UNIVERSITI PUTRA MALAYSIA

NONLINEAR FIBER OPTICAL PARAMETRIC AMPLIFIERS AND LASERS WITH IDLER REMOVAL FILTER

YEO KWOK SHIEN

FK 2013 18
NONLINEAR FIBER OPTICAL PARAMETRIC AMPLIFIERS AND LASERS WITH IDLER REMOVAL FILTER

By

YEOW KWOK SHIEN

Thesis Submitted to the School of Graduate Studies, Universiti Putra Malaysia, in Fulfillment of the Requirements for the Degree of Doctor of Philosophy

December 2013
All material contained within the thesis, including without limitation text, logos, icons, photographs and all other artwork, is copyright material of Universiti Putra Malaysia unless otherwise stated. Use may be made of any material contained within the thesis for non-commercial purposes from the copyright holder. Commercial use of material may only be made with the express, prior, written permission of Universiti Putra Malaysia.

Copyright © Universiti Putra Malaysia
To my beloved parents
Abstract of thesis presented to the Senate of Universiti Putra Malaysia in fulfillment of the requirement for the degree of Doctor of Philosophy

NONLINEAR FIBER OPTICAL PARAMETRIC AMPLIFIERS AND LASERS WITH IDLER REMOVAL FILTER

By

YEO KWOK SHIEN

December 2013

Chair: Mohd Adzir Mahdi, PhD

Faculty: Engineering

Nonlinear phenomena in optical fiber have been seen detrimental to the performance of fiber optical communication systems; however, in many niche areas optical fiber nonlinear properties are very much desired. Nonlinear Four-wave mixing (FWM) process in optical fiber is generally referred as fiber optical parametric process, for the reason that fiber parameters are deliberately designed to enhance the efficiency of FWM. Among the most important parameters that define the parametric process are the chromatic dispersion profile (related to second-order dispersion), dispersion slope (related to forth-order dispersion), zero-dispersion wavelength and fiber nonlinear coefficient. Silica-based highly nonlinear fibers (HNLFs) are the fiber medium of choice in most parametric experiments mainly because of its excellent fiber attenuation performance and low splice-loss when connected to standard single mode fiber (SMF). Even though HNLF and SMF are both silica-host optical fibers, they are nevertheless incompatible in several fiber characteristics, in which most prominently is their fiber dispersion profile. Incorporating HNLF to an SMF-based system would lead to a phenomenon known as wavelength-dependent gain modulation, where parametric gain ripples exist across the spectrum, with peak and notch gain difference as much as 20 dB. The origin of the gain ripples is investigated theoretically and experimentally. Investigation indicates that by suppressing the idler power by 60 dB, the gain ripples can be smoothened and thus restore the original gain shape of the parametric devices, but with tolerable gain loss around 6 dB. The idler removal filters (IRFs) then become the key enabling device for fiber optical parametric devices with two-segment design as well as double-pass pump configuration. Properly designed IRFs are proven to successfully smoothen gain ripples that exist in a two-segment fiber optical parametric amplifier (FOPA). Experiments also show that a parametric gain improvement of 10 dB is achieved in FOPA with double-pass pump configuration at 1.05 W pump power, and gain slope of 47.5 dB/W has been achieved. The power penalty at bit error rate $10^{-6}$ is found to be within 5 dB for this double-pass FOPA design, which successfully addresses the practicability issue of this special kind of FOPA design. The IRF is extended in fiber optical parametric oscillator (FOPO) to realize double-pass design FOPO. Besides
the significant laser tuning wavelength improvement (72 nm @ 0.45 W, limited by wavelength range of tunable bandpass filter), the double-pass pump FOPO achieves as high as 51% threshold power improvement as compared to the conventional configuration, in addition maintaining laser peak stability within 2 dB.
Abstrak tesis yang dikemukakan kepada Senat Universiti Putra Malaysia sebagai memenuhi keperluan untuk ijazah Doktor Falsafah

