YTTERBIUM DOPED AND CO-DOPED Q-SWITCHED FIBER LASERS UTILIZING PASSIVE SATURABLE ABSORBERS

NABILAH KASIM

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

Faculty of Science
Universiti Teknologi Malaysia

.

JANUARY 2015

To my beloved parents,

Kasim bin Abbas and Munirah binti Ahmad,

and my family!

Thank you for all your supports, pray and blessing.

ACKNOWLEDGEMENT

Thanks to Almighty Allah, the Most Gracious and Most Merciful for Him is the source of this success for giving me the strength and faith to complete this research. With His blessing may this work be beneficial for the whole mankind.

I am honoured to have Assoc. Prof. Dr. Yusof Munajat as my supervisor and Prof. Dr. Sulaiman Wadi Harun as my external co-supervisor. I would like to express my thanks and sincere gratitude for their guidance, support, comments and encouragement throughout my research. I would like to acknowledge Universiti Malaya for their help and kind assistance during my experimental work there.

Thanks to Ministry of Science, Technology and Innovation for financially supporting my research under scholar of National Science Fellowship.

To my family and friends, I am thankful and grateful for your endless love, support, pray, patience, encouragement and valuable advice throughout the duration of this thesis.

ABSTRACT

Q-switched 2 micron fiber laser is a new area of research. Q-switching using passive technique by means of saturable absorber is quite rare in the research work. A stable passive Q-switched lasers operating at 1 micron, 1.5 micron and 2 micron wavelength regions were demonstrated using Ytterbium doped, Erbium-Ytterbium co-doped and Thulium-Ytterbium co-doped fibers, respectively as the gain medium. Carbon nanotubes and graphene based saturable absorbers (SA) were explored as the passive Q-switcher in the proposed lasers. The Q-switched Ytterbium doped fiber laser (YDFL) operating at 1060.2 nm was realized using a multi-walled carbon nanotubes / PEO saturable absorber. The repetition rate of the laser were varied from 7.92 kHz to 24.27 kHz by varying the pump power from 53.42 mW to 65.72 mW. At the 59.55 mW pump power, the lowest pulse width and the highest pulse energy were obtained at 12.18 µs and 143.5 nJ, respectively. The YDFL was then used to demonstrate an all-fiber based MOPA system where the maximum pulse energy of 354.2 nJ was obtained at the maximum cladding pump power of 800 mW. The Q-switching of Erbium-Ytterbium fiber laser (EYFL) was demonstrated using a multi-layer graphene film based saturable absorber. The proposed laser was operated at 1532.5 nm and self-started at pump threshold of 44 mW to produce Q-switching pulse with repetition rate of 12.33 kHz and pulse width of 9.36 µs. At the maximum pump power of 78 mW, the maximum pulse energy of 5.8 nJ and the shortest pulse duration of 2.68 µs were achieved. Multi-wavelength and Q-switched fiber lasers were also demonstrated based on the newly developed octagonal shape double-clad Thulium-Ytterbium fiber (TYF) operating at 2 micron wavelength region. By incorporating the home-made multi-wall carbon nanotubes saturable absorber (MWCNTs SA) in the ring cavity, a Q-switching pulse train operating at 1983.4 nm was successfully demonstrated. By varying the 905 nm multimode pump power from 1570 to 1606 mW, the pulse repetition rate increased from 27.4 to 37.8 kHz and the pulse width fluctuated from 3.8 µs to 4.9 µs. The maximum pulse energy of 10.6 nJ was obtained at pump power of 1570 mW. Besides showing good Q-switching performance, the proposed saturable absorbers are easy to fabricate and inexpensive.

ABSTRAK

Pengsuisan-Q 2 mikron laser gentian adalah satu bidang penyelidikan yang baharu.Pengsuisan-Q menggunakan teknik pasif dengan kaedah penyerap tepu masih lagi jarang dilakukan dalam kerja penyelidikan. Sebuah laser pasif pengsuisan-Q yang stabil beroperasi di dalam kawasan panjang gelombang 1 mikron, 1.5 mikron dan 2 mikron ditunjukkan dengan menggunakan gentian terdop Ytterbium, ko-dop Erbium-Ytterbium dan ko-dopThulium-Ytterbium, masing-masing sebagai ruang penggandaan. Penyerap tepu (SA) berasaskan karbon tiub nanodan graphene diterokai sebagai pengsuis-Q pasif dalam laser yang dicadangkan.Pengsuisan-Q laser gentian terdop Ytterbium (YDFL) yang beroperasi pada 1060.2 nm telah dilaksanakan dengan menggunakan karbon tiub nanodinding berlapis / penyerap tepu PEO.Kadar ulangan laser boleh berubah daripada 7.92 kHz hingga 24.27 kHz dengan mengubah kuasa pam daripada 53.42 mW hingga 65.72 mW. Pada kuasa pam 59.55 mW, lebar denyut paling rendah dan tenaga denyut tertinggi masing-masing diperoleh pada 12.18 µs dan 143.5 nJ. YDFL kemudiannya digunakan dalam menunjukkan sistem MOPA berasaskan semua gentian di mana tenaga denyut maksimum 354.2 nJ diperoleh bila kuasa maksimum pam pelapisan pada 800 mW. Pengsuisan-Q dalam laser gentian Erbium-Ytterbium (EYFL) telah ditunjukkan dengan menggunakan SA berasaskan filem graphene pelbagai lapisan. Laser yang dicadangkan beroperasi pada 1532.5 nm dan mulai pada ambang pam 44 mW untuk menghasilkan denyut pengsuisan-Q dengan kadar ulangan 12.33 kHz dan lebar denyut 9.36 µs. Pada kuasa pam maksimum 78 mW, tenaga denyut maksimum 5.8 nJ dan tempoh denyut terpendek 2.68 µs dicapai. Pelbagai panjang gelombang dan pengsuisan-Q laser gentian juga telah ditunjukkan berdasarkan dua dinding gentian Thulium-Ytterbium (TYF) berbentuk segi lapan yang baharu dibangunkan yang beroperasi pada kawasan panjang gelombang 2 mikron.Dengan menggabungkan penyerap tepu karbon tiub nano dinding berlapis (MWCNTs SA) buatan sendiri dalam rongga cincin, siri denyut pengsuisan-Q beroperasi pada 1983.4 nm telah berjaya dipamerkan. Dengan mengubah kuasa pam pelbagai mod 905 nm daripada 1570 sehingga 1606 mW, kadar ulangan denyut bertambah daripada 27.4 sehingga 37.8 kHz dan turun naik lebar denyut sekitar 4.9 µs kepada 3.8 µs. Tenaga denyut maksimum pada 10.6 nJ diperoleh pada kuasa pam 1570 mW. Selain menunjukkan prestasi pengsuisan-Q yang baik, penyerap tepu yang dicadangkan adalah mudah untuk dicipta dan murah.

TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

LIST OF SYMBOLS

n	–	refrective index
r	–	radial coordinate
θ	–	angle of incidence
NA	–	numerical aperture
L	–	cavity length
β	–	amplification coefficient
k	–	Boltzmann constant
ΔN	–	population inversion
P	–	power
R1	–	mirror 1
R2	–	mirror 2
δo	–	round trip loss
η	–	slope efficiency
λ	–	wavelength
NF	–	noise figure
h	–	Plank constant
ν	–	frequency
G	–	gain

CHAPTER 1

INTRODUCTION

1.1 Background

A promising alternative to the conventional solid-state laser systems is the fiber laser with some advantages like compact size, high electrical efficiency, superior beam quality and reliability, great output power, lower maintenance, low ownership cost, mobility and ruggedness. It was firstly invented by Elias Snitzer in 1963 [1,2] and in late 1980s, fiber laser devices appeared in the market. These lasers emitted a few tens of milliwatts because they used single-mode diode pump. In addition, these lasers have large gain and it is possible to realise single-mode continuous-wave (CW) lasing operation using many transitions of lanthanide ions not realisable in the more-usual semiconductor material laser version. The active medium are specialized optical fibers doped with rare earth elements such as Ytterbium, Erbium and Thulium [3–5]. These rare earth elements have many advantages such as simple energy levels, long life time at high level, high quantum efficiency, and wide absorption spectrum which is good to develop high power fiber lasers for many applications such as industry, communication, military, and etc [6–9]. The most famous application of fiber-laser technology is in 1550 nm erbium-doped fiber amplifiers (EDFAs) [10].

In the late 1980s, double clad fiber was developed for high power fiber laser applications [11]. This fiber has a core, which is doped with active dopant material that functions to guide and amplify the signal light. The pump light guided by the inner cladding is used to provide the energy needed to allow amplification in the core of the fiber. In order to confine the light into the core, the outer cladding must have lowest refractive index compared to the core. Double clad fiber [12–15] is better rather than standard single clad fiber because it has low dispersion over a much wider wavelength range.

Fiber laser progress continued with the discovery of one of the rare earth material named Ytterbium. When this element is doped with fiber laser, in the 1 µm band it work as a highly efficient gain medium that can compromise high power conversion efficiencies and larger power levels than erbium-doped fiber lasers (EDFLs). Therefore, ytterbium doped fiber amplifier can provide high power fiber laser that is now used broadly in industrial, medical, military and high quality imaging applications. In addition, Ytterbium has acquired a prominent role in the form of the trivalent ion Yb^{3+}, which is used as a laser-active dopant in a variety of host materials. Particularly, wide attentions have been attracted by Yb^{3+} doped double clad fiber lasers. They have been extensively studied for some causes [16]. First, the wide bandwidth of Yb^{3+} doped fiber lasers which is larger than 1550 nm, make it well adapted for tunable laser application. Second, Yb ion has a quasi-three-level energy system that manage high efficiency because it can avoid any pump or signal excited-state absorption (ESA). Third, they allow for a low cost commercially existing laser diode as the pump source because Yb ion gifts a large absorption cross-section around 980 nm.

However, other than emission at 1 µm band, ytterbium also can be used as the sensitized element for erbium and thulium for the emission band at 1.5 µm and 2.0 µm. These bands would also give several industry applications such as in area of communication, remote sensing and biomedical applications. Yb^{3+} has the benefit to present only two multiplets which is the ground-state level $^2F_{7/2}$ and the excited-state level $^2F_{5/2}$, corresponding the highly efficiency absorption in the range of 900 nm-1000 nm. For efficient absorption emitting around 980 nm of commercially available laser diodes, this certain energy level structure is highly required and they avoid any unwanted excited-state absorption under intense optical pumping. Based on the above consideration, ytterbium co-doping in erbium and thulium doped fiber is investigated and become an interest area of research. In this work, various fiber lasers operating in both continuous wave and Q-switching mode are proposed and demonstrated using a ytterbium doped and co-doped fibers as the gain medium.

1.2 Problem Statement

Lasers operating in CW or quasi-CW mode have limited optical output power, depending on the maximum available pump power. The laser peak output power can be improved by concentrating the available energy in a single, short optical pulse, or in a periodic sequence of optical pulses as in a Q-switched fiber laser. *Q*-switching is a method that allows the generation of an optical pulse at repetition rate in kHz region and pulse width in a range of microseconds to nanoseconds by sudden switching of the cavity loss. Compared to CW fiber lasers, various applications, such as remote sensing, medicine, range finding and industrial processing are practically useful in high peak power *Q*-switched fiber lasers [17–20]. Although Q-switching does not produce the ultra-short pulses as in mode-locked lasers, it has several advantages such as inexpensive, easy to implement and efficient in extracting energy stored in upper laser level.

The Q-switched fiber laser can be achieved using either active or passive techniques. Active *Q*-switching is realised by introducing an electro-optic or an acoustic-optic modulator into the cavity. On the other hand, to simplify the cavity design and exclude the requirement for external *Q*-switching electronics, there is a convenient technique which is passive *Q*-switching by means of saturable absorbers (SAs). Different kinds of saturable absorbers (SAs), such as the transition metal-doped crystals [21–23] and semiconductor materials [24], have been applied to realize Q-switched fiber lasers especially for operation in 1550 nm region. However, extra alignment devices, such as mirrors, lens or U-bench units have to be applied when they are used in the laser cavity. This may increase the insertion loss and the complexity of the laser cavity.

