9 % dan 0.109 W. Kuasa fokus kristal laser didapati berubah dengan kuasa pam diserap pada kadar 0.228 D / W. Variasi lebar garis, panjang gelombang dan keamatan cahaya laser 1064 nm dengan suhu telah ditentukan dari spektrum keluaran pendarfluor direkodkan pada pelbagai suhu kristal. Kadar perubahan lebar garis, panjang gelombang dan keamatan cahaya dengan suhu masing-masing ialah 5.4 pm/^{o}C, 3.7 pm/^{o}C and 0.075 unit arbitrari/^{o}C. Melalui kaedah spektroskopi, variasi keratan rentas pemancaran terangsang dengan suhu didapati -0.462 %/^{o}C terhadap keratan rentas pada 20 ^{o}C. Bagi penentuan keratan rentas pemancaran terangsang melalui kaedah prestasi, sumber pam dengan jejari lebih besar dan penganding keluaran 70 % reflektif pada panjang gelombang 1064 nm digunakan. Untuk mendapatkan graf linear, graf P_{out} / f_l terhadap P_{abs} telah dilukis. Pada suhu 30 ^{o}C, kecerunan graf, kuasa ambang dan peratusan kehilangan kuasa dalam resonator masing-masing ialah 46.6 %, 0.760 W dan 6.6 %. Melalui kaedah prestasi, variasi keratan rentas pemancaran terangsang dengan suhu didapati -0.447 %/^{o}C terhadap keratan rentas pada 20 ^{o}C. Perubahan keratan rentas pemancaran terangsang dengan suhu yang diperoleh melalui kaedah prestasi setuju dengan kaedah spektroskopi.

TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

LIST OF SYMBOLS AND ABBREVIATIONS

A_e - Effective Area of the Mode
A_{21} - Einstein’s Coefficient of Spontaneous Emission
B_{12} - Einstein’s Coefficient for Stimulated Absorption
B_{21} - Einstein’s Coefficient of Stimulated Emission
c - Speed of Light
c_o - Speed of Light in Vacuum
CCD - Charge Coupled Device
CW - Continuous Wave
dn/dT - Thermal Optic Coefficient of Gain Medium
$d\upsilon$ - Interval of Frequency
dx - Small Incremental Length of Material
D - Distance from Beamwaist at which Far-field Beam Radius was measured
DPSS - Diode Pumped Solid State
e - Electronic Charge
ΔE - Energy Gap of Recombination Region
$E(r)$ - Electric Field Distribution
E_1 - Lower Energy Level
E_2 - Higher Energy Level
E_o - Maximum Electrical Field Value
f_{th} - Thermal Lens Focal Length
f_e - Effective Focal Length of Gain Medium
f_b - Occupancy of the Upper Energy Level
f_m - Focal Length of Gain Medium Caused by Mechanical Factors
F - Finesse
g - Normalized Pump Distribution

g_1 - Degeneracy of Energy Level E_1

g_2 - Degeneracy of Energy Level E_2

g_1, g_2 - Resonator Stability Criterion

$g(\upsilon,\upsilon_o)$ - Normalized Atomic Lineshape

G - Pumping Rate per Unit Volume

G_o - Total Number of Photons Absorbed per Unit Time.

