CHARACTERIZATION OF THULIUM-DOPED FIBER AS ACTIVE GAIN MEDIUM AT 2000 NANOMETER WAVELENGTH REGION

NURHANIS BINTI MOHD SHARIF

A thesis submitted in fulfilment of the
requirement for the award of the degree of
Master of Philosophy

Razak School of Engineering and Advanced Technology
Universiti Teknologi Malaysia

MARCH 2017

DEDICATION

To my parents,

Thank you for the unconditional love and supports.

To my family,

Thank you for the supports of my dreams.

To my supervisor,

Thank you for the continuous guidance, helps, and supports.

To every souls, thank you very much!

ACKNOWLEDGMENT

I praise God and thank Him for giving me all the strengths to finally complete this study and thesis within time. To my supervisor, Dr Nelidya Md. Yusoff, thank you very much for being dedicated and passionate in guiding me and letting me to join into conferences and other research activities that are mostly beneficial in contributing to my study.

I would like to thank Prof. Dr Harith, Prof Dr Sulaiman, Dr Fauzan, Anas, Hanapiah, and all members from Photonic Research Center, Universiti Malaya for providing all the facilities for my study.

Thank you to all lecturers and my friends of Razak School of Engineering and Advanced Technology for being supportive and encouraging within these two years.

To my family, thank you to both of my parents, Mohd Sharif and Norazimah for their endless love and support to me. To my beloved siblings (Nurhikmah, Nurhusna, Ikram, and Tarmize) thank you very much for their time and understanding. To Fatihah, I love you!

Finally, to those who are not mentioned, your faces and good deeds are all remembered and not forgotten. Thank you very much! May God bless us all!

ABSTRACT

Driven by huge demands and needs, the communication industry has tremendously grown in all over the world. With the development of low loss optical fiber as the main optical communication medium, high power tunable laser and other related auxiliary components are developed to practically opt as an alternative to the electrical communication system. In conjunction with the rapid growth of data traffic and high bandwidth demands, 2 μm wavelength region has been looked out for. In this study, the generation of thulium-doped fiber laser is thoroughly investigated especially in generating pulsed laser. Passively Q-switched thulium-doped fiber laser (TDFL) is successfully experimented by using graphene-based saturable absorber (SA) as a Q-switcher in modulating the intra-cavity loss experienced by the fiber laser system. In the generation of Q-switched TDFL, the laser system has been set up in two configurations; ring cavity and linear cavity. The comparison of the laser performance in terms of frequency, output power, pulse width, and pulse energy differ significantly to each laser cavity. Moreover, the effects of nonlinearities also contribute to the generation of the Q-switched TDFL. These effects can be seen in the wider spectrum of the Q-switched TDFL as being compared to the spectrum of the continuous wave (CW) laser. In this study, four set ups of Q-switched TDFL in ring cavity using four different SAs have been investigated whereas a set of Q-switched TDFL experimented in a linear cavity. Besides that, this study also focuses on the designations of thulium-doped fiber amplifier that can be applied for future generation in optical communication. As aforementioned, 2 μm wavelength region has been the interest of the optical communication society at present. In this study, the thulium-doped fiber amplifier (TDFA) is demonstrated through simulation by OptiSystem v. 13. The basic single stage TDFA is successfully demonstrated and this design is made comparable to the dual-stages TDFA which utilized the pump distribution technique. In the dual-stages with distributed pumping configuration, the pump power is distributed into two stages. Fifty percent of the pump power is being used in the first stage while another fifty percent is being used in the second stage. Tri-stages TDFA is also being demonstrated through the OptiSys and it had been made comparable to the dual-stages TDFA where both TDFAs are utilizing the same enhancement technique. It is shown that the dual-stages TDFA has successfully decreased the noise figure of about 2 dB. All TDFAs were investigated in achieving high gain, high output power with low noise figure.

