THERMAL ELECTRICAL COOLING SYSTEM BASED ON ARDUINO MODULE FOR DIODE PUMPED SOLID STATE LASER

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For my supportive supervisor, my family and beloved, Nor Amira Shikin

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ABSTRACT

Cooling system is very important in a solid state laser in order to avoid thermal damage on the gain medium and to stabilize the laser output. The cooling system is also important to prevent any unwanted phenomena such as condensation of water which can degrade the performance of laser as well as moisten the gain medium area. The previous laser system used by the local group research do not have automatic cooling system. Problem arises when the temperature went down below dew point temperature and water droplets accumulate in the gain medium crystal. In effort to overcome this drawbacks, a smart cooling system is designed and developed. A diode-pumped solid state (DPSS) laser system consists of ND:YVO_4 crystal as a gain medium, a 97% partial reflective mirror to stand as an output coupler and a diode laser at 808 nm wavelength with 3 W maximum output power as a pumping source to produce 1064 nm output laser. The pumping source, gain medium and output coupler were aligned on a heat sink platform to form a linear optical resonator. The gain medium of Nd:YVO4 was placed in a U-shape copper holder. The crystal was properly wrapped with indium to sustain good heat contact. The cooper holder was coupled with a thermoelectric cooler (TEC). A microcontroller was designed with the aid of an Arduino technology. Software was developed to command the microcontroller to set the desired temperature of the gain medium automatically. The output of the DPSS laser was tested by verifying the TEC temperature. The best laser performance was identified at an optimized TEC temperature of 18 ^{0}C with maximum power output achieved at 300 mW corresponding to a slope efficiency of 31.20%. A slight increase in slope efficiency of about 2.5% is obtained when an automatic adjustment of the TEC temperature is employed. The implementation of automatic TEC temperature control has been shown to improve the efficiency of laser output power with advantages of it being low cost and ease of assembly.

ABSTRAK

Sistem penyejukan dalam laser keadaan pepejal amat penting untuk mengelakkan kerosakan terma pada medium gandaan dan untuk menstabilkan keluaran laser. Sistem penyejukan juga penting untuk mencegah pelbagai fenomena yang tidak diingini seperti kondensasi air yang akan merendahkan prestasi keluaran laser serta menjadikan kawasan medium gandaan berair. Sistem laser terdahulu yang digunakan oleh kumpulan penyelidik tempatan tidak mempunyai kawalan suhu automatik. Masalah wujud apabila suhu menurun sehingga ke suhu titik embun dan embun mula terbentuk pada kristal medium gandaan. Bagi mengatasi masalah ini, sistem penyejukan bestari telah direka dan dibangunkan. Sistem laser diod pam keadaan pepejal (DPSS) mengandungi kristal Nd:YVO_4 sebagai medium gandaan, 97% cermin separa pantulan sebagai pengganding keluaran dan diod laser pada panjang gelombang 808 nm dengan 3W kuasa keluaran maksimum digunakan sebagai sumber pengepam untuk menghasilkan laser keluaran pada 1064 nm. Sumber pengepam, medium gandaan dan cermin keluaran diselaraskan diatas tapak penenggelam haba untuk menghasilkan sebuah resonator optik yang linear. Medium gandaan Nd:YVO_4 dipegang oleh pemegang kuprum berbentuk-U. Kristal tersebut dibalut rapi dengan indium untuk memastikan sentuhan haba yang baik. Pemegang kuprum digandingkan dengan sekeping penyejuk terma elektrik (TEC). Sebuah pengawal mikro direka dengan bantuan teknologi Arduino. Satu perisian dibangunkan untuk memerintah pengawal-mikro untuk menetapkan suhu yang dikehendaki pada medium gandaan secara automatik. Keluaran laser DPSS diuji dengan mengubah suhu TEC. Prestasi laser terbaik dikenalpasti pada suhu TEC optimum, 18 ^{0}C dengan kuasa keluaran maksima laser dicapai pada 300 mW sepadan dengan kecerunan kecekapan 31.20%. Sedikit peningkatan pada kecerunan kecekapan lebih kurang 2.5% diperoleh apabila kawalan suhu TEC automatik digunapakai. Implementasi pengawalan suhu TEC secara automatik telah ditunjukkan dapat meningkatkan kecekapan kuasa keluaran laser dengan kelebihan dari segi kos yang rendah dan mudah dipasang.