h - Planck's Constant

i - Input Current

i_s - Threshold Current

$I(r)$ - Intensity Distribution

I_o - Peak Intensity

I - Intensity of the Oscillating Beam inside the Cavity in Single Direction

I_{sat} - Saturation Intensity

k - Boltzmann's Constant

l - Gain Medium Length

L - Cavity Length

L_1 - Distance Between Beamwaist and Mirror M1

L_2 - Distance Between Beamwaist and Mirror M2

L_e - Effective Cavity Length of the Resonator

n_1 - Population Density of Energy Level E_1

n_2 - Population Density of Energy Level E_2

n - Refractive Index

N - Population of Upper State Population per Unit Volume

N_1 - Population of Energy Level E_1

N_2 - Population of Energy Level E_2

$N_2(0)$ - Population of Energy Level E_2 at Time $t=0$

Nd - Neodymium

P - Total Power in Gaussian beam

P_{out} - Output Power

P_h - Ratio of Pump Power Converted into Heat

P_{in} - Input Pump Power

P_{out} - Output Power

P_{th} - Threshold Power
P_{abs} - Absorbed Pump Power
q - Total Number of Laser Photon in the Resonator
r - Radial Distance from the Beam Centre
R - Geometric Mean of Mirror Reflectivity
R_1 - Radius Curvature of Mirror M1
R_2 - Radius Curvature of Mirror M2
T - Temperature
TEC - Thermoelectric Cooler
T - Transmission of the Output Coupler
V - Volume
z - Distance on Beam Axis
Z_R - Rayleigh Range
α_o - Absorption Coefficient
γ - Loss per Pass
$\Delta\upsilon$ - Frequency Separation between Adjacent Longitudinal Modes
$\delta\upsilon$ - Linewidth of Longitudinal mode
ε - Normalized TEM_{00} Mode Gaussian Cavity Mode Energy
$\varsigma(\upsilon)$ - Emission Energy per Unit Frequency
η_d - Differential Quantum Efficiency
η_t - Optical Transfer Efficiency
η_a - Absorption Efficiency
η_p - Pump Efficiency
θ - Full Beam Divergence Angle
λ - Wavelength
λ_L - Laser Wavelength
λ_p - Pump Wavelength
υ - Frequency of Radiation
ρ - Cavity Mode Energy Density
ρ_o - Peak Value of Energy Density in Vacuum
σ_{12} - Spectral Stimulated Absorption Cross Section
σ_{21} - Spectral Stimulated Emission Cross Section

σ_e - Effective Stimulated Emission Cross Section

σ - Cross Section of Emission Line

σ_s - Slope Efficiency

τ_{21} - Lifetime for Spontaneous Emission

τ - Upper Level Lifetime

τ_c - Photon Lifetime

ω - Beam Radius

ω_o - Beamwaist

ω_1 - Cavity Mode Radius at Mirror M1

ω_2 - Cavity Mode Radius at Mirror M2

ω_p - Average Pump Beam Radius

ω_D - Far-field Beam Radius

ω_{ps} - Minor Axis Pump Radius

ω_{pl} - Major Axis Pump Radius

ω_L - Cavity Mode Radius

LIST OF APPENDICES

CHAPTER 1

INTRODUCTION

1.1 Overview

LASER is the acronym for Light Amplification by Stimulated Emission Radiation. In present of electromagnetic field, active ions in a gain medium absorb the radiation and leap into excited state. This process known as stimulated absorption process. Ions in the excited state naturally fall back to ground state through spontaneous emission process. However, in the presence of the stimulating radiation, the ions in excited state induced by the radiation to fall back to ground state rapidly. Consequently, excessive energy of the transition releases in form of a photon which has the same characteristics as the inducing radiation field. This effect is known as stimulated emission process and it was predicted by Einstein in 1916.

Basic building blocks of a solid-state laser system are pumping source, active medium and optical cavity as shown in Figure 1.1. In this research, the pumping source is a laser diode. On the other hand, another type of pumping source for solid-state laser is flashlamp. However, laser diodes have many advantages over flashlamps in a laser system including higher energy efficiency and compact size. Furthermore, the gain medium of this research is Neodymium Orthovanadate (Nd:YVO_4) laser crystal. In this crystal, the Neodymium ions are the active ions and YVO_4(Yttrium Orthovanadate) is the host material. The other famous host material for Neodymium ions is YAG (yttrium aluminium garnet). Nd:YVO_4 laser crystal is ideal gain medium for a low power diode-pumped solid-state system due to its high stimulated emission cross section at 1064 nm and high absorption cross section at

808 nm pump wavelength. Finally, the optical resonator of this study is a plane parallel resonator which falls on stability curve of resonator stability diagram. During laser operation, the optical resonator effectively becomes more stable plano-concave configuration due to thermal lensing effect of the gain medium.

In this research, a flexible diode end-pumped Nd:YVO_4 laser system will be designed and constructed. Initially, spectroscopy properties of the gain medium will be studied which will lead to estimation of stimulated emission cross section. A linear resonator will be configured followed by optimizing and calibrating the performance of the laser system. Finally the laser system will be packaged and demonstrated as a plug and play device.

This thesis has six chapters. In chapter 1, the importance and objectives of this research will be stated. In chapter 2, literature and theories used in this study will be provided. The research methodology will be presented in chapter 3. Results will be shown and discussed in chapter 4 and chapter 5. Finally, conclusions and future works related to this study will be presented in chapter 6.