ABSTRAK

Didorong oleh permintaan dan keperluan yang besar, industri komunikasi telah berkembang pesat di seluruh dunia. Dengan pembangunan gentian optik berpenurunan rendah sebagai medium komunikasi optik yang utama, laser boleh ubah berkuasa tinggi dan lain-lain komponen tambahan yang berkaitan telah dibangunkan untuk dipraktikkan sebagai alternatif kepada sistem komunikasi elektrik. Bersempena dengan pertumbuhan permintaan data trafik yang pesat dan permintaan jalur lebar yang tinggi, rangkaian optik 2 μm telah diterokai. Dalam kajian ini, penjanaan laser gentian thulium-terdop disiasat dengan teliti terutamanya dalam penjanaan laser denyut. Laser gentian optik thulum-terdop Q-switched (Q-switched TDFL) pasif telah berjaya dieksperimentasi dengan menggunakan penyerap tepu (SA) graphene sebagai Q-penukar dalam memodulasi penurunan intra-rongga yang dialami oleh sistem laser gentian optik. Dalam penjanaan Q-switched TDFL, dua konfigurasi sistem laser telah diset, rongga cincin dan rongga linear. Oleh itu, perbandingan prestasi laser dari segi kekerapan, kuasa output, lebar denyut, dan tenaga denyut akan berbeza mengikut setiap rongga laser. Selain itu, kesan tidak linear juga menyumbang kepada penjanaan Q-switched TDFL. Kesan-kesan ini boleh dilihat dengan jelas pada spektrum Q-switched TDFL yang lebih luas jika dibandingkan dengan spektrum laser gelombang berterusan (CW). Dalam kajian ini, empat set Q-switched TDFL menggunakan empat SA yang berbeza dalam rongga cincin telah disiasat manakala satu set Q-switched TDFL dalam rongga linear telah dieksperimentasi. Selain daripada itu, kajian ini juga memberi tumpuan kepada desain-desain penguat gentian thulium-terdop yang boleh digunakan pada masa akan datang dalam komunikasi optik. Seperti yang dinyatakan di atas, rangkaian optik 2 μm telah menjadi minat dalam kalangan masyarakat komunikasi optik pada masa ini. Dalam kajian ini, penguat gentian thulium-terdop (TDFA) telah didemonstrasi melalui simulasi oleh OptiSystem v. 13. Satu peringkat TDFA berjaya didemonstrasi dan desain ini dibuat perbandingan dengan dwi-peringkat TDFA yang mengguna pakai teknik pengepaman teragih. Dalam konfigurasi dwi-peringkat, kuasa pam diagihkan kepada dua peringkat. Lima puluh peratus daripada kuasa pam digunakan di peringkat pertama manakala lima puluh peratus selebihnya digunakan di peringkat kedua. Selain itu, sebuah lagi desain iaitu tiga peringkat TDFA juga didemonstrasi melalui OptiSys dan desain ini telah dibuat perbandingan dengan dwi-peringkat TDFA mana kedua-dua TDFA mengguna pakai teknik peningkatan yang sama. Dwi-peringkat TDFA telah terbukti berjaya menurunkan angka hingar dalam kira-kira 2 dB. Semua TDFA telah disiasat dalam mencapai gandaan yang tinggi, kuasa output tinggi dengan angka hingar yang rendah.

TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

LIST OF ABBREVIATIONS

WDM	-	Wavelength Division Multiplexing
EDF	-	Erbium-Doped Fiber
OLT	-	Optical Line Terminal
ONU	-	Optical Network Unit
EDFA	-	Erbium-Doped Fiber Amplifier
TDF	-	Thulium-Doped Fiber
TDFA	-	Thulium-Doped Fiber Amplifier
ASE	-	Amplified Spontaneous Emission
TDFL	-	Thulium-Doped Fiber Laser
SA	-	Saturable Absorber
CNT	-	Carbon Nanotube
NG:PVA	-	Nitrogen-doped Graphene in Polyvynil Alcohol
NG:PEO	-	Nitrogen-doped Graphene in Polyethylene Oxide
SWCNT	-	Single-Walled Carbon Nanotube
HiPCO CNT	-	High Pressure Carbon Monoxide Carbon Nanotube
MOPA		Master Oscillator Power Amplifier

CHAPTER 1

INTRODUCTION

1.1 Background of the study

Due to the rapid growth of communication technology and wide bandwidth internet demands, the optical communication has revolved into the next wavelength region that is the 2000 nm or 2 μm window (Richardson et al., 2010). In order to provide and offer applications in this window, the optical source in 2 μm has first to be generated. Following that, 2 μm optical communication can be realized. Prior to the invention of laser in 1960s (Maiman, 1960), the using of the electromagnetic spectrum for transmitting information has led to the generation of high power fiber laser as optical sources. It has been started after the first demonstration of neodymium-doped fiber laser in 1964 by Charles J. Koester and Elias Snitzer (Snitzer, 1964). After the invention of neodymium-doped fiber laser, Ytterbium-doped fiber laser was introduced by Hanna et.al in 1988 to be applicable in 1 μm window (D. C. Hanna, 1988). It was Snitzer also who developed the first erbium-doped fiber laser (Philippe C. Becker, 1999). Later on, laser source on 2 μm has been investigated and developed to be applied in such diverse fields; such as remote sensing, medicine, national defense, communication and other relevant fields. As in pursuit of compactness and reliability, thulium-doped fiber laser is considered as the suitable candidate (D. C. Hanna, 1990).

Owing to the existing optical fiber transmission link which relies on erbium system, the research continues to explore the new region and as for that reason, 2 μm region is seen to be able to compensate the bandwidth capacity limit in 1.55 μm.

Research works and scientific experiments have mainly dedicated to works on the 1.55 μm (N. Md. Yusoff, 2012) wavelength band as the existing Wavelength Division Multiplexing (WDM) technology lies mostly on this transmission window. These significant researches have been the interest because erbium-doped fiber (EDF) as the active gain medium has significantly viable to cover the C-, and L-band region (Yusoff et al., 2012). Therefore, the needs of going to a super broadband optical communication link and ever-increasing demands for high bandwidths have caught attentions in the 2000 nm window for long-reach transmission network system in the present and near future.

