Summer 7-7-2020

**Generation of Correlated Dual Frequency Combs with PM Fiber Lasers for High-Precision Metrology**

Hanieh Afkhamiardakani  
*Center for High Technology Materials*

Follow this and additional works at: https://digitalrepository.unm.edu/ose_etds

Part of the Atomic, Molecular and Optical Physics Commons, Engineering Physics Commons, Optics Commons, and the Other Engineering Commons

**Recommended Citation**


This Dissertation is brought to you for free and open access by the Engineering ETDs at UNM Digital Repository. It has been accepted for inclusion in Optical Science and Engineering ETDs by an authorized administrator of UNM Digital Repository. For more information, please contact amywinter@unm.edu, Isloane@salud.unm.edu, sarahrk@unm.edu.
Hanieh Afkhamiardakani

Candidate

Optical Science and Engineering

Department of Physics and Astronomy, The University of New Mexico

This dissertation is approved, and it is acceptable in quality and form for publication:
Approved by the Dissertation Committee:

Dr. Jean-Claude M. Diels, Chair
07/13/2020

Dr. Ladan Arissian
07/13/2020

Dr. Matthias Lenzner
07/14/2020

Dr. Arash Mafi
07/13/2020

Dr. Wolfgang Rudolph
Generation of Correlated Dual Frequency Combs with PM Fiber Lasers for High-Precision Metrology

by

Hanieh Afkhamiardakani

M.S., University of New Mexico, 2015

DISSERTATION

Submitted in Partial Fulfillment of the Requirements for the Degree of

Doctor of Philosophy
Optical Science and Engineering

The University of New Mexico

Albuquerque, New Mexico

July 2020
Dedication

This dissertation is dedicated to my best friend, my husband, Saeid, who never stops encouraging me to go after my dreams, and to my sons, Ilya and Nima, who let me feel the beauty of having unconditional love for someone.

I also dedicate this work to my mother and father who have always encouraged me with faith and love, and to my very special sisters Elham, Aram, and Somayeh who have never left my side.
Acknowledgments

First and foremost, I would like to thank God Almighty for giving me the strength, knowledge, ability and opportunity to undertake and complete this research study.

I would like to express my deepest gratitude to Professor Jean-Claude Diels for being a knowledgeable, intelligent, patient, and supportive advisor and mentor for the past six years. Working with Dr. Diels was like swimming freely in an ocean without fear of facing the unknown situations. He was always there to help and encourage me to discover new things. He was very generous in teaching me everything I needed to know to do my project. He supported me when I wanted to chase down my curiosity even if it did not necessarily pertain to my main project. This dissertation would not have been possible without his patience and encouragement.

In addition, I am grateful to Dr. Ladan Arissian, Dr. Matthias Lenzner, Dr. Arash Mafi, and Dr. Wolfgang Rudolph for kindly agreeing to serve on my committee and taking the effort to read this manuscript. I owe many thanks to Dr. Arissian for generously providing me with her own version of Matlab program to retrieve polarization ellipses which saved me a lot of time. She is also a good friend who is always ready to provide emotional support. I always enjoy talking to Dr. Lenzner who is a very bright, positive, and supportive scientist and engineer. I am very thankful to Dr. Mafi for his continued support of my research. I will never forget when he graciously allowed me to work with his tapering system which helped me make my own tapering station. He is also an eager counselor when it comes down to discussing my future career and issues related to finding a balance between my personal and professional life. I am so honored to have Dr. Rudolph who is a knowledgeable and smart scientist in my committee.