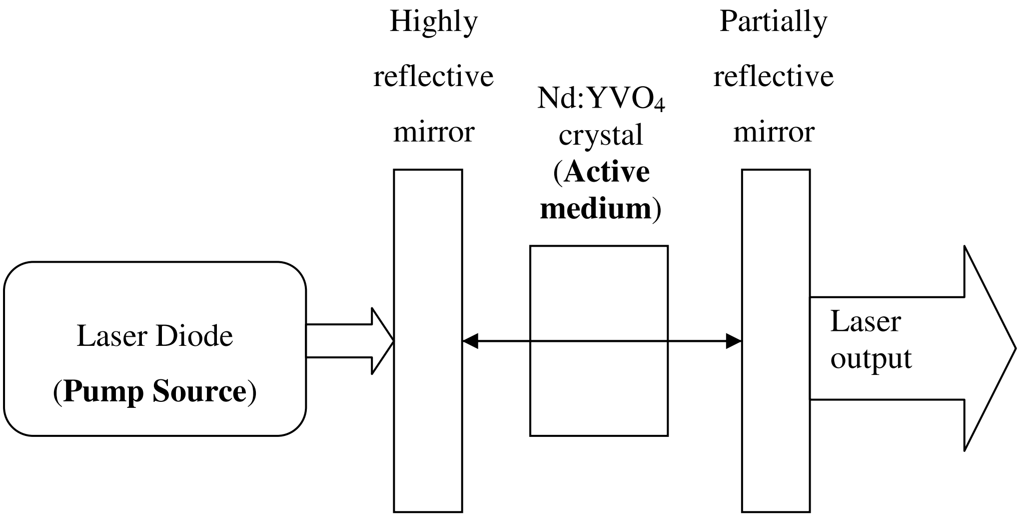

Figure 1.1: Schematic diagram of an end-pumped laser system

1.2 Problem Statement

Recently diode pumped solid state (DPSS) laser has a higher demand compared to flashlamp pumped laser in the market because of its simplicity and economical price. However, most of the commercial DPSS laser system is a rigid system this means it does not provide flexibility in the laser cavity. Usage of such laser system is limited or only applicable for specific applications. No chance to study the spectroscopy properties of the laser crystal and far from modifying the laser operation. They are designed more like a disposable system, no solutions for component upgrades or for user maintenance in case the laser system is out of order. Hence a novel diode pumped solid state laser system is designed and constructed. The flexibilities of the optical resonator allow discovery and exploration of laser system characteristics and its variations with temperature and pump power.

1.3 Research Objective

The main objective of this research is to design and construct a flexible and compact diode pumped solid state laser system. This is accomplished by completing following tasks:

1. To design a flexible diode pumped solid state laser system
2. To construct and evaluate a laser system including the power supply laser head and cooling system
3. To characterize the spectroscopy properties of the gain medium Nd:YVO_4 crystal using the developed laser system
4. To estimate the stimulated cross section upon the change on crystal temperature
5. To compare the stimulated cross section of the gain medium obtained from spectroscopic method and performance method

1.4 Scope of Study

In designing and construction of a novel diode pumped solid state laser, several aspects are considered to limit the scope of the study. These include the selection of gain medium, the pumping source technique and the cooling system to stabilize the output of laser. In this manner, Nd:YVO_4 was chosen as the gain medium in this construction. This selection is based on its physical properties including its high gain and strong absorption to selected pumping source. However, it has limitation because of its low thermal conductivity. The excitation of the active ions was done through end pumping technique by using 808 nm diode laser. In order to maintain the stability of the output laser, a Thermoelectric cooler (TEC) was installed in the laser cavity. The temperature of the TEC was controlled within the range of 5- 60°C. A variable DC power supply was provided to verify the input power of diode laser within 0- 3 W. Subsequently, this allows manipulating the laser output power of the solid state laser within 0 – 500 mW. In order to produce the flexible cavity, precise and replaceable optical component holders were designed. Spectrum analyzer was employed to analyse the laser transition line induced after excitation. Beam profiler was used to measure the beam quality, and Power meter used to calibrate the input power and measurement of the laser performance. The laser performance is studied based on temperature and pump power variation.

