UNIVERSITI PUTRA MALAYSIA

DESIGN AND DEVELOPMENT OF A NOVEL TUNABLE ERBIUM-DOPED FIBER LASER

MOHAMMED ALFAYTURI S. HOWIEG

FK 2003 24
DESIGN AND DEVELOPMENT OF A NOVEL TUNABLE ERBIUM-DOPED FIBER LASER

BY

MOHAMMED ALFAYTURI S. HOWIEG

Thesis Submitted to the School of Graduate Studies, Universiti Putra Malaysia, in Fulfilment of the Requirements for the Degree of Master of Science

May 2003
In the name of God, Most Gracious, Most Merciful

Dedication to

My parents and all of my family members
Abstract of thesis presented to the Senate of University Putra Malaysia in Fulfilment of the requirements for the degree of Master of Science

DESIGN AND DEVELOPMENT OF A NOVEL TUNABLE ERBIUM-DOPED FIBER LASER

By

MOHAMMED ALFAYTURI S. HOWIEG

May 2003

Chairman : Associate Professor Mohd Khazani Abdullah, Ph.D.

Faculty : Engineering

Widely tunable single channel fiber lasers operating in the 1550nm wavelength region are needed as laser source for applications such as wavelength-division-multiplexed (WDM) communication systems, fiber sensors, spectroscopy, and optical fiber gyroscopes.

Fiber lasers are emerging as an attractive alternative technology for wavelength-selectable WDM source for direct compatibility with fiber-optic transmission medium, excellent amplifying properties of rare-earth doped fibers, rapidly continuing progress in novel fiber gain media, maturity and robustness of the laser diode pumps used, and availability of fiber-based components.

The tunable laser applications of interest in this work have distinct performance requirement, which is the need for wide tunability (the ability to tune the lasing emission through a wide range of wavelengths).
In this thesis, the design and development of a single channel continuous wave erbium-doped fiber laser (EDFL), with novel loop mirror configuration, is experimentally studied. Based on design parameters of a fiber laser (launched pump powers, erbium-doped fiber lengths and output reflectivities of fiber laser), three fiber laser configurations; backward, forward, and bi-directional pumping are demonstrated. Throughout this work different lengths of erbium-doped fiber with various output reflectivities have been examined to extract the optimum output performance of a fiber laser. The performance of the fiber laser is presented in terms of threshold pump power, slope of efficiency, output peak power, linewidth, tuning range, and side mode suppression ratio (SMSR). This new fiber loop configuration exhibits considerably high performance. Output power of 27.7 mW and efficient noise suppression of more than 70 dB have been achieved. A threshold power as low as 2.5 mW and slope efficiency of 20% is realized. Narrow spectral width of 0.058 nm over a tuning range of 40 nm is obtained.
Abstrak tesis yang dikemukakan kepada Senat Universiti Putra Malaysia sebagai memenuhi keperluan untuk ijazah Master Sains

REKABENTUK DAN PEMBINAAN NOBEL UNTUK GENTIAN LASER BOLEH
TALA TERDOP ERBIUM BOLEH TALA

Oleh
MOHAMMED ALFAYTURI S. HOWIEG

Mei 2003

Pengerusi : Associate Professor Mohd Khazani Abdullah, Ph.D.

Fakulti : Kejuruteraan

Laser boleh tala beroperasi dalam julat gelombang 1550 nm dan diperlukan dalam aplikasi seperti sistem komunikasi pemultipleks bahagi jarak gelombang (WDM), sensor gentian optik, spektroskopi dan giroskop gentian optik.

Laser gentian kini muncul sebagai teknologi alternatif untuk sistem WDM jarak gelombang terpilih kerana keserasiannya sebagai punca cahaya untuk gentian optik. Selain dari faktor keserasian, keupayaan gentian optik jenis bumi nadir untuk mengamplifikasikan isyarat kecil, keteguhan/kelasakan pam diod laser dan ketersediaan komponen asas gentian optik merupakan beberapa faktor lain yang menyebabkan laser gentian mula mendapat perhatian.

Laser boleh tala yang diselidiki memerlukan keperluan prestasi yang berbeza dari laser biasa iaitu ia memerlukan laser ini ditala pada jarak gelombang yang lebar.
Dalam tesis ini, rekabentuk dan pembangunan laser gelombang selanjut konfigurasi unggul yang didopan menggunakan bahan Erbium dengan keluaran saluran tunggal akan dikaji.