Continuos wave and pulsed laser sources have started to be employed in a broad fields of application especially in the industrial sector which requires the compact, maintenance-free, low-cost, and efficient with high beam quality has made fiber laser the suitable candidate. In various industrial and scientific applications, continuos wave and pulsed fiber lasers are needed in the fields of material processing, bio-medicine, optical communication, spectroscopy, imaging and ranging (Canat, 2014). In specific, ultrafast fiber laser (Zhang, 2014), either mode-locking or Q-switching (Shi et al., 2014) have proven to deliver pulses in a short duration.

In order to enable the 2 μm optical communication system, high quality optical amplifiers are required (Soref, 2015). Optical amplifiers are one of the most important devices in the WDM technology as they are crucial in amplifying input signal from the optical line terminal (OLT) to be transmitted through the optical link to the optical network unit (ONU). In WDM technology (Tanabe, 2015), EDFA is commonly used in order to meet the demand higher data capacity. Optical communication system, in its traditional ways has been using optoelectronic regenerators to convert optical to the electrical and then back to optical. The first introduction of erbium-doped fiber amplifier (EDFA) in 1987 has made a big change (Philippe C. Becker, 1999) in optical transmission system. Optical amplifiers will replace the electronic repeaters to boost up the signal power along the fiber span; all optical signals can be amplified simultaneously without the need of signal conversion within the EDFA in a single fiber. Therefore, the WDM technology has been a great interest in enabling the multi wavelength communication. Due to bandwidth limitation, thulium-doped fiber amplifier (TDFA) (Li et al., 2015, Heidt et al., 2014, Zhang et al., 2015) at 2000 nm is being introduced in these recent years. It is believed that the development and enhancement in the generation of ultrafast laser source together with the thulium-doped fiber amplifier (TDFA) in the range 2 µm might be able to compensate the growing and demanding applications especially in the optical communication system.

Today, in conjunction with the rapid growth of data traffic and high bandwidth demands, the exploration in 2 µm wavelength region is in the fast pace. This optical waveband lies in the range from ~1650 nm to 2100 nm (Ahmad, 2014). Researches and developments in 2 µm optical communication system have been rigorously done and still continued for the advantages and benefits offered for the sake of occupying the internet needs. With that, thulium-doped fiber amplifier (TDFA) is introduced these recent years for the applications as high performance optical amplifier in the future communication network system that will be operating at around 2 µm wavelength (Z. Li, 2013).

1.2 Problem Statement

The study concentrates on the characterization of the thulium-doped fiber as active gain medium to be applied on the 2 µm system. Due to the saturation of system applications in 1.55 µm region, future access generation is predicted to face the over demanding of high bandwidth and limited data traffic availability. Around the globe, the optical communication system relies on the Erbium-based system to transmit the optical signal through the terrestrial and undersea link transmission.

Since the generation of actively Q-switched TDFL faces high cost due to the expensive active modulator, passive Q-switching is introduced as an alternative technique in establishing ultrafast pulse laser system. Another problem that crosses to mind which drives the research is that, there are various kinds of lasers that is made available in the industry as well as in the research and development activities. In this study, research works aimed on the generation of the passively Q-switched thulium-doped fiber laser as to make it competent with the pulse semiconductor laser that is actively modulated by active components. This is due to the nature of the fiber laser cavity that constitute only of fiber components. Furthermore, this study focus specifically on the development of Q-switched TDFL operating at new wavelength regime of 2 µm. Pulse generation in Q-switched TDFL employing saturable absorbers (SAs) are studied. Besides that, the light beam quality is of the main concern as the light travels and routed to specific target in fiber optic.

In order to set up an optical link, optical amplifier has found the extensive use in diverse applications ranging from the long undersea links to short links in access networks such as Metro Access Network (MAN) and Local Access Network (LAN). However, since EDFA has been widely used in optical communication network especially in the C- and L- band, TDFA is seen to be the best candidature (Li, 2013, Yamada et al., 2014) to be applied in the 2 μm optical communication link. Therefore, the design of the proposed TDFA has first to be verified to be made applicable in compensating optical loss suffered by the active gain medium in the specified region. Despite of having high gain in accomplishing the purpose of optical amplifier (for signal amplification), reducing the noise figure is one of the complement. High noise figure might distract and interrupt the signal propagation in the optical link. Low population inversion has also been the problem since it affects the degradation of the gain that will consequently affect the noise figure value. Here, noise figure reduction has the paramount concern prior to achieving higher gain in the proposed amplification system.

1.3 Objectives of the study

The objectives of the study are as below:

i. To investigate and generate a stable Q-switched thulium-doped fiber laser (TDFL) at near 2000 nm wavelength region by using graphene-based and carbon nanotube-based saturable absorbers.
ii. To develop thulium-doped fiber amplifier (TDFA) with distributed pumping technique.
iii. To evaluate the performance of the Q-switched TDFL and the developed TDFA.