I will forever be thankful to my great colleagues at Diels’ research group for their kindness, help, and support during these years. Dr. James Hendrie, Ali Rastegari, Ning Hsu, and Luke Horstman were always available to help and listen to me when I needed someone to talk to. Special thanks to all my friends who have always been supportive. I would like to acknowledge all the people (so many to name here) at Center for High Technology Materials and Physics Department for allowing me to conduct my research in a friendly and supportive environment. Lastly, thanks to the National Aeronautics and Space Administration (NASA) for funding my research project.
Intracavity Phase Interferometry (IPI) using two correlated, counter-propagating frequency combs (pulse trains) in mode-locked lasers has evolved into a powerful technique for high-precision metrology. In this method a physical parameter to be measured imparts a phase shift onto a pulse circulating in the laser cavity. Inside a laser cavity, that phase shift becomes a frequency shift (phase shift/round-trip time) applied to the whole frequency comb created by this pulse as it exits the cavity at each round-trip. This frequency shift is measured by interfering this comb with a reference comb created by a reference pulse circulating in the same mode-locked laser cavity. A phase sensitivity better than $10^{-8}$ radians allowed this method to successfully measure minuscule changes in flow velocity, electric field, magnetic field, rotation, acceleration, and displacements, using discrete element lasers. Although fiber lasers appear to be ideal for environment insensitive, robust, reliable and compact implementation of IPI, previous attempts have so far been unsuccessful. This is partly due to the fact that generating dual frequency combs in fiber lasers is a new field with hitherto unanticipated challenges. This thesis is a first step
in identifying and solving some of the basic problems. For instance, the large intensity in the core, coupled with the nonlinear index of glass, result in a cumulative nonlinear index on axis which dwarfs the signal to be measured. The large saturable gain changes in an unpredictable way the repetition rate of the laser impeding the creation of frequency combs with identical repetition rate. The huge amount of phase coupling between pulses crossing at the saturable absorber eliminates the small signal response (deadband).

The study and resolution of these hurdles culminates in a successful observation of a beat signal in a polarization maintaining mode-locked fiber laser operating with orthogonally polarized pulses.
Contents

List of Figures xiv
List of symbols xix
List of Acronyms xxii

1 Introduction 1
  1.1 Frequency Combs 1
  1.2 Mode-Locking and Frequency Combs 2
  1.3 IPI in Fiber Lasers 3
  1.4 Nonlinear Transmission in PM Fibers 4
References 4

References 4

2 Frequency Combs 7
  2.1 Introduction 7
Contents

2.2 Fundamentals .......................................................... 7
2.3 Generating a Soliton Pulse .............................................. 10
References ................................................................. 12

References 12

3 Passive Mode-Locking in Fiber Lasers 13
3.1 Introduction ............................................................... 13
3.2 Saturable Absorbers Based on Nonlinear Effect of Multi-Mode Interference in Tapered Fiber ................................................. 15
3.3 Saturable Absorbers based on CNTs Squeezed Between Two Fiber Ferrules 20
3.4 Saturable Absorbers Based on Tapered Fiber Embedded in CNT/Polymer Composite ............................................................... 24
  3.4.1 Polarization Study on SAs Based on Tapered PM Fibers Covered with CNTs ................................................................. 28
  3.4.2 Unidirectional Fiber Laser ............................................ 32
  3.4.3 Thermal Effect .......................................................... 36
3.5 Saturable Absorbers Based on Power-Dependent Birefringence of PM Fibers 39
References ................................................................. 43

References 43

4 Intracavity Phase Interferometry 47
Contents

4.1 Introduction ................................................................. 47
4.2 Fundamentals of IPI ......................................................... 48
4.3 Mode-Locked Lasers For IPI ............................................. 50
4.4 Deadband in IPI ............................................................. 53
4.5 IPI in Mode-Locked Linear Fiber Lasers ............................. 55
References ................................................................. 59

References 59

5 Implementation of IPI in Mode-Locked Ring Fiber Lasers 63

5.1 Introduction ................................................................. 63
5.2 Sagnac Effect ................................................................. 64
5.3 Implementing IPI in Laser Gyroscopes ............................... 65
5.4 IPI in Mode-Locked Ring Fiber Laser;
    Parallel Polarization ..................................................... 66
    5.4.1 Experimental Results ............................................. 67
    5.4.2 Group Velocity Modification Through Gain Dynamics .... 73
    5.4.3 Comparison of Theory and Experiment ....................... 74
5.5 IPI in Mode-Locked Ring Fiber Laser;
    Orthogonal Polarization .............................................. 75
    5.5.1 Polarizing Beam Splitter ........................................ 78
    5.5.2 Beat-note Measurement ......................................... 79
Contents