Recently carbon nanotubes and graphene are normally used as the SA for the *Q*-switched fiber lasers [25–27]. These SAs are a comparatively simple and costeffective alternative compared to semiconductor SA (SESAM). This is because of their inherent advantages, as well as wide operating bandwidth, good compatibility with optical fibers, fast recovery time and low saturation intensity. On the other hand, due to their relatively big volume, SAs based on semiconductor and crystal cannot be used for an all fiber laser structure. However, most of the current works are focusing on Erbium-doped fiber lasers (EDFLs). There are still a lack of research works on Q-switching in both 1 micron and 2 micron regions. In this work, various types of low cost CNT and graphene based SAs are developed for Q-switching applications in Yb doped and co-doped fiber lasers.

1.3 Research Objectives

The main objective of this research is to design and construct an efficient and low cost Q-switched Ytterbium doped and co-doped fiber lasers operating in 1.0, 1.5 and 2.0 µm regions. This can be achieved by performing the following tasks;

1. To characterize CW and Q-switched fiber laser operating at 1 micron region using Ytterbium doped fiber as the gain medium. Both core and cladding pumping approaches are used in this study.
2. To characterize various types of passive saturable absorber based on multi-walled carbon nanotubes and graphene.
3. To demonstrate a Q-switched Erbium Ytterbium co-doped fiber laser using a multi-layer graphene film based SA.
4. To design a lasing characteristic on the newly developed Thulium Ytterbium co-doped fiber.

5. To demonstrate a Q-switched fiber laser operating at 2 micron region using the TYDF as the gain medium.

1.4 Organization of the Thesis

This thesis is organized into five chapters which comprehensively demonstrate the development of Q-switched fiber lasers operating in 1.0, 1.5 and 2.0 µm region using Ytterbium doped and co-doped fibers as the gain medium. Chapter 1 gives a brief description on the recent development of fiber lasers. The motivation and objective of this study are also highlighted. Chapter 2 furnishes a detailed literature on the basic theory of optical fibers, fiber lasers, Ytterbium fibers and Q-switching are described.

Chapter 3 presents the methodology used in the experimental works. All the components and measuring equipment that used in this work are discussed in details through this section. Chapter 4 presents thorough study on Yb^{3+} doped fiber laser (YDFLs) for both CW and pulse operations. Due to their compactness, low cost, and flexibility, this lasers become very attractive. An enormous range of applications of Yb^{3+} doped fiber laser have been found in in recent years including optical imaging, material processing and fiber communications. A passively Q-switched YDFL is then demonstrated by using multi-walled carbon nanotubes, which is embedded in PEO polymer as saturable absorber. The SA film was prepared by mixing the MWCNTs homogeneous solution into a dilute PEO polymer solution. It is sandwiched between two FC/PC fiber connectors and integrated into the laser cavity to generate a stable Q-switching pulse operating at 1 µm region.

Q-switched Erbium Ytterbium fiber laser (EYFL) operating at 1.5 µm region is demonstrated in Chapter 5 using a multi-layer graphene film based SA. The SA was fabricated by sandwiching a thin graphene film produced via electrochemical exfoliation technique between two FC fiber connectors. In addition, the amplification characteristic of a double-clad Erbium Ytterbium co-doped fiber (EYDF) under 927 nm multimode pumping are investigated. The EYDF amplifier (EYDFA) combines the multimode pump into the star shape inner cladding EYDF using a multimode combiner.

Chapter 6 aims to develop 2 micron fiber laser using a Thulium Ytterbium co-doped fiber (TYDF) as the gain medium. A 2 micron laser is demonstrated using two types of double-clad TYDF. Both TYDFs are fabricated using a MCVD process in conjunction with solution doping. Chapter 6 also demonstrates multi-wavelength and Q-switched fiber lasers based on the newly developed octagonal shape double-clad TYDF operating at 2 micron region. A homemade MWCNTs SA is used in this experiment. Finally, Chapter 7 summarizes the findings for this PhD work.

REFERENCES

1. Snitzer, E. Proposed fiber cavities for optical lasers. *J. Appl. Phys.* 1961; **32**: 36–39.

2. Koester, C. J., and Snitzer, E. Amplification in a Fiber Laser. *Appl. Opt.* 1964; **3** (**10**): 1182–1186.

3. R. Paschotta, J. Nilsson, A. C. Tropper, D. C. H. Ytterbium-doped fiber amplifiers. 1997;

4. Hayward, R. A., Clarkson, W. A., Turner, P. W., Nilsson, J., Grudinin, A. B., and Hanna, D. C. Efficient cladding-pumped Tm-doped silica fibre laser with high power single-mode output at 2µm. *Electron. Lett.* 2000; **36** (**8**): 711–712.

5. Feng, X., Tam, H., Liu, H., and Wai, P. K. a. Multiwavelength erbium-doped fiber laser employing a nonlinear optical loop mirror. *Opt. Commun.* 2006; **268**: 278–281.

6. Poulsen, H. N., Varming, P., Buxens, A., Clausen, A. T., Muñoz, I., Jeppesen, P., et al. 1607 nm DFB Fibre Laser for Optical Communication in the L-band. *ECOC'99, Tech. Dig. Pap. MO B2.1,* 1999;

7. Spuler, S. M., and Mayor, S. D. Raman shifter optimized for lidar at a 1.5 microm wavelength. *Appl. Opt.* 2007; **46** (**15**): 2990–2995.

8. Philippov, V., Codemard, C., Jeong, Y., Alegria, C., Sahu, J. K., Nilsson, J., et al. High-energy in-fiber pulse amplification for coherent lidar applications. *Opt.Lett.* 2004;**29**(**22**): 2590–2592.

9. McCulloch, S., Hassey, A., and Harrison, P. Fiber laser performance in industrial applications. *Proc. SPIE* 2013; **8603**: 86030C–1–86030C–14.