1.4 Scope of the study

The task of achieving the research objectives have been divided into its perspective scope. The scope of the study is as follows:

i. Designing the experimental setup of TDFL

   The experimental setup is designed with close similarity to any experiments involving fiber laser. All the passive components have been characterised. As for the doped-fiber, thulium-doped fiber (TDF) had been chosen as the active gain medium with 1552 nm laser diode to provide pump power to the whole laser system. The pumping scheme is chosen based on the energy level diagram of thulium (Tm^{3+}) ions.

ii. Characterisation of the fiber parameter

   At the initial stage, the TDF has been characterised. The Amplified Spontaneous Emission (ASE) spectrum is observed and recorded. The highest absorption peak on the ASE spectrum would determine at which wavelength the TDF will emit the highest gain.

iii. Demonstration of the 2000 nm TDFL

   The experiment of TDFL is conducted and all the performance parameters of the TDFL were recorded to be analysed and discussed.

iv. Design a simulation for TDFA

   For the simulation purpose, designs of the TDFA is constructed via simulation tool; OptiSystem version 13.0.1 provided by the Optiwave System Inc.

v. Run the proposed design of TDFA

   Three designs of TDFA have been made. They are single stage, dual stage, and distributed pumping. All these designs were run via OptiSystem and the results obtained were solely from the software.

1.5 Thesis Outline

This thesis comprises of five chapters. Chapter 1 provides the introduction to the problem and the topic. The research area is the fiber laser and fiber amplifier. It gives a brief description of the objectives and the scope of the study.

Chapter 2 will go through the details of literature review and recent works done by other researchers related to the proposed work such as the very fundamentals of thulium ions energy level, important parameters of fiber laser and fiber amplifier, operating principle of Q-switched laser and fiber amplifier. Chapter 3 present the research methodology of this study. The experimental setups for the Q-switched TDFL and TDFA are presented here. Chapter 4 provides the whole description of generating Q-switched TDFL by using passive saturable absorber, (SA). Data collection for Q-switched TDFL is obtained from the experimental works conducted in Photonic Research Center (PRC) Universiti Malaya, Kuala Lumpur. Chapter 5 presents the study of thulium-doped fiber amplifier (TDFA). The designs and the enhancement technique applied to the system to make it better is also presented in this chapter. Lastly, Chapter 6 presents the summary of this study and future work that can be explored in the related fields. The organization of the thesis is illustrated in Figure 1.1.

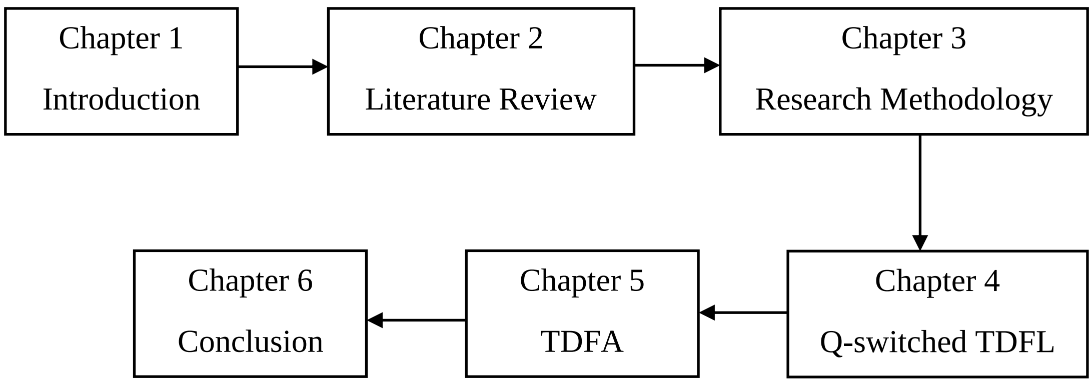

Figure 1.1 Thesis Organization

PUBLICATIONS

1. Sharif, N. M., Yusoff, N. M., Izhar, M. M., Ahmad, F., Harun, S. W., & Ahmad, H. (2016). GENERATION OF Q-SWITCHED THULIUM-DOPED FIBER LASER (TDFL) USING DIFFERENT SATURABLE ABSORBERS.*Jurnal Teknologi*, *78*(5-9) (SCOPUS INDEXED) (IF:0.43 2015)

2. N. M. Sharif, N. M. Yusoff, F. Ahmad, S. W. Harun and H. Ahmad, "Investigation of nitrogen doped graphene as saturable absorber in Thulium-Doped Fiber Laser," *2015 1st International Conference on Telematics and Future Generation Networks (TAFGEN),* , Kuala Lumpur, 2015, pp. 103-106. (SCOPUS INDEXED)

3. N. M. Sharif, N. M. Yusoff and S. A. Zaki, "Q-switched Thulium-doped fiber laser using nitrogen-doped graphene in linear and ring cavity," *2016 IEEE 6th International Conference on Photonics (ICP),* Kuching, 2016, pp. 1-3. (SCOPUS INDEXED)

4. N. M. Sharif, N. M. Yusoff, S. A. Zaki, and M. A. Mahdi, Thulium-doped Fiber Amplifier at near 2000 nm with Different Pumping Scheme (2016), **Advanced Science Letters** (to be published)

REFERENCES

Ahmad, H., Zulkifli, A. Z., Thambiratnam, K. & Harun, S. W. 2013. 2.0-M Q-Switched Thulium-Doped Fiber Laser With Graphene Oxide Saturable Absorber. *IEEE Photonics Journal,* 5.