5.5.3 Summary ................................................. 81

References ..................................................... 83

References 83

6 New Fiber Development Enabling IPI 85

6.1 Introduction .............................................. 86

6.2 Temperature-Dependent Birefringence of PM Fibers .......... 87

6.2.1 Method of Measurement ............................... 87

6.2.2 Adjusting Parameters for Optimum Sensitivity .......... 89

6.3 Power-Dependent Polarization Changes ..................... 92

6.3.1 Response Time of Power/Temperature Changes .......... 93

6.4 Fiber Core Temperature Measurement ........................ 94

6.5 Optical Length Stabilization ................................ 97

References ..................................................... 99

References 99

7 Conclusion and Future Work 101

7.1 Mode-Locking ............................................. 101

7.2 IPI and Applications ...................................... 102

7.3 Fiber Sensor Based on Birefringence of PM Fibers .......... 104
## Contents

<table>
<thead>
<tr>
<th>Section</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>References</td>
<td>106</td>
</tr>
<tr>
<td><strong>A  Polarization Maintaining Fibers</strong></td>
<td>107</td>
</tr>
<tr>
<td>References</td>
<td>110</td>
</tr>
<tr>
<td>References</td>
<td>110</td>
</tr>
<tr>
<td>Appendices</td>
<td>107</td>
</tr>
<tr>
<td><strong>B  Polarization Ellipse Measurement</strong></td>
<td>111</td>
</tr>
<tr>
<td>References</td>
<td>115</td>
</tr>
<tr>
<td>Chapter 1</td>
<td>115</td>
</tr>
<tr>
<td>References</td>
<td>115</td>
</tr>
<tr>
<td>Chapter 2</td>
<td>117</td>
</tr>
<tr>
<td>References</td>
<td>117</td>
</tr>
<tr>
<td>Chapter 3</td>
<td>117</td>
</tr>
<tr>
<td>References</td>
<td>117</td>
</tr>
<tr>
<td>Chapter 4</td>
<td>121</td>
</tr>
<tr>
<td>References</td>
<td>121</td>
</tr>
</tbody>
</table>

xii
List of Figures

2.1 Optical pulse train and frequency comb ........................................ 8

3.1 Schematic of a saturable absorber based on nonlinear effect of multi-
mode interference .............................................................. 16

3.2 Experimental setup for making SA based on nonlinear multi-mode inter-
action .............................................................................. 17

3.3 Power-dependent transmission through a SA based on nonlinear multi-mode
interaction in a tapered fiber ................................................. 18

3.4 Q-switched pulse train at different powers .................................... 18

3.5 Optical and RF spectra of a Q-switched fiber laser ...................... 19

3.6 Optical characteristic of Q-switched pulses .................................. 19

3.7 Absorption spectrum of carbon nanotubes ................................... 21

3.8 SA based on CNTs between two fiber ferrules .......................... 22

3.9 Microscope images of burned spot on CNT/polymer layer .......... 23

3.10 A schematic of saturable absorber based on tapered fiber embedded in
CNT/polymer composite ..................................................... 24
### List of Figures

3.11  Schematic of fiber tapering station .............................................. 25  
3.12  Microscope image of a tapered fiber ............................................. 25  
3.13  Saturation curve of carbon nanotubes ........................................... 26  
3.14  A comparison between saturation intensities of SAs based on Kerr effect of multi-mode interaction in tapered fiber and tapered fiber covered with CNTs ...................................................... 27  
3.15  The final product for a SA based on tapered fiber covered with CNTs . . 27  
3.16  Polarization measurement of a SA based on tapered fiber covered with CNT/PDMS composite ...................................................... 29  
3.17  Experimental setup for unidirectional mode-locked fiber laser ............ 32  
3.18  Optical properties of the output of an unidirectional fiber laser mode-locked using PP and non-PP tapered fiber covered with CNTs ............. 33  
3.19  Intensity autocorrelation traces of the laser output mode-locked with a PP and non-PP saturable absorbers .............................................. 34  
3.20  Temperature-dependent transmission of a SA based on tapered fiber covered with CNTs ...................................................... 36  
3.21  Thermal effect on the long-term operation of a fiber laser mode-locked with a SA based on tapered fiber covered with CNTs ................. 38  
3.22  Experimental setup for power-dependent polarization change in PM fibers 40  
3.23  Polarization modification in PM fibers versus light power ................. 41  
3.24  Saturation curve of a SA based on birefringence in PM fibers ............. 42  
4.1   Passive (Michelson) interferometer .................................................. 49
### List of Figures