10. Ono, H., Yamada, M., and Ohishi, Y. Gain-Flattened Er3+-Doped Fiber Amplifier for a WDM Signal in the 1.57-1.60 micrometer Wavelength Region. *IEEE Photonics Technol. Lett.*1997;**9**(**5**): 596–598.

11. Po, H., Snitzer, E., Tumminelli, R., Zenteno, L., Hakimi, F., Cho, N. ., et al. Double Clad High Brightness Nd Fiber Laser Pumped By Gaalas Phased Array. 1989; 71–74.

12. Hideur, A., Chartier, T., and Ozkul, C. Dynamics and stabilization of a high power side-pumped Yb- doped double-clad fiber laser. *Opt. Commun.* 2000; **186**: 311–317.

13. Jackson, S. D., and King, T. a. Dynamics of the output of heavily Tm-doped double-clad silica fiber lasers. *J. Opt. Soc. Am. B* 1999; **16** (**12**): 2178–2188.

14. Nilsson, J., Turner, P. W., Clarkson, W. A., Renaud, C. C., and Grudinin, A. B. Widely tunable high-power diode-pumped double-clad yb3 ’ -doped fiber laser. *Adv. Solid State Lasers, Tech. Dig.*1999;**147**:

15. Auerbach, M., Wandt, D., Fallnich, C., Welling, H., and Unger, S. High-power tunable narrow line width ytterbium-doped double-clad fiber laser. *Opt.Commun.* 2001;**195**: 437–441.

16. Pask, H. M., Robert J. Carman, David C. Hanna, Anne C. Tropper, Mackechnie, C. J., Barber, P. R., et al. Ytterbium-doped Silica Fiber Lasers: Versatile Sources for the 1-1.2 micrometer Region. *IEEE J. Quantum Electron.* 1995; **1** (**1**): 2–13.

17. Chen, Z. J., Grudinin, a B., Porta, J., and Minelly, J. D. Enhanced Q switching in double-clad fiber lasers. *Opt. Lett.* 1998; **23** (**6**): 454–456.

18. Alvarez-Chavez, J. ., Offerhaus, H. L., Nilsson, J., Turner, P. W., Clarkson, W. A., and Richardson, D. J. High-energy, high-power ytterbium-doped Q -switched fiber laser. *Opt. Lett.* 2000; **25** (**1**): 37–39.

19. Fan, Y.-X., Lu, F.-Y., Hu, S.-L., Lu, K.-C., Wang, H.-J., Dong, X.-Y., et al. Tunable high-peak-power, high-energy hybrid Q-switched double-clad fiber laser. *Opt. Lett.* 2004; **29** (**7**): 724–726.

20. Wang, Y., and Xu, C.-Q. Modeling and optimization of Q-switched double-clad fiber lasers. *Appl. Opt.* 2006; **45** (**9**): 2058–2071.

21. Laroche, M., Chardon, a M., Nilsson, J., Shepherd, D. P., Clarkson, W. a, Girard, S., et al. Compact diode-pumped passively Q-switched tunable Er-Yb double-clad fiber laser. *Opt. Lett.* 2002; **27** (**22**): 1980–1982.

22. Philippov, V. N., Kir’yanov, A. V, and Unger, S. Advanced Configuration of Erbium Fiber Passively Q -Switched Laser With Co 2 + : ZnSe Crystal as Saturable Absorber.*IEEE Photonics Technol. Lett.* 2004; **16** (**1**): 57–59.

23. Qamar, F. Z., and King, T. a. Passive Q-switching of the Tm-silica fibre laser near 2µm by a Cr2+:ZnSe saturable absorber crystal. *Opt. Commun.* 2005; **248**: 501–508.

24. Paschotta, R., Häring, R., Gini, E., Melchior, H., Keller, U., Offerhaus, H. L., et al. Passively Q-switched 0.1-mJ fiber laser system at 1.53 mum. *Opt. Lett.* 1999; **24** (**6**): 388–390.

25. Ismail, M. A., Harun, S. W., Zulkepely, N. R., Nor, R. M., Ahmad, F., and Ahmad, H. Nanosecond soliton pulse generation by mode-locked erbium-doped fiber laser using single-walled carbon-nanotube-based saturable absorber. *Appl.Opt.* 2012;**51**(**36**): 8621–8624.

26. Su, L. M., Wang, Y. G., Liu, J., Zheng, L. H., Su, L. B., and Xu, J. Double-wall carbon nanotube absorber for passively mode-locked Yb3+:Sc2SiO5 laser. *Laser Phys. Lett.* 2012;**9**(**2**): 120–125.

27. Bonaccorso, F., Sun, Z., Hasan, T., and Ferrari, A. C. Graphene photonics and optoelectronics. *Nat. Photonics* 2010; **4** (**9**): 611–622.

28. Snitzer, E. Optical Maser Action of Nd in a Barium Crown Glass. *Phys. Rev.Lett.* 1961;**7**(**12**): 444–446.

29. Eidam, T., Hanf, S., Seise, E., Andersen, T. V, Gabler, T., Wirth, C., et al. Femtosecond fiber CPA system emitting 830 W average output power. *Opt.Lett.* 2010;**35**(**2**): 94–96.

30. Jeong, Y., Sahu, J., Payne, D., and Nilsson, J. Ytterbium-doped large-core fiber laser with 1 kW continuous-wave output power. *Electron. Lett.* 2004; **40** (**8**): 1– 2.

31. Quintino, L., Costa, A., Miranda, R., Yapp, D., Kumar, V., and Kong, C. J. Welding with high power fiber lasers – A preliminary study. *Mater. Des.* 2007; **28**: 1231–1237.

32. Grattan, K. T. V., and Sun, T. Fiber optic sensor technology: an overview. *Sensors Actuators A Phys.* 2000;**82**(**1-3**): 40–61.

33. Dickinson, B. . ., Golding, P. S., Pollnau, M., King, T. A., and Jackson, S. D. Investigation of a 791-nm pulsed-pumped 2 . 7- mm Er-doped ZBLAN fibre laser. *Opt. Commun.* 2001; **191**: 315–321.