Ahmad, M. T., Latiff, A. A., Zakaria, Z., Zen, D. I. M., Saidin, N., Haris, H., Ahmad, H. & Harun, S. W. 2014. Q-Switched Thulium-Doped Fiber Laser Operating At 1920 nm Region With Multiwalled Carbon Nanotubes Embedded In Polyvinyl Alcohol. *Microwave And Optical Technology Letters,* 56**,** 2817-2819.

Ahmed, M. H. M., Ali, N. M., Salleh, Z. S., Rahman, A. A., Harun, S. W., Manaf, M. & Arof, H. 2015. Q-Switched Erbium Doped Fiber Laser Based On Single And Multiple Walled Carbon Nanotubes Embedded In Polyethylene Oxide Film As Saturable Absorber. *Optics & Laser Technology,* 65**,** 25-28.

Ahmed, M. H. M., Salleh, Z. S., Ali, N. M., Harun, S. W. & Arof, H. 2014. Q-Switched Erbium Doped Fiber Laser Using Single-Walled Carbon Nanotubes Embedded In Polyethylene Oxide Film Saturable Absorber. *Microwave And Optical Technology Letters,* 56**,** 2734-2737.

Al-Masoodi, A. H. H., Ismail, M. F., Ahmad, F., Kasim, N., Munajat, Y., Ahmad, H. & Harun, S. W. 2014. Q-Switched Yb-Doped Fiber Laser Operating At 1073 nm Using A Carbon Nanotubes Saturable Absorber. *Microwave And Optical Technology Letters,* 56**,** 1770-1773.

Azooz, S., Harun, S. W., Ahmad, H., Halder, A., Paul, M. C., Das, S. & Bhadra, S. K. 2015. A Q-Switched Fibre Laser Operating in the 2 µm Region Based On Nonlinear Polarization Rotation Technique. *Ukrainian Journal Of Physical Optics,* 16**,** 32-37.

Bai, D. B., Li, W. X., Yang, K. W., Shen, X. L., Chen, X. L. & Zeng, H. P. 2014. Nonlinear Polarization Rotation-Induced Pulse Shaping In A Stretched-Pulse Ytterbium-Doped Fiber Laser. *Chinese Physics B,* 23.

Boguslawski, J., Sotor, J., Sobon, G., Kozinski, R., Librant, K., Aksienionek, M., Lipinska, L. & Abramski, K. M. 2015. Graphene Oxide Paper As A Saturable Absorber For Er- And Tm-Doped Fiber Lasers. *Photonics Research,* 3**,** 119-124.

Bonaccorso, F., Sun, Z., Hasan, T. & Ferrari, A. C. 2010. Graphene Photonics And Optoelectronics. *Nat Photon,* 4**,** 611-622.

Breck Hitz, J. J. E., Jeff Hecht 2001. *Introduction To Laser Technology,* New York, Institute Of Electrical And Electronics Engineers.

Canat, G., Renard, W., Lucas, E., Lombard, L., Le Gouet, J., Durecu, A., Bourdon, P., Bordais, S., And Jaouen, Y. 2014. Eyesafe High Peak Power Pulsed Fiber Lasers Limited By Fiber Nonlinearity. *Optical Fiber Technology,* 20**,** 678-687.

D. C. Hanna, R. M. P., I. R. Perry, R. G. Smart, P. J. Sunni, J. E. Townsend, And A. C. Tropper 1988. Continuos-Wave Oscillation Of A Monomode Ytterbium-Doped Fibre Laser. *Electronics Letter,* 24**,** 1111-1113.

D. C. Hanna, R. M. P., R. G. Smart, And A. C. Tropper 1990. Efficient An Tunabe Operation Of A Tm-Doped Fibre Laser. *Optics Communication,* 75**,** 283-286.

Da, L., Heping, L., Handing, X., Shangjian, Z., Yang, L., Zegao, W. & Yuanfu, C. Passively Q-Switched Linear-Cavity Erbium-Doped Fiber Laser Based On Graphene Saturable Absorber. Optical Communications And Networks (Icocn), 2013 12th International Conference On, 26-28 July 2013 2013. 1-3.