1.5 Significance of Study

The design and construction of flexible diode pumped solid state have a high potential to be commercialized as a laser kits system or as a source of light for scientific research. Moreover, determination of stimulated emission cross section variation with temperature by performance method studied in this thesis can be used as an alternative method to spectroscopic technique.

properties of the laser crystals can be studied including, the changing percentage of ion neodymium doping level in the host, vary the thickness as well as the surface size of the crystal, changing the type of rare earth doping ions. The pumped power may be can verify by changing the input power by utilizing more powerful fiber laser, changing the wavelength to increase the quantum efficiency and also to consider the pumping technique by deploying side pumping through different emitter size and number.

This experimental work which investigated on alternative method to measure stimulated emission cross section had open up varieties of future works also. Since not much works were done on this subject, there are some in depth works had to be done to enhance this research. This study can be done on any other laser crystal and determine its stimulated emission cross section at various temperatures during laser operation. Secondly, the range of temperature also can be extended to check the validity of this study with wider temperature range. Thirdly, the theoretical part can be refined to suit this study with fewer assumptions made.

Beside the laser system itself, many other works need to be done, including modified the laser output. Currently the designed laser is operating in continuous mode. May be in the future, the diode pumped solid state laser can be operated in pulse mode either applying saturation absorber for Q-switching mode or fiber Bragg grating for femtosecond operation. There is also possibility to generate tunability of operation system.

REFERENCES

Asundi, A. K., Peng, X., Chen, Y., Xiong, Z., Lim, G. C., & Zheng, H. (1999). *Thermal effects of diode-end-pumped Nd: YVO_4 solid state laser.* Paper presented at the International Symposium on Photonics and Applications.

Bass, M., Weichman, L. S., Vigil, S., & Brickeen, B. K. (2003). The temperature dependence of Nd 3+ doped solid-state lasers. *Quantum Electronics, IEEE Journal of, 39*(6), 741-748.

Bidin, N., Krishnan, G., Khamsan, N. E., Hassan, H. M., Shaharin, M. S. (2010). *Thermal efffects in diode pumped vanadate laser.* 3rd International Conferences and Workshops on Basic and Applied Sciences 2010, 14-20.

Blows, J. L., Omatsu, T., Dawes, J., Pask, H., & Tateda, M. (1998). Heat generation in Nd:YVO_4 with and without laser action. *Photonics Technology Letters, IEEE, 10*(12), 1727-1729.

Chang, Y., Huang, Y., Su, K., & Chen, Y. (2008). Comparison of thermal lensing effects between single-end and double-end diffusion-bonded Nd:YVO_4 crystals for $^4F_{3/2}\rightarrow {}^4I_{11/2}$ and $^4F_{3/2}\rightarrow {}^4I_{13/2}$ transitions. *Optics express, 16*(25), 21155-21160.

Chen, F., Yu, X., Gao, J., Li, X., Zhang, Z., Yan, R., et al. (2008). Efficient generation of 914 nm laser with high beam quality in Nd:YVO_4 crystal pumped by π-polarized 808 nm diode-laser. *Laser Physics Letters, 5*(9), 655.

Chen, X., & Di Bartolo, B. (1993). Phonon effects on sharp luminescence lines of Nd^{3+} in $Gd_3Sc_2Ga_3O_{12}$ garnet (GSGG). *Journal of luminescence, 54*(5), 309-318.

Chen, Y.-F., Lan, Y., & Wang, S. (2000). Efficient high-power diode-end-pumped TEM_{00} Nd:YVO_4 laser with a planar cavity. *Optics letters, 25*(14), 1016-1018.

Chen, Y. (1999). Design criteria for concentration optimization in scaling diode end-pumped lasers to high powers: influence of thermal fracture. *Quantum Electronics, IEEE Journal of, 35*(2), 234-239.

Chénais, S., Druon, F., Forget, S., Balembois, F., & Georges, P. (2006). On thermal effects in solid-state lasers: The case of ytterbium-doped materials. *Progress in Quantum Electronics, 30*(4), 89-153.

Clarkson, W., & Hanna, D. (1998). Resonator design considerations for efficient operation of solid-state lasers end-pumped by high-power diode-bars. *Optical Resonator – Science and Engineering*, 327-361.

Délen, X., Balembois, F., & Georges, P. (2011). Temperature dependence of the emission cross section of Nd:YVO_4 around 1064 nm and consequences on laser operation. *JOSA B, 28*(5), 972-976.