PENGUAT PARAMETRIK GENTIAN OPTIK DAN LASER TIDAK LINEAR DENGAN TURAS PENAPISAN IDLER

Oleh

YEOK KWOK SHIEN

Disember 2013

Pengerusi: Mohd Adzir Mahdi, PhD

Fakulti: Kejuruteraan

Dalam kebanyakan masa, fenomena tidak linear dalam gentian optik dilihat sebagai sesuatu yang akan menjejaskan prestasi sistem komunikasi optik. Tetapi dalam keadaan tertentu, fenomena tidak linear gentian adalah dikehendaki. Pergaulan empat gelombang tidak linear (‘Four-wave Mixing’, FWM) dikenali sebagai proses parametrik, disebabkan pelbagai penyesuaian teliti atas parameter gentian boleh menjana proses tersebut dengan berkesan. Antara parameter-parameter penentu yang penting untuk menjana proses parametrik efektif termasuklah penyerakan kromat gentian, kecerunan penyerakan, jarak gelombang penyerakan sifar dan pekali tidak linear gentian. Gentian silika amat tidak linear (‘highly nonlinear fiber’, HNLF) adalah medium gentian popular yang digunakan dalam kebanyakan eksperimen disebabkan ia mempunyai ciri-ciri seperti kehilangan kuasa minimum sama ada ketika penyaluran ataupun cantuman dengan gentian mod tunggal (‘single mode fiber’, SMF). Walaupun HNLF dan SMF adalah gentian silika, tetapi mereka mempunyai parameter-parameter gentian yang amat berbeza, antara percanggahan yang utama adalah kepadanan dari segi penyerakan kromat. Akibatnya, pemodulatan gandaan bergantung dengan jarak gelombang akan berlaku di mana riak gandaan parametrik dengan nisbah setinggi 20 dB akan wujud di seluruh spektrum. Tesis ini menyiasat asal-usul riak gandaan tersebut secara teori dan experimen. Siasatan menunjukan pengecilan kuasa idler sebanyak 60 dB dapat menghapuskan riak gandaan tetapi akan mengakibatkan pegecilan gandaan sebanyak 6 dB yang dianggap munasabah. Dengan rekacipta turas penapisan idler (IRF) yang bersesuaian, riak gandaan dalam penguat gentian optik parametrik jenis dua segmen dapat ditangani. Keputusan eksperimen-eksperimen menyatakan dengan konfigurasi lintas-kembar, peningkatan gandaan sebanyak 10 dB dicapai oleh penguat isyarat parametric dengan hanya 1.05 W kuasa pam, dan 47.5 dB/W kecerunan penguatan. Pinalti kuasa pada kadar ralat bit 10^{-6} adalah kurang daripada 5 dB dan ini berjaya menunjukkan praktikaliti rekacipta lintas-kembar penguat isyarat ini. Kegunaan IRF boleh dilanjutkan seterusnya dalam pengayun parametric dengan rekacipta lintas-kembar. Di samping penalaan jarak gelombang dapat dipanjangkan dengan ketara (sebanyak 72 nm @ 0.45 W, dihadkan oleh jalur lebar penala laluan gelombang), sebanyak 51% penurunan laser ambang dapat dicapai oleh pengayun parametric dengan rekacipta
lintas-kembar berbanding dengan rekacipta konvensional, tambahan atas pengekalan kestabilan laser dalam lingkungan 2 dB.
ACKNOWLEDGEMENTS

Many thanks to my adviser, Prof. Dr. Mohd Adzir Mahdi, for his persevering support and discussion to make this thesis a success. Also thanks to National Science Fellowship program by MOSTI to fund the entire duration of this study.
I certify that a Thesis Examination Committee has met on 20 December 2013 to conduct the final examination of Yeo Kwok Shien on his thesis entitled "Nonlinear Fiber Optical Parametric Amplifiers and Lasers with Idler Removal Filter" in accordance with the Universities and University Colleges Act 1971 and the Constitution of the Universiti Putra Malaysia [P.U.(A) 106] 15 March 1998. The Committee recommends that the student be awarded the Doctor of Philosophy.

Members of the Thesis Examination Committee were as follows:

**Borhanuddin bin Mohd Ali, PhD**
Professor
Faculty of Engineering
Universiti Putra Malaysia
(Chairman)

**Hairul Azhar Abdul Rashid, PhD**
Professor Ir.
Universiti Multimedia
Malaysia
(External Examiner)

**Abu Sahmah bin Mohd Supa'at, PhD**
Professor Ir.
Universiti Teknologi Malaysia
Malaysia
(External Examiner)

**Lars Magnus Ingemar Karlsson, PhD**
Professor
Chalmers University of Technology
Sweden
(External Examiner)

\[\text{Signature}\]

**NORITAH OMAR, PhD**
Associate Professor and Deputy Dean
School of Graduate Studies
Universiti Putra Malaysia

Date: 17 February 2014
This Thesis was submitted to the Senate of Universiti Putra Malaysia and has been accepted as fulfillment of the requirement for the degree of Doctor of Philosophy. The members of the Supervisory Committee were as follows:

Mohd Adzir Mahdi, PhD  
Professor  
Faculty of Engineering  
Universiti Putra Malaysia  
(Chairman)

Salasiah Hitam, PhD  
Associate Professor  
Faculty of Engineering  
Universiti Putra Malaysia  
(Member)

Makhfudzah Mokhtar, PhD  
Senior Lecturer  
Faculty of Engineering  
Universiti Putra Malaysia  
(Member)

BUJANG BIN KIM HUAT, PhD  
Professor and Dean  
School of Graduate Studies  
Universiti Putra Malaysia

Date:
DECLARATION

Declaration by graduate student

I hereby confirm that

- This thesis is my original work;
- Quotations, illustrations, and citations have been duly referenced;
- This thesis has not been submitted previously or concurrently for any other degree at any other institutions;
- Intellectual property from the thesis and copyright of thesis are dully-owned by Universiti Putra Malaysia, as according to the Universiti Putra Malaysia (Research) Rules 2012;
- Written permission must be obtained from supervisor and the office of Deputy Vice-Chancellor (Research and Innovation) before thesis is published (in the form of written, printed or in electronic form) including books, journal, modules, proceedings, popular writings, seminar papers, manuscripts, posters, reports, lecture notes, learning modules or any other materials as stated in the Universiti Putra Malaysia (Research) Rules 2012;
- There is no plagiarism or data falsification/fabrication in the thesis, and scholarly integrity is upheld as according to the Universiti Putra Malaysia (Graduate Studies) Rules 2003 (Revision 2012-2013) and the Universiti Putra Malaysia (Research) Rule 2012. The thesis has undergone plagiarism detection software.