Das, G., Chaboyer, Z. J., Navratil, J. E. & Drainville, R. A. 2015. Passively Q-Switched Yb- And Sm-Doped Fiber Laser At 1064 Nm. *Optics Communications,* 334**,** 258-264.

Eisberg, R. A. R., R. 1974. *Quantum Physics Of Atoms, Molecules, Solids, Nuclei, And Particles,* New York, John Wiley & Sons, Inc.

Feng, L., Haibin, Z. & Yong, Z. 2015. High-Power Widely Tunable Q-Switched Thulium Fiber Lasers. *Laser Physics Letters,* 12**,** 095102.

Fu, S., Sheng, Q., Shi, W., Tian, X., Fang, Q. & Yao, J. 2015. 2µm Actively Q-Switched All Fiber Laser Based On Stress-Induced Birefringence And Commercial Tm-Doped Silica Fiber. *Optics & Laser Technology,* 70**,** 26-29.

Halley, P. 1987. *Fibre Optic Systems,* Great Britain, John Wiley & Sons.

Harun, S. W., Sabran, M. B. S., Azooz, S. M., Zulkifli, A. Z., Ismail, M. A. & Ahmad, H. 2015. Q-Switching And Mode-Locking Pulse Generation With Graphene Oxide Paper-Based Saturable Absorber. *The Journal Of Engineering* [Online].

Hasan, T., Sun, Z., Tan, P., Popa, D., Flahaut, E., Kelleher, E. J. R., Bonaccorso, F., Wang, F., Jiang, Z., Torrisi, F., Privitera, G., Nicolosi, V. & Ferrari, A. C. 2014. Double-Wall Carbon Nanotubes For Wide-Band, Ultrafast Pulse Generation. *Acs Nano,* 8**,** 4836-4847.

He, Y., Li, Z., Luo, H., Wang, L., Han, L. & Li, J. 2015. Cr2+: Znse Crystal Based High Power Passively Q-Switched Tm-Doped Fiber Laser. *Optics Communications,* 336**,** 84-87.

Heidt, A. M., Li, Z., Sahu, J., Shardlow, P. C., Becker, M., Rothhardt, M., Ibsen, M., Phelan, R., Kelly, B., Alam, S. U. & Richardson, D. J. 2013. 100 kW Peak Power Picosecond Thulium-Doped Fiber Amplifier System Seeded By A Gain-Switched Diode Laser At 2µm. *Optics Letters,* 38**,** 1615-1617.

Heidt, A. M., Zhihong, L. & Richardson, D. J. 2014. High Power Diode-Seeded Fiber Amplifiers At 2 µm;From Architectures To Applications. *Selected Topics In Quantum Electronics, IEEE Journal Of,* 20**,** 525-536.

Honzatko, P., Baravets, Y., Kasik, I., And Podraski, O. 2014. Wideband thulium and holmium-doped fiber source with combined forward and backward amplified spontaneous emission at 1600-2300 nm Spectral Band. *Optics Letter*, 3650-3653.

Husein, A. H. M. & El-Nahal, F. I. 2013. Optimizing the Thulium Doped Fiber Amplifier (TDFA) Gain and Noise Figure for S-Band 16 × 10 Gb/S WDM Systems. *Optik*, 124, 4052-4057.

Jackson, S. D. 2012. Towards High-Power Mid-Infrared Emission From a Fibre Laser. *Nat Photon*, 6, 423-431.

Keiser, G. 2010. *Optical Fiber Communications*, Singapore, Mcgraw-Hill.

Ken-Ichi Suzuki, Y. F., Takashi Nakanishi, Naoto Yoshimoto, and Makoto Tsubokawa 2008. Burst-Mode Optical Amplifier for Long-Reach 10gbit/S PON Application. *Optical Society Of America*.

Kivistö, S. 2010. Short Pulse Lasers Using Advanced Fiber Technology and Saturable Absorbers. *Tampereen Teknillinen Yliopisto. Julkaisu-Tampere University Of Technology. Publication; 889*.

Kivistö, S., Koskinen, R., Paajaste, J., Jackson, S. D., Guina, M. & Okhotnikov, O. G. 2008. Passively Q-Switched Tm3+, Ho3+-Doped Silica Fiber Laser Using a Highly Nonlinear Saturable Absorber and Dynamic Gain Pulse Compression. *Optics Express*, 16, 22058-22063.

Kozak, M. M., Caspary, R. & Kowalsky, W. Thulium-Doped Fiber Amplifier for the S-Band. Transparent Optical Networks, 2004. Proceedings Of 2004 6th International Conference on, 4-8 July 2004 2004. 51-54 Vol.2.

Li, Z., Heidt, A. M., Daniel, J. M., Jung, Y., Alam, S. U. & Richardson, D. J. 2013. Thulium-Doped Fiber Amplifier for Optical Communications at 2 micron. *Opt Express*, 21, 9289-97.

Li, Z., Heidt, A. M., Daniel, J. M. O., Jung, Y., Alam, S. U., Richardson, D. J. 2013. Thulium-Doped Fiber Amplifier for Optical Communication at 2 µm. *Optics Express*, 9289-9297.