Berdasarkan parameter rekabentuk laser gentian iaitu kuasa masukan pam, panjang gentian optik dopan Erbium dan nisbah kuasa keluaran laser gentian, tiga jenis konfigurasi akan dikaji iaitu konfigurasi laser dengan pam kehadapan, kebelakang dan kedua-dua arah pam. Di dalam ujikaji menggunakan konfigurasi yang dinyatakan, panjang gentian optik Erbium yang berbeza dengan nisbah keluaran kuasa yang berbeza akan dikaji bagi mencapai prestasi (nilai ambang pam, kecekapan laser, keluaran kuasa puncak, garis lebar, julat jarak gelombang dan SMSR) laser gentian yang terbaik.

Konfigurasi laser gentian yang dihasilkan mempunyai nilai keluaran kuasa sebanyak 27.7 mW dan kecekapan SMSR lebih dari 70 dB. Nilai ambang untuk penghasilan laser serendah 2.5 mW dengan kecekapan 20% disamping lebar garis 0.058 nm bagi jarak tala 40 nm telah diperolehi.
ACKNOWLEDGEMENTS

First of all, I would like to express my greatest gratitude to ALLAH the almighty, for his help and support during the course of life and moment of truth.

I would like to thank and to acknowledge the people who have helped and encouraged me in the last two years as I worked toward my master. First I want to thank my supervisor Associate Professor Dr. Mohamad Khazani Abdullah. I am profoundly grateful for his tremendous support, encouragement, careful reading, and mentoring through my research.

I am also grateful to my committee members, Professor W. Mahmood Mat Yunus and Associate Professor Dr. Kaharudin Dimyati for their help, quick response and valuable suggestions. Special thanks go to Mr. Bouzid Belloui for his support and constructive suggestions. I thank him for the advice, wisdom, and encouragement he has shared with me through my work.

I would like to thank my home mates Ramadan Rajab, Ahmed Mustafa, Omar Abossada and my brother Abdurrahman for their encouragement and understanding. They were always there for me whenever I needed help, someone to discuss burning problems, or just a good joke to bring up my spirit.
I would also like to thank my colleagues, Mohamed Al-Mansoori, Aiman Kaser, Shamsuri ben Ali, Suhaire, Ahmed Ashrif, Naseer matrood, Ahmed Shukri, mohamad Hamarsheh, Hisham Zuhdi, and Fairuze Abdullah for their friendship, support, and encouragement.

Last, but definitely not least, there is no word can express my gratitude to my parents, brothers and sisters for their great sacrifice and unlimited support.
# TABLE OF CONTENTS

<table>
<thead>
<tr>
<th>DEDICATION</th>
<th>ii</th>
</tr>
</thead>
<tbody>
<tr>
<td>ABSTRACT</td>
<td>iii</td>
</tr>
<tr>
<td>ABSTRAK</td>
<td>v</td>
</tr>
<tr>
<td>ACKNOWLEDGEMENTS</td>
<td>vii</td>
</tr>
<tr>
<td>APPROVELS</td>
<td>ix</td>
</tr>
<tr>
<td>DECLARATION</td>
<td>xi</td>
</tr>
<tr>
<td>TABLE OF CONTENTS</td>
<td>xii</td>
</tr>
<tr>
<td>LIST OF TABLES</td>
<td>xvi</td>
</tr>
<tr>
<td>LIST OF FIGURES</td>
<td>xix</td>
</tr>
<tr>
<td>LIST OF ABBREVIATION</td>
<td></td>
</tr>
</tbody>
</table>

## CHAPTERS

1 INTRODUCTION

1.1 Background          1
1.2 What is Fiber Laser 2
1.3 Merits of Fiber Lasers 5
1.4 Problem Statement   6
1.5 Research Objectives 6
1.6 Organization of the Thesis 7

2 LITERATURE REVIEW OF FIBER LASERS

2.1 Introduction        8
2.2 Background Review of Erbium-Doped Fiber Lasers 8
2.3 Critical Review of Fiber laser 10
2.4 Optical Resonators for CW Fiber Laser 17
   2.4.1 Fabry Perot Resonator 17
   2.4.2 All-fiber Fabry-Perot Resonator 18
   2.4.3 All-fiber Ring Resonator 19
   2.4.4 Fox-Smith Resonator 20
2.5 Summary 21