Signature: ___________________________ Date: 20 December 2013

Name and Matric No: Yeo Kwok Shien GS23366
Declaration by Members of Supervisory Committee

This is to confirm that:

- the research conducted and the writing of this thesis was under our supervision;
- supervision responsibilities as stated in the Universiti Putra Malaysia (Graduate Studies) Rules 2003 (revision 2012-2013) are adhered to.

Signature: ____________________
Name of Chairman of Supervisory Committee: Mohd Adzir Mahdi, PhD, Professor
Faculty of Engineering, Universiti Putra Malaysia

Signature: ____________________
Name of Member of Supervisory Committee: Salasiah Hitam, PhD, Associate Professor
Faculty of Engineering, Universiti Putra Malaysia

Signature: ____________________
Name of Member of Supervisory Committee: Makhfudzah Mokhtar, PhD, Senior Lecturer
Faculty of Engineering, Universiti Putra Malaysia
# TABLE OF CONTENTS

<table>
<thead>
<tr>
<th>Section</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>DEDICATION</td>
<td>ii</td>
</tr>
<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>APPROVAL</td>
<td>viii</td>
</tr>
<tr>
<td>DECLARATION</td>
<td>x</td>
</tr>
<tr>
<td>LIST OF TABLES</td>
<td>xiv</td>
</tr>
<tr>
<td>LIST OF FIGURES</td>
<td>xv</td>
</tr>
<tr>
<td>LIST OF ABBREVIATIONS</td>
<td>xx</td>
</tr>
</tbody>
</table>

## CHAPTER

1 INTRODUCTION

1.1 Overview

1.2 Problem Statement

1.3 Scope and Significance of the Research

1.4 Methodology Flow Chart

1.5 Thesis Outline

2 LITERATURE REVIEW

2.1 Fiber Optical Parametric Amplifier

2.1.1 Phase Insensitive and Phase Sensitive Amplifier

2.1.2 One-pump and Two-pump FOPA

2.2 Fiber Optical Parametric Oscillator

2.2.1 FOPO Architecture

2.2.2 Narrowband Oscillation

2.3 Dispersion Compensation in FOPA

2.4 Fundamental of Phase-Insensitive Single-pumped Parametric Amplification

2.4.1 Four-wave Mixing

2.4.2 Parametric Gain

2.4.3 Highly Nonlinear Fiber

2.4.4 Stimulated Brillouin Scattering

2.4.5 Combined effect of parametric gain and Raman gain

2.4.6 Summary

3 GAIN PROFILE COMPENSATION FOR TWO-SEGMENT/D双倍 PASS FIBER OPTICAL PARAMETRIC AMPLIFIER

3.1 Two-Segment Fiber Optical Parametric Amplifier

3.1.1 Characteristics of Two-Segment FOPA

3.1.2 Theoretical Analysis & Proposed Solution

3.1.3 Experiment & Result
### Chapter 3: Double-Pass Fiber Optical Parametric Amplifier

<table>
<thead>
<tr>
<th>Section</th>
<th>Title</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>3.2.1</td>
<td>The Double-Pass Design &amp; Characteristics</td>
<td>49</td>
</tr>
<tr>
<td>3.2.2</td>
<td>Result and Discussion</td>
<td>54</td>
</tr>
<tr>
<td>3.2.3</td>
<td>Second Order Idler: Generation &amp; Transmission</td>
<td>65</td>
</tr>
</tbody>
</table>

### Chapter 4: Continuous Wave Tunable Fiber Optical Parametric Oscillator with Double-Pass Pump Configuration

<table>
<thead>
<tr>
<th>Section</th>
<th>Title</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>4.1</td>
<td>Introduction</td>
<td>71</td>
</tr>
<tr>
<td>4.2</td>
<td>Fabry-Perot Design</td>
<td>71</td>
</tr>
<tr>
<td>4.3</td>
<td>Threshold</td>
<td>70</td>
</tr>
<tr>
<td>4.4</td>
<td>Tunable Bandwidth</td>
<td>82</td>
</tr>
<tr>
<td>4.5</td>
<td>Laser Stability</td>
<td>86</td>
</tr>
<tr>
<td>4.6</td>
<td>Conclusion</td>
<td>87</td>
</tr>
</tbody>
</table>

### Chapter 5: Conclusions and Recommendations for Future Work

<table>
<thead>
<tr>
<th>Section</th>
<th>Title</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>5.1</td>
<td>Conclusion</td>
<td>89</td>
</tr>
<tr>
<td>5.2</td>
<td>Recommendation For Future Work</td>
<td>90</td>
</tr>
</tbody>
</table>

- REFERENCES: 92
- BIODATA OF STUDENT: 103
- LIST OF PUBLICATIONS: 104