34. Qin, G., Suzuki, T., and Ohishi, Y. Stable gain-switched 845 nm pulse generation by a weak 1550 nm seed laser. *Opt. Lett.* 2008; **33** (**3**): 249–251.

35. Jackson, S. D., Dickinson, B. C., and King, T. A. Sequence lasing in a gain-switched Yb3+,Er(3+)-doped silica double-clad fiber laser. *Appl. Opt.* 2002; **41** (**9**): 1698–1703.

36. Jiang, M., and Tayebati, P. Stable 10 ns, kilowatt peak-power pulse generation from a gain-switched Tm-doped fiber laser. *Opt. Lett.* 2007; **32** (**13**): 1797–1799.

37. Zhang, Y. ., Yao, B. ., Ju, Y. ., and Wang, Y. . Gain-switched Tm3+-doped double-clad silica fiber laser. *Opt. Express* 2005; **13** (**4**): 1085–1089.

38. Dickinson, B. C., Jackson, S. D., and King, T. A. 10 mJ total output from a gain-switched Tm-doped fibre laser. *Opt. Commun.* 2000; **182**: 199–203.

39. Giesberts, M., Geiger, J., Traub, M., and Hoffmann, H.-D. Novel Design of a Gain-Switched Diode-Pumped Fiber Laser Martin. *Proc. SPIE* 2009; **7195** (**0**): 71952P–1–71952P–9.

40. Sintov, Y., Katz, M., Blau, P., Glick, Y., Lebiush, E., and Nafcha, Y. A frequency doubled gain switched Yb3+ doped fiber laser. *Proc. SPIE* 2009; **7195**: 719529–719529–8.

41. Saleh, B. E. a., and Teich, M. C. *Fundamentals of Photonics*. New York, USA: John Wiley & Sons, Inc. 1991.

42. Kao, K. C., and Hockham, G. A. Dielectric- fibre surface waveguides for optical frequencies. *Proc. IEE* 1966; **113**: 1151–1158.

43. Miya, T., Terunuma, Y., Hosaka, T., and Miyoshita, T. Ultimate low-loss single-mode fiber at 1.55 µm. *Electron. Lett.* 1979; **15**: 106–108.

44. MALITSON, I. H. Interspecimen Comparison of the Refractive Index of Fused Silica. *J. Opt. Soc. Am.* 1965; **55** (**10**): 1205–1209.

45. Born, M. A. X. Principles of Optics. 1980;

46. Kapron, F. P., Keck, D. B., and Maurer, R. D. Radiation Losses In Glass Optical Waveguides. *Appl. Phys. Lett.* 1970; **17**: 423.

47. Stone, J., and Burrus, C. A. Neodymium-doped silica lasers in end- pumped fiber geometry. *Appl. Phys. Lett.* 1973; **23**: 388.

48. Stone, J., and Burrus, C. A. Neodymium-Doped Fiber Lasers : Room Temperature cw Operation with an Injection Laser Pump. *Appl. Opt.* 1974; **13** (**6**): 1256–1258.

49. Etzel, H. W., Gandy, H. W., and Ginther, R. J. Stimulated Emission of Infrared Radiation from Ytterbium Activated Silicate Glass. *Appl. Opt.* 1962; **1** (**4**): 534– 536.

50. Ebendorffheidepriem, H., Ehrt, D., Philippsb, J., Töpfer, T., Speghinic, A., Bettinelli, M., et al. Properties of Er3 Doped Glasses for Waveguide and Fiber Lasers. *Proc. SPIE* 2000; **3942**: 29–39.

51. Frith, G., Lancaster, D. G., and Jackson, S. D. High Power 2µm Tm3+-Doped Fibre Lasers. *Proc. SPIE* 2004; **5620**: 36–45.

52. Digonnet, M. J. .*Rare - Earth - Doped Fiber Lasers and Amplifiers, Revisedand Expanded*. 2001.

53. Poole, S. B., Payne, D. N., and Fermann, M. E. Fabrication of low-loss optical fibres containing rare-earth ions. *Electron. Lett.* 1985; **21** (**17**): 737–738.

54. Mears, R. J., L. Reekie, S.B. Poole, and D.N. Payne. Neodymium-doped silica single-mode fibre lasers. *Electron. Lett.* 1985; **21** (**17**): 738–740.

55. Snitzer, E., Po, H., Hakimi, F., Tumminelli, R., and Mccollum, B. . Double Clad, Offset Core Nd Fiber Laser. *Polaroid Corp. Cambridge***02139**: 553–556.

56. Sahu, J. ., Jeong, Y., Richardson, D. ., and Nilsson, J. A 103 W erbium–ytterbium co-doped large-core fiber laser. *Opt. Commun.* 2003; **227**: 159–163.

57. Yin, X., and Meng, J. Semiconductor saturable-absorber mirror passively Q - switched Yb : YAG microchip laser. *Chinese Opt. Lett.* 2013; **11** (**8**): 081402–1–081402–3.

58. Reisfeld, R., and Jorgensen, C. . Lasers and Excited States of Rare Earths. *Springer-Verlag Berlin Heidelb. New York* 1977;

59. Jabczynski, J. K., Zendzian, W., and Kwiatkowski, J. Q-switched mode-locking with acousto-optic modulator in a diode pumped Nd:YVO 4 laser. *Opt. Express* 2006; **14** (**6**): 2184–2190.

60. Cautaerts, V. Stretched pulse Yb3+: Silica Fibre Laser. *Opt. Lett.* 1997; **22** (**5**): 316–318.

61. Walton, D. T., Nees, J., and Mourou, G. Broad-bandwidth pulse amplification to the 10-microJ level in an ytterbium-doped germanosilicate fiber. *Opt. Lett.* 1996; **21** (**14**): 1061–1063.

62. Zhu, R., Wang, J., Zhou, J., Liu, J., and Chen, W. Single-frequency high-energy Yb-doped pulsed all-fiber laser. *Chinese Opt. Lett.* 2012; **10** (**9**): 091402–1– 091402–4.