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CHAPTER 1

INTRODUCTION

1.1 Background of the Study

Laser diode is the most efficient as pumping source for solid state laser. With low power output, low packaging density and extremely high cost of laser diode is difficult to be applied in any serious application for laser pumping until mid 1980s. The progress of development of laser diode is gradually increases by starting the linear laser diode arrays based on aluminum gallium arsenide (AlGaAs) quantum technology with output powers of 10 W/cm at room temperature and 30% of efficiency. Then, the combination of linear laser diode arrays and monolithic in the laser diode exhibits the improvement of the output power, slope efficiency, laser threshold and wavelength control. Today, the laser diode can produce 50 W/cm with efficiency in range between 40-50% (Koechner, 2006). The variety of laser designs and lasing materials have developed in order to optimize the laser performance. Thereby, the solid state lasers are most favourable due to its vigorous development in recent years. This solid laser system leads to the benefits in medical, science, industrial and military field by focusing to the improvement and maintaining nowadays. With high efficiency, high output power, a good spatial beam profile, and good stability is highly desired by a diode-pumped solid-state laser (DPSSL). A lot of applications are widely used such as material processing holography, range finding, target illumination and designation, satellite and lunar ranging, thermonuclear fusion, plasma experiments, and in general for scientific work requiring high power densities such as pumping laser crystals. Laser diode can efficiently pump solid state laser with 808 nm wavelength in the development of diode pumped solid state laser (DPSSL). The high intensity of stimulated emission in this semiconductor laser can contribute to high rates of energy generation but also leads to high amount of heat dissipation compared to other types of laser. However, the effects of temperature on laser diode output should be considered as the variation of temperature results in the spectrum intensity change.

1.2 Problem Statement

One of the major problems in diode pumped solid state laser is it unstable especially if operation in long duration. The gain medium started to cover with water due to the effect of condensation. The laser is always needed to wipe otherwise the laser will flood with water. This is entirely due to thermal electric cooling (TEC) which tends to become overcooling. The temperature of TEC is uncontrollable. Every time the crystal reaches a dew point condensation will occur. Such condition affects the laser performance which tends to reduce the output power. Thus the intention of this work is to overcome this problem by developing a smart cooling system for diode pumped solid state laser.

1.3 Objectives

The main objective of the research is to develop a smart cooling system for diode pumped solid state laser. In attempt to achieve this goal, the follow tasks are accomplished:

a) To design an electronic circuit of cooling system

b) To construct and built in the circuit of cooling system

c) To determine the optimum operating temperature of the laser

d) To characterize the performance of diode pumped solid state laser

1.4 Scope of Study

A diode pumped solid state laser was constructed using a Nd: YVO4 crystal as a gain medium. A pumping source of the laser is a diode laser operating at 808 nm. The laser was stabilized using a Thermal electric cooling (TEC). The cooling system is controlled by An Arduino Nano. A dew point is sensed by the aid of DHT22 sensor. A special program was designed and developed to control and display the crystal temperature and the dew point. A Powermeter and oscilloscope were employed to characterize the laser performance.

1.5 Significances and Original Contributions of This Study

A smart cooling system is capable to control automatically the temperature of thermal electric cooling. Such smart cooling system is beneficial to produce an efficient diode pumped solid state laser.

1.6 Thesis outlines

This thesis comprised of five chapters. The overall project, problem statement objective, scope and significant are written in chapter one. Literature survey and some theories related to the project is described in chapter 2. The detail of research methodology including, material, equipment and technique is contained in chapter 3. The results and discussion is elaborated in chapter 4. Finally the summary of the project is concluded in chapter 5.

REFERENCES

1. Newman, R., Excitation of the Nd3+ Fluorescence in CaWO4 by Recombination Radiation in GaAs. *J. Appl. Phys.* 1963, 34, 437.

2. Keyes, R.J., Quist, T.M., Injection luminescent pumping of CaF2:U3+ with GaAs diode lasers. *Appl. Phys. Lett.* 1964, 4, 50–52.