DeLoach, L. D., Payne, S. A., Chase, L., Smith, L. K., Kway, W. L., & Krupke, W. F. (1993). Evaluation of absorption and emission properties of Yb^{3+} doped crystals for laser applications. *Quantum Electronics, IEEE Journal of, 29*(4), 1179-1191.

Didierjean, J., Forget, S., Chenais, S., Druon, F., Balembois, F., Georges, P., et al. (2005). *High-resolution absolute temperature mapping of laser crystals in diode-end-pumped configuration.* Paper presented at the Lasers and Applications in Science and Engineering.

Dong, J., Bass, M., & Walters, C. (2004). Temperature-dependent stimulated-emission cross section and concentration quenching in Nd^{3+}-doped phosphate glasses. *JOSA B, 21*(2), 454-457.

Dong, J., Rapaport, A., Bass, M., Szipocs, F., & Ueda, K. i. (2005). Temperature-dependent stimulated emission cross section and concentration quenching in highly doped Nd^{3+}:YAG crystals. *physica status solidi (a), 202*(13), 2565-2573.

Edwards, J. (1968). Measurement of the cross section for stimulated emission in neodymium-doped glass from the output of a free-running laser oscillator. *Journal of Physics D: Applied Physics, 1*(4), 449.

Fan, S., Zhang, X., Wang, Q., Li, S., Ding, S., & Su, F. (2006). More precise determination of thermal lens focal length for end-pumped solid-state lasers. *Optics communications, 266*(2), 620-626.

Fan, T. Y., & Byer, R. L. (1988). Diode laser-pumped solid-state lasers. *Quantum Electronics, IEEE Journal of, 24*(6), 895-912.

Fields, R., Birnbaum, M., & Fincher, C. (1987). Highly efficient Nd:YVO$_4$ diode-laser end-pumped laser. *Applied physics letters, 51*(23), 1885-1886.

Goncz, J. H., & Newell, P. B. (1966). Spectra of pulsed and continuous xenon discharges. *JOSA, 56*(1), 87-91.

Jing-Liang, H., Wei, H., Heng-li, Z., Ling-an, W., Zu-yan, X., Guo-zhen, Y., et al. (1998). Continuous-wave output of 5.5 W at 532 nm by intracavity frequency doubling of an Nd:YVO$_4$ laser. *Chinese Physics Letters, 15*(6), 418.

Jun-hai, L., Jian-ren, L., Jun-hua, L., Zong-shu, S., & Min-hua, J. (1999). Thermal lens determination of end-pumped solid-state lasers by a simple direct approach. *Chinese physics letters, 16*(3), 181.

Kalisky, Y. Y. (2006). *The physics and engineering of solid state lasers* (Vol. 71): SPIE Press.

Kaminskii, A., & Vylegzhanin, D. (1971). Stimulated emission investigations of effects of electron-phonon interaction in crystals activated with Nd^{3+} ions. *Quantum Electronics, IEEE Journal of, 7*(7), 329-338.

Koechner, W. (2006). *Solid-state laser engineering* (Vol. 1): Springer.

Kogelnik, H. (1965). On the propagation of Gaussian beams of light through lenslike media including those with a loss or gain variation. *Applied optics, 4*(12), 1562-1569.

Kogelnik, H., & Li, T. (1966). Laser beams and resonators. *Applied optics, 5*(10), 1550-1567.

Krennrich, D., Knappe, R., Henrich, B., Wallenstein, R., & L'huillier, J. (2008). A comprehensive study of Nd:YAG, Nd:YAlO$_3$, Nd:YVO$_4$ and Nd:YGdVO$_4$ lasers operating at wavelengths of 0.9 and 1.3 μm. Part 1: cw-operation. *Applied Physics B, 92*(2), 165-174.

Kubodera, K. i., & Otsuka, K. (1979). Single-transverse-mode LiNdP$_4$O$_{12}$ slab waveguide laser. *Journal of applied physics, 50*(2), 653-659.

Laporta, P., & Brussard, M. (1991). Design criteria for mode size optimization in diode-pumped solid-state lasers. *Quantum Electronics, IEEE Journal of, 27*(10), 2319-2326.