<table>
<thead>
<tr>
<th>Figure</th>
<th>Description</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>4.2</td>
<td>Laser designs for Intracavity phase interferometry</td>
<td>51</td>
</tr>
<tr>
<td>4.3</td>
<td>Typical measured beat note of two counter-propagating frequency combs</td>
<td>53</td>
</tr>
<tr>
<td>4.4</td>
<td>IPI characteristic graph indicating the deadband region</td>
<td>54</td>
</tr>
<tr>
<td>4.5</td>
<td>Sketch of a linear mode-locked fiber laser with orthogonally polarized pulses for IPI application</td>
<td>57</td>
</tr>
<tr>
<td>5.1</td>
<td>Sagnac effect in a rotating ring</td>
<td>64</td>
</tr>
<tr>
<td>5.2</td>
<td>Experimental setup for IPI in a ring fiber laser; parallel polarization</td>
<td>68</td>
</tr>
<tr>
<td>5.3</td>
<td>Oscilloscope images of counter-propagating pulse trains in a fiber laser; parallel polarization</td>
<td>68</td>
</tr>
<tr>
<td>5.4</td>
<td>Beat note measurement of a bidirectional fiber laser; parallel polarization</td>
<td>69</td>
</tr>
<tr>
<td>5.5</td>
<td>Beat note frequency variations by increasing asymmetry in the laser cavity</td>
<td>70</td>
</tr>
<tr>
<td>5.6</td>
<td>Pump power dependence of beat note frequency and delay line displacement in a bidirectional fiber laser</td>
<td>71</td>
</tr>
<tr>
<td>5.7</td>
<td>Beat note frequency versus displacement in delay line</td>
<td>73</td>
</tr>
<tr>
<td>5.8</td>
<td>Experimental setup for a ring bidirectional fiber laser; orthogonal</td>
<td>76</td>
</tr>
<tr>
<td>5.9</td>
<td>The experimental setup of polarization separation</td>
<td>77</td>
</tr>
<tr>
<td>5.10</td>
<td>The operation of the lossless polarizing beam splitter</td>
<td>78</td>
</tr>
<tr>
<td>5.11</td>
<td>RF spectrum of two orthogonally polarized pulse trains of a fiber laser</td>
<td>80</td>
</tr>
<tr>
<td>5.12</td>
<td>Beat note measurement in the fiber laser with orthogonally polarized pulses</td>
<td>81</td>
</tr>
<tr>
<td>6.1</td>
<td>Experimental setup to monitor temperature changes of an object</td>
<td>88</td>
</tr>
</tbody>
</table>
List of Figures

6.2 Temperature-dependent polarization change in a PM fiber at temperatures from 2 to 30°C ........................................ 89
6.3 Temperature-dependent polarization change in a PM fiber at temperatures from 20 to 20.8°C ................................. 89
6.4 Transmission of circularly polarized light through a piece of PM fiber at different temperatures ................................. 91
6.5 Transmitted power through a piece of PM fiber at different temperatures followed by a polarizer at 46° ......................... 91
6.6 Temperature-power calibration curve .................................................. 93
6.7 Response time of a sensor based on birefringence of PM fiber to environmental changes ............................................. 94
6.8 Different methods to measure a fiber core temperature variations using the sensor based on birefringence of PM fiber .......... 95
6.9 Experimental setup to measure the temperature changes of a fiber core ................................................................. 96
6.10 Experimental results of fiber core temperature measurement ................................................................. 97
6.11 Proposed setup for optical length stabilization method based on the birefringence of PM fibers ................................. 98