3. Hall, R.N., Fenner, G.E., Kingsley, J.D., Soltys, T.J., Carlson, R.O., Coherent light emission from GaAs junctions. *Phys. Rev. Lett.* 1962, 9, 366–368.

4. Nathan, M.I., Dumke, W.P., Burns, G., Dill, F.H., Lasher, G., Stimulated emission of radiation from GaAs p-n junctions. *Appl. Phys. Lett.* 1962, 1, 62–64.

5. Holonyak, N., Bevacqua, S.F., Coherent (visible) light emission from Ga(As1-xPx) junctions. *Appl. Phys. Lett.* 1962, 1, 82–83.

6. Quist, T.M., Rediker, R.H., Keyes, R.J., Krag, W.E., et al., Semiconductor maser of GaAs. *Appl. Phys. Lett.* 1962, 1, 91–92.

7. Dr. Rüdiger Paschotta, Neodymium-doped Gain Media 2008.

8. Fujikawa, S., Furuta, K., Yasui, K., 28% electrical-efficiency operation of a diode-side-pumped Nd:YAG rod laser. *Opt. Lett.* 2001, 26, 602–4.

9. Lü, Y., Zhang, X., Cheng, W., Xia, J., All-solid-state cw frequency-doubling Nd:YLiF4/LBO blue laser with 4.33 W output power at 454 nm under in-band diode pumping at 880 nm. *Appl. Opt.* 2010, 49, 4096–4099.

10. Liu, Q., Yan, X.P., Fu, X., Gong, M., Wang, D.S., High power all-solid-state fourth harmonic generation of 266 nm at the pulse repetition rate of 100 kHz. *Laser Phys. Lett.* 2009, 6, 203–206.

11. Yan, X.P., Liu, Q., Gong, M., Wang, D.S., Fu, X., Over 8 W high peak power UV laser with a high power Q-switched Nd:YVO4 oscillator and the compact extra-cavity sum-frequency mixing. *Laser Phys. Lett.* 2009, 6, 93–97.

12. Sun, W.J., Wang, Q.P., Liu, Z.J., Zhang, X.Y., et al., An efficient 1103 nm Nd:YAG/BaWO4 Raman laser. *Laser Phys. Lett.* 2011, 8, 512–515.

13. Zhang, S.B., Cui, Q.J., Xiong, B., Guo, L., et al., High electrical-to-green efficiency high stability intracavity-frequency-doubled Nd:YAG-LBO QCW 532 nm laser with a straight cavity. *Laser Phys. Lett.* 2010, 7, 707–710.

14. Jelínek, M., Kubeček, V., Čech, M., Hiršl, P., 0.8 mJ quasi-continuously pumped sub-nanosecond highly doped Nd:YAG oscillator-amplifier laser system in bounce geometry. *Laser Phys. Lett.* 2011, 8, 205–208.

15. Wang, H.X., Yang, X.Q., Zhao, S., Zhang, B.T., et al., 2 ns-pulse, compact and reliable microchip lasers by Nd:YAG/Cr4+ YAG composite crystal. *Laser*

Phys. 2009, 19, 1824–1827.

16. Zhang, C., Zhang, X.Y., Wang, Q.P., Fan, S.Z., et al., Efficient extracavity Nd:YAG/BaWO 4 Raman laser. *Laser Phys. Lett.* 2009, 6, 505–508.

17. Zhang, S.S., Wang, Q.P., Zhang, X.Y., Liu, Z.J., et al., High power and highly efficient Nd:YAG laser emitting at 1123 nm. *Laser Phys.* 2009, 19, 2159–2162.

18. Yan, X., Guo, L., Zhang, L., Chen, R., et al., LD side-pumped 41 W high beam quality acousto-optical Q-switched single-rod Nd:YAG laser. *Laser Phys.* 2011, 21, 323–326.

19. Tauer, J., Kofler, H., Wintner, E., Millijoule Q-switched Nd:YAG laser operating at 946 nm. *Laser Phys. Lett.* 2010, 7, 280–285.

20. Qi, Y., Zhu, X., Lou, Q., Ji, J., et al., High-energy LDA side-pumped electro-optical Q-switched Nd:YAG ceramic laser. *J. Opt. Soc. Am. B* 2007, 24, 1042.