3 BASIC PRINCIPLE OF ERBIUM-DOPED FIBER LASERS

3.1 Introduction        22
3.2 Theoretical Models  22
   3.2.1 Pump and Gain  23
   3.2.2 Threshold Power and Slope Efficiency 27
      3.2.2.1 Threshold Power 27
      3.2.2.2 Slope Efficiency 28
   3.2.3 Spectral Width and Tuning Range 30
      3.2.3.1 Spectral Width 30
      3.2.3.2 Tuning Range 32
3.2.4 Side Mode Suppression Ratio (SMSR)  
3.3 Longitudinal Modes Operation of Fiber Lasers  
3.4 Summary  

4 METHODOLOGY  
4.1 Introduction  
4.2 Fiber Laser Parameters under Study  
4.2.1 Design Parameters  
4.2.1.1 Pump Power and Wavelength  
4.2.1.2 Output Reflectivity  
4.2.1.3 Length of the Active Material  
4.2.2 Performance Parameters  
4.2.2.1 Output Peak Power  
4.2.2.2 Threshold Pump Power and Slope of Efficiency  
4.2.2.3 Tuning Range  
4.2.2.4 Side Mode Suppression Ratio (SMSR)  
4.2.2.5 Spectral Width  
4.3 Related Fiber Laser Components  
4.3.1 Pump Source  
4.3.2 Gain Medium and Splicing  
4.3.3 Optical Circulators  
4.3.4 Optical Filters  
4.4 Experimental Setup  
4.5 Principle of Operation  
4.6 Summary  

5 RESULTS AND DISCUSSIONS  
5.1 Introduction  
5.2 Experimental Results and Discussion of the Fiber Laser Design with Backward Pump Power  
5.2.1 Threshold Pump Power and Slope of Efficiency  
5.2.2 Output Peak Power  
5.2.3 Tuning Range and Spectral Width  
5.2.4 Side Mode Suppression Ratio (SMSR)  
5.3 Experimental Results and Discussion of the Fiber Laser Design with Bidirectional Pump Power  
5.3.1 Threshold Power and Slope Efficiency  
5.3.2 Output Peak Power  
5.3.3 Tuning Range and Spectral Width  
5.3.4 Side Mode Suppression Ratio (SMSR)  
5.4 Summary  

6 CONCLUSION AND FUTURE WORK  
6.1 Conclusion  
6.2 Future Work  
REFERENCES
APPENDICES
APPENDIX A  85
APPENDIX B  86

BIODATA OF AUTHORS

xiv
# LIST OF TABLES

<table>
<thead>
<tr>
<th>Table</th>
<th>Description</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>2.1</td>
<td>Wavelengths emitted by rare-earth-doped fiber lasers</td>
<td>10</td>
</tr>
<tr>
<td>4.1</td>
<td>Specifications of EDF</td>
<td>51</td>
</tr>
<tr>
<td>4.2</td>
<td>Performance Specification of optical circulator</td>
<td>52</td>
</tr>
<tr>
<td>4.3</td>
<td>Specifications of the tunable filters employed in this work</td>
<td>53</td>
</tr>
</tbody>
</table>
# LIST OF FIGURES

<table>
<thead>
<tr>
<th>Figure</th>
<th>Description</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.1</td>
<td>Fiber laser configurations</td>
<td>4</td>
</tr>
<tr>
<td>2.1</td>
<td>MOPA configuration with fiber Bragg grating</td>
<td>15</td>
</tr>
<tr>
<td>2.2</td>
<td>A Setup of erbium-doped fiber ring laser</td>
<td>16</td>
</tr>
<tr>
<td>2.3</td>
<td>Schematic diagram of Fabry-Perot resonator</td>
<td>18</td>
</tr>
<tr>
<td>2.4</td>
<td>Schematic diagram of all-fiber Fabry-Perot resonator</td>
<td>19</td>
</tr>
<tr>
<td>2.5</td>
<td>Schematic diagram of All-fiber Ring Resonator</td>
<td>20</td>
</tr>
<tr>
<td>2.6</td>
<td>Schematic diagram of a Fox-Smith resonator</td>
<td>21</td>
</tr>
<tr>
<td>3.1</td>
<td>Relevant energy levels of Er$^{3+}$ in silica glasses</td>
<td>23</td>
</tr>
<tr>
<td>3.2</td>
<td>Absorption spectrum of an erbium doped silica fiber</td>
<td>24</td>
</tr>
<tr>
<td>3.3</td>
<td>Absorption and emission cross-section of EDF</td>
<td>25</td>
</tr>
<tr>
<td>3.4</td>
<td>Spectral width of the optical signal on an actual spectrum</td>
<td>31</td>
</tr>
<tr>
<td>3.5</td>
<td>SMSR of the output optical signal</td>
<td>33</td>
</tr>
<tr>
<td>3.6</td>
<td>Number of groups of modes oscillates in the laser cavity</td>
<td>37</td>
</tr>
<tr>
<td>4.1</td>
<td>Threshold pump power of fiber laser at 90% output reflectivity and 10 m EDF</td>
<td>45</td>
</tr>
<tr>
<td>4.2</td>
<td>Tuning range of the optical band pass filters as measured by (OSA)</td>
<td>46</td>
</tr>
<tr>
<td>4.3</td>
<td>SMSR of output optical signal of 18m EDFL and 90% output reflectivity.</td>
<td>47</td>
</tr>
<tr>
<td>4.4</td>
<td>Optical spectrum of 980 nm laser module as measured by (OSA)</td>
<td>49</td>
</tr>
<tr>
<td>4.5</td>
<td>Output power as function of drive current</td>
<td>50</td>
</tr>
<tr>
<td>4.6</td>
<td>Three ports optical fiber circulator</td>
<td>52</td>
</tr>
</tbody>
</table>
4.7 Experimental setup of loop mirror erbium-doped fiber laser with bi-directional pump power