Lee, H. C., Choi, J. W., & Kim, Y. P. (2013). A Nd:YAG laser in the 1400 nm region of the spectrum. *Laser Physics Letters, 10*(4), 045002.

Li, D., Xu, X., Cheng, S., Zhou, D., Wu, F., Zhao, Z., et al. (2010). Polarized spectral properties of Nd^{3+} ions in $CaYAlO_4$ crystal. *Applied Physics B, 101*(1-2), 199-205.

MacDonald, M., Graf, T., Balmer, J., & Weber, H. (2000). Reducing thermal lensing in diode-pumped laser rods. *Optics communications, 178*(4), 383-393.

Maiman, T. H. (1960). Stimulated optical radiation in ruby.

McCumber, D., & Sturge, M. (1963). Linewidth and temperature shift of the R lines in ruby. *Journal of applied physics, 34*(6), 1682-1684.

Mukhopadhyay, P. K., George, J., Ranganathan, K., Sharma, S., & Nathan, T. (2002). An alternative approach to determine the fractional heat load in solid state laser materials: application to diode-pumped Nd: YVO_4 laser. *Optics & Laser Technology, 34*(3), 253-258.

Mukhopadhyay, P. K., George, J., Sharma, S., Ranganathan, K., & Nathan, T. (2002). Experimental determination of effective stimulated emission cross-section in a diode pumped Nd: YVO_4 micro-laser at 1064nm with various doping concentrations. *Optics & Laser Technology, 34*(5), 357-362.

Niu, R., Lu, C., Wu, D., Fan, X., Liu, C., Liu, J., et al. (2011). Thermal lensing study based on the heat transfer of diode-pumped Yb^{3+}:$Y2SiO_5$ lasers. *The European Physical Journal Applied Physics, 54*(01), 10103.

O'Connor, J. (1966). Unusual crystal-field energy levels and efficient laser properties of YVO_4: Nd. *Applied physics letters, 9*(11), 407-409.

Pavel, N., & Taira, T. (1999). Pump-beam M_2 factor approximation for design of diode fiber-coupled end-pumped lasers. *Optical Engineering, 38*(11), 1806-1813.

Pavel, N., Taira, T., & Furuhata, M. (1998). High-efficiency longitudinally-pumped miniature Nd: YVO_4 laser. *Optics & Laser Technology, 30*(5), 275-280.

Payne, S. A., Chase, L., Newkirk, H. W., Smith, L. K., & Krupke, W. F. (1988). $LiCaAlF_6$:Cr3+: a promising new solid-state laser material. *Quantum Electronics, IEEE Journal of, 24*(11), 2243-2252.

Peng, X., Chen, Y., Xiong, Z., & Asundi, A. (2001). Heating measurements in diode-end-pumped Nd:YVO_4 lasers. *Optical Engineering, 40*(6), 1100-1105.

Peng, X., Xu, L., & Asundi, A. (2002). Power scaling of diode-pumped Nd:YVO_4 lasers. *Quantum Electronics, IEEE Journal of, 38*(9), 1291-1299.

Peterson, R., Jenssen, H., & Cassanho, A. (2002). Investigation of the spectroscopic properties of Nd: YVO_4. *Advanced Solid-State Lasers, 68.*

Pourmand, S. E., Bidin, N., & Bakhtiar, H. (2012). Temperature and Input Energy Dependence of the 946-nm Stimulated Emission Cross Section of Nd^{3+}:YAG Pumped by a Flashlamp. *Chinese Physics Letters, 29*(3), 034206.

Quan, Z., Yi, Y., Bin, L., Dapeng, Q., & Ling, Z. (2009). 13.2 W laser-diode-pumped Nd: YVO_4/LBO blue laser at 457 nm. *JOSA B, 26*(6), 1238-1242.

Rapaport, A., Zhao, S., Xiao, G., Howard, A., & Bass, M. (2002). Temperature dependence of the 1.06-μm stimulated emission cross section of neodymium in YAG and in GSGG. *Applied optics, 41*(33), 7052-7057.

Safari, E. (2011). Influence of the laser-diode temperature on crystal absorption and output power in an end-pumped Nd: YVO_4 laser. *Pramana, 76*(1), 119-125.

Sardar, D. K., & Yow, R. M. (1998). Optical characterization of inter-Stark energy levels and effects of temperature on sharp emission lines of Nd^{3+} in $CaZn_2Y_2Ge_3O_{12}$. *Optical Materials, 10*(3), 191-199.