21. Amzajerdian, F., Gao, C., Xie, T., China Aerospace Science and Industry Corporation. Tianjin Jinhang Institute of Technical Physics., Y.-J., et al., International Symposium on Photoelectronic Detection and Imaging 2009. Laser sensing and imaging : 17-19 June 2009, Beijing China, SPIE, 2009.

22. Minassian, A., Thompson, B., Damzen, M.J., Ultrahigh-efficiency TEM00 diode-side-pumped Nd:YVO4 laser. *Appl. Phys. B Lasers Opt.* 2003, 76, 341–343.

23. Demidovich, A.A., Shkadarevich, A.P., Danailov, M.B., Apai, P., et al.,

Comparison of cw laser performance of Nd : KGW, Nd : YAG, Nd : BEL, and Nd : YVO4 under laser diode pumping. *Appl. Phys. B-Lasers Opt.* 1998, 67, 11–15.

24. Minnich, A.J., Dresselhaus, M.S., Ren, Z.F., Chen, G., Bulk nanostructured thermoelectric materials: current research and future prospects. *Energy Environ. Sci.* 2009, 2, 466.

25. Nolas, G.S., Cohn, J.L., Slack, G.A., Schujman, S.B., Semiconducting Ge clathrates: Promising candidates for thermoelectric applications. *Appl. Phys. Lett.* 1998, 73, 178–180.

26. X.Shi, Application of thermoelectric cooling to electronic equipment: a\nreview and analysis. *Sixt. Annu. IEEE Semicond. Therm. Meas. Manag. Symp. (Cat. No.00CH37068)* 2000, 1–9.

27. Lawrence, M.G., The relationship between relative humidity and the dewpoint temperature in moist air: A simple conversion and applications. *Bull. Am. Meteorol. Soc.* 2005, 86, 225–233.

28. Brown, D.C., Nelson, R., Billings, L., Efficient cw end-pumped, end-cooled Nd:YVO_4 diode-pumped laser. *Appl. Opt.* 1997, 36, 8611.

29. Ogilvy, H., Withford, M., Dekker, P., Piper, J., Efficient diode double-end-pumped Nd:YVO4 laser operating at 1342nm. *Opt. Express* 2003, 11, 2411–2415.

30. McDonagh, L., Wallenstein, R., Knappe, R., Nebel, A., High-efficiency 60 W

TEM00 Nd:YVO4 oscillator pumped at 888 nm. *Opt. Lett.* 2006, 31, 3297–3299.

31. McDonagh, L., Optimized pumping of neodymium-doped vanadate yields high-power lasers. *SPIE Newsroom* 2007, 10–12.

32. Hong, H., Huang, L., Liu, Q., Yan, P., Gong, M., Compact high-power, TEM 00 acousto-optics Q-switched Nd: YVO 4 oscillator pumped at 888 nm. *Appl. Opt.* 2012, 51, 323–327.

33. McDonagh, L., Wallenstein, R., Nebel, A., 111 W, 110 MHz repetition-rate, passively mode-locked TEM00 Nd:YVO4 master oscillator power amplifier pumped at 888 nm. *Opt. Lett.* 2007, 32, 1259–1261.

34. Nadeau, M.-C., Petit, S., Balcou, P., Czarny, R., et al., Picosecond pulses of variable duration from a high-power passively mode-locked Nd:YVO(4) laser free of spatial hole burning. *Opt. Lett.* 2010, 35, 1644–6.

35. Lührmann, M., Theobald, C., Wallenstein, R., L'huillier, J. a, High energy cw-diode pumped Nd:YVO4 regenerative amplifier with efficient second harmonic generation. *Opt. Express* 2009, 17, 22761–22766.

36. McDonagh, L., Wallenstein, R., Low-noise 62 W CW intracavity-doubled TEM00 Nd:YVO4 green laser pumped at 888 nm. *Opt. Lett.* 2007, 32, 802–4.

37. Schäfer, C., Fries, C., Theobald, C., L'huillier, J. a, Parametric Kerr lens mode-locked, 888 nm pumped Nd:YVO4 laser. *Opt. Lett.* 2011, 36, 2674–6.