Li, Z., Jung, Y.-M., Daniel, J. M. O., Simakov, N., Shardlow, P. C., Heidt, A. M., Clarkson, A., Alam, S.-U. & Richardson, D. J. Extreme Short Wavelength Operation (1.65 - 1.7 µm) of Silica-Based Thulium-Doped Fiber Amplifier. Optical Fiber Communication Conference, 2015/03/22 2015 Los Angeles, California. Optical Society of America

Lu, B., Chen, H., Jiang, M., Chen, X., Ren, Z. & Bai, J. 2013. Graphene-Based Passive Q-Switching for a 2 µm Thulium-Doped Fiber Laser. *Laser Physics,* 23.

Lucas, E., Lombard, L., Jaouën, Y., Bordais, S. & Canat, G. 2014. 1 kW and 2 kW Peak Power, 110 ns Single-Frequency Thulium Doped Fiber Amplifier at 2050 nm. *Applied Optics,* 53**,** 4413-4419.

Luo, Z. Q., Huang, Y. Z., Zhong, M., Li, Y. Y., Wu, J. Y., Xu, B., Xu, H. Y., Cai, Z. P., Peng, J. & Weng, J. 2014. 1-, 1.5-, and 2 µm Fiber Lasers Q-Switched By A Broadband Few-Layer Mos2 Saturable Absorber. *Journal Of Lightwave Technology,* 32**,** 4077-4084.

Maiman, T. H. 1960. Stimulated Optical Radiation In Ruby. *Nature,* 187**,** 493-494.

Martinez, A. & Yamashita, S. 2011. *Carbon Nanotube-Based Photonic Devices: Applications In Nonlinear Optics*, Intech Open Access Publisher.

Mohamad, H., Yusoff, N. M., Abu Bakar, M., Shahabuddin, N., Abdul-Rashid, H., Yusoff, Z., Ismail, A., Anas, S. A. & Mahdi, M. Ultrashort Pulse Laser Generation in Ring-type EDFL using Carbon-Nanotube Saturable Absorber. Photonics (Icp), 2011 Ieee 2nd International Conference On, 2011. IEEE, 1-3.

N/A. (2016, December 3). *Optical Fibers*. Retrieved from Nufern: http://www.nufern.com/pam/optical_fibers/1051/SM-TSF-9/125/

N. Md. Yusoff, A. A. 2012. Bidirectional-Pumped L-Band Erbium-Doped Fiber Amplifier with Pump Distribution Technique. *Laser Physics***,** 1-5.

Nagel, J. M. P. D. A. J. A. 1995. Multi-Stage Erbium-Doped Fiber Amplifier Designs. *Journal Of Lightwave Technology,* 13**,** 703-720.

Palais, J. C. 1992. *Fiber Optic Communications,* New Jersey, Prentice Hall.

Philippe C. Becker, N. A. O., and Jay R. Simpson 1999. *Erbium-Doped Fiber Amplifiers, Fundamenals And Technology,* London, Academic Press.

Powers, J. 1996. *An Introduction To Fiber Optic Systems,* Tom Casson.

Richardson, D. J., Nilsson, J. & Clarkson, W. A. 2010. High Power Fiber Lasers: Current Status and Future Perspectives [Invited]. *Journal Of The Optical Society Of America B,* 27**,** B63.

Saidin, N., Zen, D. I. M., Ahmad, F., Damanhuri, S. S. A., Ahmad, H., Dimyati, K. & Harun, S. W. 2014. Q-Switched Thulium-Doped Fibre Laser Operating at 1900 nm Using Multi-Layered Graphene Based Saturable Absorber. *Optoelectronics, Iet,* 8**,** 155-160.

Schmidt, A., Rivier, S., Cho, W. B., Yim, J. H., Choi, S. Y., Lee, S., Rotermund, F., Rytz, D., Steinmeyer, G., Petrov, V. & Griebner, U. 2009. Sub-100 Fs Single-Walled Carbon Nanotube Saturable Absorber Mode-Locked Yb-Laser Operation Near 1 µm. *Optics Express,* 17**,** 20109-20116.

Shi, W., Fang, Q., Zhu, X., Norwood, R. A. & Peyghambarian, N. 2014. Fiber Lasers and Their Applications [Invited]. *Applied Optics,* 53**,** 6554-6568.

Shi, W., Fang, Q., Zhu, X., Norwood, R. A., And Peyghambarian, N. 2014. Fiber Lasers And Their Applications [Invited]. *Applied Optics***,** 6554-6568.