63. Zhou, C. High-energy nanosecond all-fiber Yb-doped amplifier. *Chinese Opt.Lett.* 2013;**11**(**8**): 11–13.

64. Yang, J., Tang, Y., and Xu, J. Development and applications of gain-switched fiber lasers Invited..*Photonics Res.* 2013; **1** (**1**): 52–57.

65. Snitzer, E. Rare earth fiber lasers. *J. Less-Common Met.* 1989; **148**: 45–58.

66. Ohishi, Y., Kanamori, T., Kitagawa, T., Takahashi, S., Snitzer, E., and Sigel, G. H. Pr(3+)-doped fluoride fiber amplifier operating at 1.31 micrometer. *Opt.Lett.* 1991;**16**(**22**): 1747–1749.

67. Jeong, Y., Sahu, J. K., Williams, R. B., Richardson, D. J., Furusawa, K., and Nilsson, J. Ytterbium-doped large core fibre laser with 272 W of output power. *Electron. Lett.* 2003;**39**(**73**): 977–978.

68. Limpert, J., Liem, A., Zellmer, H., and Tünnermann, A. 500 W continuous-wave fibre laser with excellent beam quality. *Electron. Lett.* 2003; **39** (**8**): 645– 647.

69. Jeong, Y., Sahu, J. K., Baek, S., Alegria, C., Soh, D. B. S., Codemard, C., et al. Cladding-pumped ytterbium-doped large-core fiber laser with 610 W of output power. *Opt. Commun.* 2004; **234**: 315–319.

70. Gross, P., Klein, M. E., Walde, T., Boller, K.-J., Auerbach, M., Wessels, P., et al. Fiber-laser-pumped continuous-wave singly resonant optical parametric oscillator. *Opt. Lett.* 2002; **27** (**6**): 418–420.

71. Jeong, Y., Yoo, S., Codemard, C. A., Nilsson, J., Sahu, J. K., Payne, D. N., et al. Erbium : Ytterbium Codoped Large-Core Fiber Laser With 297-W Continuous-Wave Output Power. *IEEE J. Quantum Electron.* 2007; **13** (**3**): 573–579.

72. Lee, J., Koo, J., Chang, Y. M., Debnath, P., Song, Y., and Lee, J. H. Experimental investigation on a Q -switched , mode-locked fiber laser based on the combination of active mode locking and passive Q switching. *J. Opt. Soc.Am. B* 2012;**29**(**6**): 1479–1485.

73. Yu, Z., Song, Y., Tian, C., Li, J., Zhang, X., and Wang, Y. Q-switched Yb-doped double cladding fiber laser with single wall carbon nanotube saturable absorber. *Proc. SPIE* 2012; **8551**: 8551151–8551156.

74. Zhang, L., Wang, Y. G., Yu, H. J., Sun, L., Hou, W., Lin, X. C., et al. Passive mode-locked Nd:YVO4 laser using a multi-walled carbon nanotube saturable absorber. *Laser Phys.* 2011; **21** (**8**): 1382–1386.

75. Ramadurai, K., Cromer, C. L., Lewis, L. A., Hurst, K. E., Dillon, A. C., Roop, L., et al. High-performance carbon nanotube coatings for high-power laser radiometry. 2011; **013103** (**2008**): 2–8.

76. Lin, X. C., Zhang, L., Tsang, Y. H., Wang, Y. G., Yu, H. J., Yan, S. L., et al. Multi-walled carbon nanotube as a saturable absorber for a passively mode-locked Nd:YVO 4 laser. *Laser Phys. Lett.* 2013; **10**: 055805.

77. Ferrari, a. C., Meyer, J. C., Scardaci, V., Casiraghi, C., Lazzeri, M., Mauri, F., et al. Raman Spectrum of Graphene and Graphene Layers. *Phys. Rev. Lett.* 2006; **97** (**18**): 187401.

78. Harun, S. W., Akbari, R., Arof, H., and Ahmad, H. Mode-locked bismuth-based erbium-doped fiber laser with stable and clean femtosecond pulses output. *Laser Phys. Lett.* 2011;**8**(**6**): 449–452.

79. Wang, Q., Chen, T., Li, M., Zhang, B., Heberle, A. P., and Chen, K. P. Passively Q- switched Thulium -doped fiber laser by graphene saturable absorber. *Opto-Electronics Commun. Conf.* 2012; (**July**): 55–56.

80. Saidin, N., Zen, D. I. M., Hamida, B. a, Khan, S., Ahmad, H., Dimyati, K., et al. A Q -switched thulium-doped fiber laser with a graphene thin film based saturable absorber. *Laser Phys.* 2013; **23** (**11**): 115102.

81. Li, X. H., Wang, Y. G., Wang, Y. S., Zhang, Y. Z., Wu, K., Shum, P. P., et al. All-normal-dispersion passively mode-locked Yb-doped fiber ring laser based on a graphene oxide saturable absorber. *Laser Phys. Lett.* 2013; **10**: 075108.

82. Harun, S. W., Ismail, M. a., Ahmad, F., Ismail, M. F., Nor, R. M., Zulkepely, N. R., et al. A Q-Switched Erbium-Doped Fiber Laser with a Carbon Nanotube Based Saturable Absorber. *Chinese Phys. Lett.* 2012; **29** (**11**): 114202.

83. Zhou, D. ., Wei, L., Dong, B., and Liu, W. . Tunable Passively Q-switched Erbium-Doped Fiber Laser With Carbon Nanotubes as a Saturable Absorber. *IEEE Photonics Technol. Lett.*2010;**22**(**1**): 9–11.

84. Yu, H., Zhang, L., Wang, Y., Yan, S., Sun, W., Li, J., et al. Sub-100ns solid-state laser Q-switched with double wall carbon nanotubes. *Opt. Commun.* 2013; **306**: 128–130.

85. Nodop, D., Limpert, J., Hohmuth, R., Richter, W., Guina, M., and Tünnermann, A. High-pulse-energy passively Q-switched quasi-monolithic microchip lasers operating in the sub-100-ps pulse regime. *Opt. Lett.* 2007; **32** (**15**): 2115–2117.