38. Huang, Z., Huang, Y., Chen, Y., Luo, Z., Theoretical study on the laser performances of Nd3+:YAG and Nd3+:YVO4 under indirect and direct pumping. *Josa B* 2005, 22, 2564–2569.

39. Graf, T., Balmer, J.E., Weber, R., Weber, H.P., Multi-Nd: YAG-rod variable-configuration resonator (VCR) end pumped by multiple diode-laser bars. *Opt. Commun.* 1997, 135.

40. Driedger, K.P., Ifflander, R.M., Weber, H., Multirod Resonators for High-Power Solid-State Lasers with Improved Beam Quality. *IEEE J. Quantum Electron.* 1988, 24, 665–674.

41. Yan, X., Liu, Q., Fu, X., Chen, H., et al., Comparative investigation on performance of acousto-optically Q-switched dual-rod Nd:YAG-Nd:YVO(4) laser and dual-rod Nd:YVO(4)-Nd:YVO(4) laser. *Appl. Opt.* 2010, 49, 4131–4138.

42. Song, J., Li, C., Ueda, K.I., Thermal influence of saturable absorber in passively Q-switched diode-pumped cw Nd:YAG/Cr4+:YAG laser. *Opt. Commun.* 2000, 177, 307–316.

43. Zhang, S., Wang, X., Thermal model of continuous wave end-pumped passively Q-switched laser. *Opt. Commun.* 2013, 295, 155–160.

44. Li, S., Li, Y., Zhao, S., Li, G., et al., Thermal effect investigation and passively Q-switched laser performance of composite Nd:YVO4 crystals. *Opt. Laser Technol.* 2015, 68, 146–150.

45. Wang, S., Eichler, H.J., Wang, X., Kallmeyer, F., et al., Diode end pumped Nd:YAG laser at 946 nm with high pulse energy limited by thermal lensing. *Appl. Phys. B Lasers Opt.* 2009, 95, 721–730.

46. Li, T., Zhang, S., Zhao, S., Yang, K., Zhuo, Z., Thermal modeling of the continuous-wave end-pumped Q-switched lasers. *Opt. Commun.* 2010, 283, 3070–3075.

47. Guy, S., Bonner, C.L., Shepherd, D.P., Hanna, D.C., et al., High-inversion densities in Nd:YAG-upconversion and bleaching. *IEEE J. Quantum Electron.* 1998, 34, 900–909.

48. Chen, X., Wu, J., Wu, C., Sun, H., et al., Analysis of thermal effects in a pulsed laser diode end pumped single-ended composite Tm:YAG laser. *Laser Phys.* 2015, 45003, 45003.

49. Pollnau, M., Hardman, P.J., Kern, M. a, Clarkson, W. a, Hanna, D.C., Upconversion-induced heat generation and thermal lensing in Nd : YLF and Nd : YAG. *Phys. Rev. B* 1998, 58, 16076–16092.

50. Shen, Y., Gong, M., Ji, E., Fu, X., Sun, L., Spatial dynamic thermal iteration model for 888??nm end-pumped Nd:YVO4 solid-state laser oscillators and amplifiers. *Opt. Commun.* 2017, 383, 430–440.

51. Eichhorn, M., Quasi-three-level solid-state lasers in the near and mid infrared based on trivalent rare earth ions. *Appl. Phys. B Lasers Opt.* 2008, 93, 269–316.

52. Chen, Y.F., Lan, Y.P., Comparison between c-cut and a-cut Nd:YVO4 lasers

passively Q-switched with a Cr4+:YAG saturable absorber. *Appl. Phys. B Lasers Opt.* 2002, 74, 415–418.

53. Hawkes, E.P.W., Board, E., Siegman, A.L.S.A.E., Lotsch, M.E.H.K. V, Springer Series in Optical Sciences Volume 45 Springer-Verlag Berlin Heidelberg GmbH Springer Series in Optical Sciences, vol. 45, 1998.

54. Dekker, P., Pask, H.M., Spence, D.J., Piper, J. a, Continuous-wave, intracavity doubled, self-Raman laser operation in Nd:GdVO(4) at 586.5 nm. *Opt. Express* 2007, 15, 7038–7046.