4.8 Experimental setup of loop mirror erbium-doped fiber laser with backward pump power

4.9 Experimental setup of loop mirror erbium-doped fiber laser with forward pump power

5.1 Output Power versus Pump Power for Different Output Reflectivities

5.2 Pump Power versus Output Peak Power to Show the Threshold Powers for Different EDF Lengths

5.3. Output Power versus Output Reflectivities for Different Pump Powers

5.4. Output Power over Tuning Range of EDFL with 5nm Step for Different Output Reflectivities

5.5. Tuning Range of the Fiber Laser as Measured by using Optical Spectrum Analyzer (OSA)

5.6 Erbium-Doped Fiber Gain with the Limitation of the TBPFs

5.7 Erbium-Doped Fiber Gain without the TBPFs

5.8 Spectrum Width of the Output Optical Signal Measured by (OSA)

5.9 Effect of the Coupler Position on SMSR

5.10 SMSR over 40nm Tuning Range for Different Output Reflectivities

5.11 Output Power against Pump Power to Show the Threshold Point and Slope Efficiency

5.12 Output Peak Power versus Wavelength at Different Output Reflectivities

5.13 Output Peak Power as Measured by using (OSA)

5.14 Output Spectral Widths of the Fiber Laser over All Tuning Range
5.15 Output Spectral Width of the Fiber Laser 76
5.16 SMSR of the Fiber Laser by Placing the TBPF after the Output Coupler 77
# LIST OF ABBREVIATIONS

<table>
<thead>
<tr>
<th>Abbreviation</th>
<th>Definition</th>
</tr>
</thead>
<tbody>
<tr>
<td>ACS</td>
<td>Absorption Cross-Section</td>
</tr>
<tr>
<td>ASE</td>
<td>Amplified Spontaneous Emission</td>
</tr>
<tr>
<td>BPF</td>
<td>Band Pass Filter</td>
</tr>
<tr>
<td>CW</td>
<td>Continuous Wave</td>
</tr>
<tr>
<td>ECS</td>
<td>Emission Cross-Section</td>
</tr>
<tr>
<td>EDF</td>
<td>Erbium Doped Fiber</td>
</tr>
<tr>
<td>EDFL</td>
<td>Erbium Doped Fiber Laser</td>
</tr>
<tr>
<td>ESA</td>
<td>Excited State Absorption</td>
</tr>
<tr>
<td>FBG</td>
<td>Fiber Bragg Grating</td>
</tr>
<tr>
<td>FP</td>
<td>Fabry-Perot</td>
</tr>
<tr>
<td>FWHM</td>
<td>Full Width Half Maximum</td>
</tr>
<tr>
<td>GSA</td>
<td>Ground State Absorption</td>
</tr>
<tr>
<td>LDM</td>
<td>Laser Diode Module</td>
</tr>
<tr>
<td>LED</td>
<td>Laser Emitting Diode</td>
</tr>
<tr>
<td>MOPA</td>
<td>Master-Oscillator Power-Amplifier</td>
</tr>
<tr>
<td>NA</td>
<td>Numerical Aperture</td>
</tr>
<tr>
<td>OSA</td>
<td>Optical Spectrum Analyzer</td>
</tr>
<tr>
<td>RIN</td>
<td>Relative Intensity Noise</td>
</tr>
<tr>
<td>SLM</td>
<td>Single-longitudinal Mode</td>
</tr>
<tr>
<td>SMF</td>
<td>Single Mode Fiber</td>
</tr>
<tr>
<td>SMSR</td>
<td>Side Mode Suppression Ratio</td>
</tr>
<tr>
<td>TBPF</td>
<td>-</td>
</tr>
<tr>
<td>--------</td>
<td>-----</td>
</tr>
<tr>
<td>WDM</td>
<td>-</td>
</tr>
</tbody>
</table>
CHAPTER 1