Sardar, D. K., & Yow, R. M. (2000). Stark components of $^4F_{3/2}$, $^4I_{9/2}$ and $^4I_{11/2}$ manifold energy levels and effects of temperature on the laser transition of Nd^{3+} in YVO_4. *Optical Materials, 14*(1), 5-11.

Sardar, D. K., Yow, R. M., Gruber, J. B., Allik, T. H., & Zandi, B. (2006). Stark components of lower-lying manifolds and emission cross-sections of intermanifold and inter-stark transitions of $Nd^{3+}(4f^3)$ in polycrystalline ceramic garnet $Y_3Al_5O_{12}$. *Journal of luminescence, 116*(1), 145-150.

Sato, Y., Pavel, N., & Taira, T. (2004). *Spectroscopic properties and near quantum-limit laser-oscillation in Nd: $GdVO_4$ single crystal.* Paper presented at the Advanced Solid-State Photonics.

Sato, Y., & Taira, T. (2012). Temperature dependencies of stimulated emission cross section for Nd-doped solid-state laser materials. *Optical Materials Express, 2*(8), 1076-1087.

Song, F., Zhang, C., Ding, X., Xu, J., Zhang, G., Leigh, M., et al. (2002). Determination of thermal focal length and pumping radius in gain medium in laser-diode-pumped Nd:YVO_4 lasers. *Applied physics letters, 81*(12), 2145-2147.

Sturm, V., Treusch, H.-G., & Loosen, P. (1997). *Cylindrical microlenses for collimating high-power diode lasers.* Paper presented at the Lasers and Optics in Manufacturing III.

Sun, C., Zhong, K., Zhang, C., Yao, J., Xu, D., Zhang, F., et al. (2012). Stimulated emission cross section of the $^4F_{3/2} \rightarrow {}^4I_{11/2}$ of Nd: GYSGG. *Laser Physics Letters, 9*(6), 410.

Svelto, O., & Hanna, D. C. (1998). Principles of lasers.

Tucker, A., Birnbaum, M., Fincher, C., & Erler, J. (1977). Stimulated-emission cross section at 1064 and 1342 nm in Nd:YVO_4. *Journal of applied physics, 48*(12), 4907-4911.

Turri, G., Jenssen, H. P., Cornacchia, F., Tonelli, M., & Bass, M. (2009). Temperature-dependent stimulated emission cross section in Nd^{3+}:YVO_4 crystals. *JOSA B, 26*(11), 2084-2088.

Wang, Z., Sun, L., Zhang, S., Meng, X., Cheng, R., & Shao, Z. (2001). Investigation of LD end-pumped Nd: YVO_4 crystals with various doping levels and lengths. *Optics & Laser Technology, 33*(1), 47-51.

Yan, X., Liu, Q., Huang, L., Wang, Y., Huang, X., Wang, D., et al. (2008). A high efficient one-end-pumped TEM_{00} laser with optimal pump mode. *Laser Physics Letters, 5*(3), 185.

Yaney, P. P., & DeShazer, L. (1976). Spectroscopic studies and analysis of the laser states of Nd^{3+} in YVO_4. *JOSA, 66*(12), 1405-1414.

Yao, A.-Y., Hou, W., Bi, Y., Lin, X.-C., Kong, Y.-P., Cui, D.-F., et al. (2005). High-power cw 671 nm output by intracavity frequency doubling of a double-end-pumped Nd:YVO_4 laser. *Applied optics, 44*(33), 7156-7160.

Zhang, H., Chao, M., Gao, M., Zhang, L., & Yao, J. (2003). High power diode single-end-pumped Nd:YVO_4 laser. *Optics & Laser Technology, 35*(6), 445-449.

Zheng, W.-C., Su, P., Liu, H.-G., & Feng, G.-Y. (2013). A study of thermal shift of the popular laser line E1(R1 → Y1 transition) transition for Nd^{3+}-doped YVO_4 crystal. *Optik-International Journal for Light and Electron Optics, 124*(13), 1564-1566.

Zheng, W., Su, P., Liu, H., & Feng, G. (2012). Analyses of the thermal shifts of spectral lines in Nd^{3+}-doped $LiYF_4$ laser crystal. *Applied Physics B, 109*(1), 43-46.