86. Spühler, G. J., Paschotta, R., Kullberg, M. P., Graf, M., Moser, M., Mix, E., et al. A passively Q-switched Yb:YAG microchip laser. *Appl. Phys. B* 2001; **72**: 285–287.

87. Graham-Rowe, D. Lasers for engine ignition. *Nat. Photonics* 2008; **2**: 515–517.

88. Park, N., Wysocki, P., Pedrazzani, R., Grubb, S., Digiovanni, D., and Walker, K. High-Power Er-Yb-Doped Fiber Amplifier with Multichannel Gain Flatness within 0.2 dB over 14 nm. *IEEE Photonics Technol. Lett.* 1996; **8** (**9**): 1148– 1150.

89. Federighi, M., and Pasquale, F. Di. The Effect of Pair-Induced Energy Transfer on the Performance of Silica Waveguide Amplifiers with High Er3 + / Yb3 + Concentrations. *IEEE Photonics Technol. Lett.* 1995; **7** (**3**): 303–305.

90. Yahel, E., and Hardy, A. Efficiency optimization of high-power , Er 3+ – Yb 3+ -codoped fiber amplifiers for wavelength-division-multiplexing applications. *J. Opt. Soc. Am. B* 2003; **20** (**6**): 1189–1197.

91. Harun, S. W., Abdul-Rashid, H. a., Muhd-Yassin, S. Z., Abd-Rahman, M. K., Jayapalan, K. K., and Ahmad, H. 37.2dB small-signal gain from Er/Yb Co-doped fiber amplifier with 20mW pump power. *Opt. Laser Technol.* 2008; **40** (**1**): 88–91.

92. Jeong, Y., Sahu, J. K., Soh, D. B. S., Codemard, C. A., and Nilsson, J. High-power tunable single-frequency single-mode erbium : ytterbium codoped large-core fiber master-oscillator power amplifier source. *Opt. Lett.* 2005; **30** (**22**): 2997–2999.

93. Myslinski, P., Nguyen, D., and Chrostowski, J. Effects of concentration on the performance of erbium-doped fiber amplifiers. *J. Light. Technol.* 1997; **15** (**1**): 112–120.

94. Nilsson, J., Jaskorzynska, B., and Blixt, P. Performance reduction and design modification of erbium-doped fiber amplifiers resulting from pair-induced quenching. *IEEE Photonics Technol. Lett.* 1993; **5** (**12**): 1427–1429.

95. Dubinskii, M., Zhang, J., and Ter-Mikirtychev, V. Record-efficient, resonantly-pumped, Er-doped singlemode fibre amplifier. *Electron. Lett.* 2009; **45** (**8**):

96. Harun, S. W., Abd Rahman, F., Dimyati, K., and Ahmad, H. An efficient gain-flattened C-band Erbium-doped fiber amplifier. *Laser Phys. Lett.* 2006; **3** (**11**): 536–538.

97. Yeh, C.-H., Lee, C.-C., and Chi, S. S- plus C-band erbium-doped fiber amplifier in parallel structure. *Opt. Commun.* 2004; **241**: 443–447.

98. Yu, H., Zhou, J., Wushouer, X., Yan, P., Wang, D., and Gong, M. 40 W picosecond fiber amplifier with the large mode-area polarized crystal fiber. *Laser Phys. Lett.* 2009;**6**(**9**): 653–656.

99. Md Samsuri, N., Harun, S. W., and Ahmad, H. Comparison of performances between partial double-pass and full double-pass systems in two-stage L-band EDFA. *Laser Phys. Lett.* 2004; **1** (**12**): 610–612.

100. Wang, Y., Inoue, K., Kan, H., Ogawa, T., and Wada, S. A MOPA with double-end pumped configuration using total internal reflection. *Laser Phys.* 2010; **20** (**2**): 447–453.

101. Daud, S. A., Emami, S. D., Mohamed, K. S., Yusoff, N. M., Aminudin, L., Abdul-Rashid, H. A., et al. Gain and noise figure improvements in a shorter wavelength region of EDFA using a macrobending approach. *Laser Phys.* 2008; **18** (**11**): 1362–1364.

102. Harun, S. W., Emami, S. D., Abd Rahman, F., Muhd-Yassin, S. Z., Abd-Rahman, M. K., and Ahmad, H. Multiwavelength Brillouin/Erbium-Ytterbium fiber laser. *Laser Phys. Lett.* 2007; **4** (**8**): 601–603.

103. Laroche, M., Chardon, a M., Nilsson, J., Shepherd, D. P., Clarkson, W. a, Girard, S., et al. Compact diode-pumped passively Q-switched tunable Er-Yb double-clad fiber laser. *Opt. Lett.* 2002; **27** (**22**): 1980–1982.

104. Dong, B., Hao, J., Hu, J., and Liaw, C. Short linear-cavity Q-switched fiber laser with a compact short carbon nanotube based saturable absorber. *Opt. FiberTechnol.* 2011;**17**: 105–107.

105. Li, X., Wang, Y., Wang, Y., Liu, X., Zhao, W., Hu, X., et al. Yb-doped passively mode-locked fiber laser based on a single wall carbon nanotubes wallpaper absorber. *Opt. Laser Technol.* 2013; **47**: 144–147.

106. Wang, F., Rozhin, a G., Scardaci, V., Sun, Z., Hennrich, F., White, I. H., et al. Wideband-tuneable, nanotube mode-locked, fibre laser. *Nat. Nanotechnol.* 2008; **3**: 738–742.

107. Rozhin, A. G., Scardaci, V., Wang, F., Hennrich, F., White, I. H., Milne, W. I., et al. Generation of ultra-fast laser pulses using nanotube mode-lockers. *Phys.Status Solidi* 2006;**243**(**13**): 3551–3555.

108. Schibli, T., Minoshima, K., Kataura, H., Itoga, E., Minami, N., Kazaoui, S., et al. Ultrashort pulse-generation by saturable absorber mirrors based on polymer-embedded carbon nanotubes. *Opt. Express* 2005; **13** (**20**): 8025–8031.

109. Ramadurai, K., Cromer, C. L., Lewis, L. a., Hurst, K. E., Dillon, A. C., Mahajan, R. L., et al. High-performance carbon nanotube coatings for high-power laser radiometry. *J. Appl. Phys.* 2008; **103**: 013103.