55. Bowman, S.R., O'Connor, S.P., Biswal, S., Condon, N.J., Rosenberg, A., Minimizing heat generation in solid-state lasers. *IEEE J. Quantum Electron.* 2010, 46, 1076–1085.

56. Lenhardt, F., Nittmann, M., Bauer, T., Bartschke, J., L'Huillier, J.A., High-power 888-nm-pumped Nd:YVO4 1342-nm oscillator operating in the TEM00 mode. *Appl. Phys. B Lasers Opt.* 2009, 96, 803–807.

57. Jacinto, C., Oliveira, S.L., Catundab, T., Andrade, A.A., et al., Upconversion effect on fluorescence quantum efficiency and heat generation in Nd3+-doped materials. *Opt. Express* 2005, 13, 2040.

58. Zuegel, J.D., Seka, W., lifetime in intensely pumped Nd : YLF. *Appl. Opt.* 1999, 38.

59. Jacinto, C., Messias, D.N., Andrade, A.A., Catunda, T., Energy transfer upconversion determination by thermal-lens and Z-scan techniques in Nd3+-

doped laser materials. *J. Opt. Soc. Am. B Opt. Phys.* 2009, 26, 1002–1007.

60. De Camargo, A.S.S., Jacinto, C., Catunda, T., Nunes, L.A.O., Auger upconversion energy transfer losses and efficient 1.06 ??m laser emission in Nd3+ doped fluoroindogallate glass. *Appl. Phys. B Lasers Opt.* 2006, 83, 565–569.

61. Blows, J.L., Omatsu, T., Dawes, J., Pask, H., Tateda, M., Heat generation in Nd:YVO_4 with and without laser action. *IEEE Photonics Technol. Lett.* 1998, 10, 1727–1729.

62. Délen, X., Balembois, F., Musset, O., Georges, P., Characteristics of laser operation at 1064 nm in Nd:YVO4 under diode pumping at 808 and 914 nm. *J. Opt. Soc. Am. B* 2011, 28, 52–57.

63. Meilhac, L., Pauliat, G., Roosen, G., Determination of the energy diffusion and of the Auger upconversion constants in a Nd:YVO4 standing-wave laser. *Opt. Commun.* 2002, 203, 341–347.

64. Chen, Y.F., Liao, C.C., Lan, Y.P., Wang, S.C., Determination of the Auger upconversion rate in fiber-coupled diode end-pumped Nd:YAG and Nd:YVO 4 crystals. *Appl. Phys. B Lasers Opt.* 2000, 70, 487–490.

65. Chuang, T., Verdún, H.R., Energy transfer up-conversion and excited state absorption of laser radiation in Nd : YLF laser crystals. *IEEE J. Quantum Electron.* 1996, 32, 79–91.

66. Jacinto, C., Catunda, T., Jaque, D., Bausá, L.E., García-Solé, J., Thermal lens

and heat generation of Nd:YAG lasers operating at 1.064 and 1.34 microm. *Opt. Express* 2008, 16, 6317–6323.

67. Ariyanto, G., Nixon, M., ePrints Soton. *Proc. Int. Jt. Conf. Biometrics* 2011.

68. Délen, X., Balembois, F., Georges, P., Temperature dependence of the emission cross section of Nd:YVO4 around 1064 nm and consequences on laser operation. *J. Opt. Soc. Am. B Opt. Phys.* 2011, 28, 972–976.

69. Turri, G., Jenssen, H., Cornacchia, F., Tonelli, M., Bass, M., Temperature-dependent stimulated emission cross section in Nd 3+: YVO 4 crystals. *Josa B* 2009, 26, 2084.

70. Rapaport, A., Zhao, S., Xiao, G., Howard, A., Bass, M., Temperature dependence of the 1.06-um stimulated emission cross section of neodymium in YAG and in GSGG. *Appl. Opt.* 2002, 41, 7052.

71. Wang, Y., Yang, W., Zhou, H., Huo, M., Zheng, Y., Temperature dependence of the fractional thermal load of Nd:YVO4 at 1064 nm lasing and its influence on laser performance. *Opt. Express* 2013, 21, 18068–78.