INTRODUCTION

1.1 Background

Optical fiber communications are systems that employ optical wave as information carrier and optical fiber as information transmission line. In theory the greater the carrier frequency, the larger the available transmission bandwidth and thus the information-carrying capacity of the communication systems. Such a system at optical frequencies offers an increase in the potential usable bandwidth by a factor of 103 over traditional microwave transmission [Li Wei, 2000]. The proposal for optical communication via optical fibers was made almost simultaneously in 1966 by Kao and Hockham and Werts. It is obvious that the suitable optical source and the optical fiber are the key elements for the development of optical fiber communication. Although, previously the availability of laser sources had stimulated research into optical fiber communication, optical fiber communication was not considered to be practical until 1970, when optical fiber technology had advanced to a point where the fiber with loss of 0.2 dB/km or less was achieved [Kapron, Keck, and Maurer, 1970]. Since then, silica fiber and optoelectronics including laser sources have been the subject of large-scale world wide research and product development. As a result, optical fiber communication is established today as one of the most promising technologies within the area of short and long distance data transmissions [Green, 1993 and Arieli, 2003].
The development of technology in optical fiber communication systems has passed through a few distinct stages to increase the capacity of the optical systems. It is found that the ultimate capacity is determined by the quality of the optical source and the fiber [Agrawal, 1992]. The optical source has advanced from broad-spectrum LEDs to multi-mode laser diodes and then to single-mode laser diodes.

The progress in the optical source plays a very important rule in minimizing the dispersion, a major factor limiting the performance. For example, a laser source with a very narrow linewidth would be very desirable; Fiber lasers have the potential of being an excellent candidate as a source in optical communication systems [Mizrahi and Digiovanni 1993, Zyskind and Sulhoff 1993]. Compared to the laser diode, whose linewidths are limited by the short cavity length. A fiber laser [Lee, 1998 and Gloag, 1996] could have a much narrower linewidth. A linewidth as narrow as 0.95 kHz was obtained in fiber laser [Gloa, 1996]. Moreover, fiber lasers are the most natural source for fiber-optic communications, since the light is already in the fiber and they can be directly spliced to the systems.

1.2 What is a Fiber Laser

A fiber laser is a laser system, which uses a piece of specially doped fiber as the active medium. Different types of dopants in different host materials give different characteristics of the laser system [Abdullah, 1999]. Silica is the most popular material as a host while fluoride is also being used for different purposes. Rare earth ions such as erbium and ytterbium are the
most widely used dopants to emit signals at 1550nm and 1310nm wavelengths respectively. The principles behind a fiber laser are the same as in any other solid-state lasers, with amplification accruing via stimulated emission. In common with other lasers it has a non-linear output power with respect to the pump power. Below the threshold pump power where the gain is the same as the cavity loss, the output from the device is incoherent and composed mainly of spontaneous emission. At pump power greater than this, the gain remains clamped at the cavity loss with the output from the device being contained in a narrower bandwidth of coherent radiation. Above threshold, the output power normally has a linear yield with respect to pump power. It is useful to define a parameter termed as slope efficiency of the laser, $\eta_s$, which is given by the expression $\eta_s = \Delta P_{\text{out}} / \Delta P_{\text{pump}}$ where $\Delta P_{\text{out}}$ is the change in output power for the change of pump power of $\Delta P_{\text{pump}}$ when the laser is operating above threshold.

Fiber lasers can generally be designed in two configurations that are the Fabry-Perot or rectilinear configuration and the ring configuration [Abdullah, 1999]. Figure 1.1 shows the schematics of the two configurations. In this study fiber loop back mirror linear cavity configuration is employed as the fiber laser design.
Figure 1.1: Fiber laser configurations, (a) Fabry-Perot or linear cavity, (b) ring cavity