110. Novoselov, K. S., Geim, a K., Morozov, S. V, Jiang, D., Zhang, Y., Dubonos, S. V, et al. Electric field effect in atomically thin carbon films. *Science* 2004; **306** (**5696**): 666–669.

111. Zhang, H., Tang, D. Y., Zhao, L. M., Bao, Q. L., and Loh, K. P. Large energy mode locking of an erbium-doped fiber laser with atomic layer graphene. *Opt.Express* 2009;**17**(**20**): 17630–17635.

112. Popa, D., Sun, Z., Torrisi, F., Hasan, T., Wang, F., and Ferrari, a. C. Sub 200 fs pulse generation from a graphene mode-locked fiber laser. *Appl. Phys. Lett.* 2010; **97**: 203106.

113. Sun, Z., Hasan, T., Torrisi, F., Popa, D., Privitera, G., Wang, F., et al. Graphene mode-locked ultrafast laser. *ACS Nano* 2010; **4** (**2**): 803–10.

114. Zhang, L. Q., Zhuo, Z., Wang, J. X., and Wang, Y. Z. Passively Q-switched fiber laser based on graphene saturable absorber. *Laser Phys.* 2012; **22** (**2**): 433– 436.

115. Chen, S., Brown, L., Levendorf, M., Cai, W., Ju, S.-Y., Edgeworth, J., et al. Oxidation resistance of graphene-coated Cu and Cu/Ni alloy. *ACS Nano* 2011; **5** (**2**): 1321–1327.

116. Denisov, A. V., Kuznetsov, A. G., Kharenko, D. S., Kablukov, S. I., and Babin, S. A. Frequency doubling and tripling in a Q-switched fiber laser. *Laser Phys.* 2011; **21** (**2**): 277–282.

117. Wu, J., Yao, Z., Zong, J., and Jiang, S. Highly efficient high-power thulium-doped germanate glass fiber laser. *Opt. Lett.* 2007; **32** (**6**): 638–640.

118. Zhang, Z., Boyland, a. J., Sahu, J. K., Clarkson, W. a., and Ibsen, M. High-Power Single-Frequency Thulium-Doped Fiber DBR Laser at 1943 nm. *IEEEPhotonics Technol. Lett.* 2011;**23**(**7**): 417–419.

119. Gumenyuk, R., Vartiainen, I., Tuovinen, H., and Okhotnikov, O. G. Dissipative dispersion-managed soliton 2 μm thulium/holmium fiber laser. *Opt. Lett.* 2011; **36** (**5**): 609–611.

120. Slobodtchikov, E., Moulton, P. F., and Frith, G. Efficient, High-Power, Tm-Doped Silica Fiber Laser. *Adv. Solid-State Photonics* 2007; MF2.

121. Jander, P., and Brocklesby, W. S. Spectroscopy of yttria-alumina-silica glass doped with thulium and erbium. *IEEE J. Quantum Electron.* 2004; **40** (**5**): 509– 512.

122. Pal, A., Dhar, A., Das, S., Chen, S. Y., Sun, T., Sen, R., et al. Ytterbium-sensitized Thulium-doped fiber laser in the near-IR with 980 nm pumping. *Opt.Express* 2010;**18**(**5**): 5068–5074.

123. Kurkov, a. S., Sadovnikova, Y. E., Marakulin, a. V., and Sholokhov, E. M. All fiber Er-Tm Q-switched laser. *Laser Phys. Lett.* 2010; **7** (**11**): 795–797.

124. Fried, N. M., Blackmon, R. L., and Irby, P. B. A Review of Thulium Fiber Laser Ablation of Kidney Stones. *Proc. SPIE* 2011; **7914**: 791402–1–791402–10.

125. Pierce, M., Jackson, S., Goldinga, P., Dickinsona, B., Dickinsona, M., Kinga, T., et al. Development and application of fibre lasers for medical applications. *Proc. SPIE* 2001;**4253**(**0**): 144–154.

126. Pierce, M. C., Jackson, S. D., Dickinson, M. R., and King, T. a. Laser-tissue interaction with a high-power 2-microm fiber laser: preliminary studies with soft tissue. *Lasers Surg. Med.* 1999; **25**: 407–413.

127. Opsommer, E., Weiss, T., Miltner, W. H. R., and Plaghki, L. Scalp topography of ultralate (C- fibres) evoked potentials following thulium YAG laser stimuli to tiny skin surface areas in humans. *Clin. Neurophysiol.* 2001; **112**: 1868–1874.

128. El-Sherif, A. ., and King, T. . . Soft and hard tissue ablation with short-pulse high peak power and continuous thulium-silica fibre lasers. *Lasers Med. Sci.* 2003; **18**: 139–47.

129. Wang, F., Shen, D. Y., Fan, D. Y., and Lu, Q. S. High power widely tunable Tm:fiber laser with spectral linewidth of 10 pm. *Laser Phys. Lett.* 2010; **7** (**6**): 450–453.

130. Tian, Y., Zhao, J. Q., Gao, W., Wang, W., and Wang, Y. Z. Narrow line-width Tm 3+ doped double-clad silica fiber laser based on in-line cascade biconical tapers filter. *Laser Phys. Lett.* 2010; **7** (**4**): 298–302.

131. Yang, D. Z., Liu, W., Chen, T., Ye, W., and Shen, Y. H. Linearly-polarized Tm-doped double-clad fiber laser. *Laser Phys.* 2010; **20** (**8**): 1752–1755.

132. Yamamoto, T., Miyajima, Y., and Komukai, T. 1.9 micrometer Tm-doped silica fibre laser pumped at 1.57 micrometer. *Electron. Lett.* 1994; **30** (**3**): 220–221.

133. Clarkson, W. A., Barnes, N. P., Turner, P. W., Nilsson, J., and Hanna, D. C. High-power cladding-pumped Tm-doped silica fiber laser with wavelength tuning from 1860 to 2090 nm. *Opt. Lett.* 2002; **27** (**22**): 1989–1991.