Simakov, N., Li, Z., Alam, S.-U., Shardlow, P. C., Daniel, J. M. O., Jain, D., Sahu, J. K., Hemming, A., Clarkson, A. & Richardson, D. J. Holmium Doped Fiber Amplifier for Optical Communications at 2.05 - 2.13 µm. Optical Fiber Communication Conference, 2015/03/22 2015 Los Angeles, California. Optical Society of America

Simakov, N., Li, Z., Alam, S. U., Shardlow, P. C., Daniel, J. M. O., Jain, D., Sahu, J. K., Hemming, A., Clarkson, A., Richardson, D. J. Holmium Doped Fiber Amplifier for Optical Communications At 2.05-2.13 µm. Optical Fiber Communication Conference, 2015 Los Angeles. Optical Society of America.

Snitzer, C. J. K. A. E. 1964. Amplification In Fiber Laser. *Applied Optics,* 3**,** 1182-1186.

Sobon, G., Sotor, J., Jagiello, J., Kozinski, R., Librant, K., Zdrojek, M., Lipinska, L. & Abramski, K. M. 2012. Linearly Polarized, Q-Switched Er-Doped Fiber Laser Based on Reduced Graphene Oxide Saturable Absorber. *Applied Physics Letters*, 101**,** 241106.

Soref, R. 2015. Group Iv Photonics: Enabling 2 μm Communications. *Nat Photon,* 9**,** 358-359.

Sun, Y., Srivastava, A. K., Zhou, J. & Sulhoff, J. W. 1999. Optical Fiber Amplifiers for WDM Optical Networks. *Bell Labs Technical Journal,* 4**,** 187-206.

Tanabe, S. 2015. Glass and Rare-Earth Elements: A Personal Perspective. *International Journal Of Applied Glass Science***,** N/A-N/A.

Tang, Y., Yu, X., Li, X., Yan, Z. & Wang, Q. J. 2014. High-Power Thulium Fiber Laser Q Switched with Single-Layer Graphene. *Optics Letters,* 39**,** 614-617.

Tian, Y. 2012. Optical Properties of Single-Walled Carbon Nanotubes and Nanobuds.

Tiu, Z. C., Zarei, A., Tan, S. J., Ahmad, H. & Harun, S. W. 2014. Q-Switching Pulse Generation with Thulium-Doped Fiber Saturable Absorber. *Chinese Physics Letters,* 31.

Wang, Z. T., Zou, Y. H., Chen, Y., Wu, M., Zhao, C. J., Zhang, H. & Wen, S. C. 2013. Graphene Sheet Stacks for Q -Switching Operation of an Erbium-Doped Fiber Laser. *Laser Physics Letters,* 10**,** 075102.

Xia, H., Li, H., Wang, Z., Chen, Y., Zhang, X., Tang, X. & Liu, Y. 2014. Nanosecond Pulse Generation in a Graphene Mode-Locked Erbium-Doped Fiber Laser. *Optics Communications,* 330**,** 147-150.

Yamada, M., Ono, H. & Ono, J. 1.7 μm Band Optical Fiber Amplifier. Optical Fiber Communication Conference, 2014/03/09 2014 San Francisco, California. Optical Society of America

Yusoff, N. M., Abas, A. F., Hitam, S. & Mahdi, M. A. 2012. Dual-Stage L-Band Erbium-Doped Fiber Amplifier with Distributed Pumping From Single Pump Laser. *Optics Communications,* 285**,** 1383-1386.

Z. Li, A. M. H., N. Simakov, Y. Jung, J. M. O. Daniel, S. U. Alam, and D. J. Richardson 2013. Diode-Pumped Wideband Thulium-Doped Fiber Amplifiers for Optical Communications in the 1800-2050 nm Window. *Optics Express*.

Zhang, H., Kavanagh, N., Li, Z., Zhao, J., Ye, N., Chen, Y., Wheeler, N. V., Wooler, J. P., Hayes, J. R., Sandoghchi, S. R., Poletti, F., Petrovich, M. N., Alam, S. U., Phelan, R., O'carroll, J., Kelly, B., Grüner-Nielsen, L., Richardson, D. J., Corbett, B. & Garcia Gunning, F. C. 2015. 100 Gbit/S WDM Transmission at 2 µm: Transmission Studies in Both Low-Loss Hollow Core Photonic Bandgap Fiber and Solid Core Fiber. *Optics Express,* 23**,** 4946-4951.

Zhang, M., Kelleher, E. J. R., Torrisi, F., Sun, Z., Hasan, T., Popa, D., Wang, F., Ferrari, A. C., Popov, S. V. & Taylor, J. R. 2012. Tm-Doped Fiber Laser Mode-Locked by Graphene-Polymer Composite. *Optics Express,* 20**,** 25077-25084.

Zhang, M., Kelleher, E. J. R., Popov, S. V., And Taylor, J. R. 2014. Ultrafast Fibre Laser Sources: Examples of Recent Developments. *Optical Fiber Technology,* 20**,** 666-677.

Zhou, B., Lin, H. & Pun, E. Y. 2010. Tm3+-Doped Tellurite Glasses for Fiber Amplifiers in Broadband Optical Communication at 1.20 micron Wavelength Region. *Opt Express,* 18**,** 18805-10.