7.1 Future work: a practical design of a saturable absorber based on nonlinear transmission in PM fibers .............................. 103

A.1 Different methods of making PM fibers .................................................. 108
A.2 A schematic of polarization rotation along a PM fiber .............................. 109
List of Figures

B.1 Schematic of a simple home-made polarimeter ........................................ 111
B.2 Transmitted patterns of different polarization states through a rotating polarizer .......................................................... 112
B.3 An example of a retrieved polarization ellipse ........................................ 113
# List of symbols

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Meaning</th>
</tr>
</thead>
<tbody>
<tr>
<td>$a$</td>
<td>Radius of a fiber core</td>
</tr>
<tr>
<td>$A$</td>
<td>Surface area of a gyroscope</td>
</tr>
<tr>
<td>$\alpha$</td>
<td>Small signal gain coefficient</td>
</tr>
<tr>
<td>$c$</td>
<td>Speed of light</td>
</tr>
<tr>
<td>$°C$</td>
<td>Degrees Celsius</td>
</tr>
<tr>
<td>$\Delta \varphi$</td>
<td>Carrier to envelope phase</td>
</tr>
<tr>
<td>$\Delta \phi$</td>
<td>Phase difference</td>
</tr>
<tr>
<td>$\Delta \epsilon$</td>
<td>Change in ellipticity of an ellipse</td>
</tr>
<tr>
<td>$\Delta I$</td>
<td>Difference of two pulse intensities</td>
</tr>
<tr>
<td>$\Delta n$</td>
<td>Birefringence</td>
</tr>
<tr>
<td>$\Delta \nu$</td>
<td>Measured beat note</td>
</tr>
<tr>
<td>$\Delta P$</td>
<td>Change in cavity perimeter</td>
</tr>
<tr>
<td>$\Delta T$</td>
<td>Temperature change</td>
</tr>
<tr>
<td>$\Delta \theta$</td>
<td>Change in the angle of an ellipse</td>
</tr>
<tr>
<td>$E$</td>
<td>Electric field</td>
</tr>
<tr>
<td>$\epsilon_{\text{max}}$</td>
<td>Maximum ellipticity of an ellipse</td>
</tr>
<tr>
<td>$\epsilon_{\text{min}}$</td>
<td>Minimum ellipticity of an ellipse</td>
</tr>
</tbody>
</table>
### List of symbols

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Meaning</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\phi_{nl}$</td>
<td>nonlinear phase along the core of a fiber</td>
</tr>
<tr>
<td>$\gamma$</td>
<td>Loss coefficient (per unit length).</td>
</tr>
<tr>
<td>$I$</td>
<td>Intensity of light</td>
</tr>
<tr>
<td>$k$</td>
<td>Wave number</td>
</tr>
<tr>
<td>$k''$</td>
<td>Second derivative of the wave vector with respect to frequency</td>
</tr>
<tr>
<td>$k_{\text{av}}$</td>
<td>Average wave vector</td>
</tr>
<tr>
<td>$\lambda$</td>
<td>Wavelength of light</td>
</tr>
<tr>
<td>$L$</td>
<td>Length of fiber</td>
</tr>
<tr>
<td>$L_b$</td>
<td>Self-imaging beat length in multi-mode fibers</td>
</tr>
<tr>
<td>$\ell_g$</td>
<td>Length of gain fiber</td>
</tr>
<tr>
<td>$M$</td>
<td>Number of modes in a fiber</td>
</tr>
<tr>
<td>$\mu\text{m}$</td>
<td>Micrometer</td>
</tr>
<tr>
<td>$N$</td>
<td>A frequency index</td>
</tr>
<tr>
<td>$n_0$</td>
<td>Linear refractive index</td>
</tr>
<tr>
<td>$n_2$</td>
<td>Nonlinear refractive index</td>
</tr>
<tr>
<td>$n_{\text{air}}$</td>
<td>Refractive index of air</td>
</tr>
<tr>
<td>$n_{\text{clad}}$</td>
<td>Refractive index of the cladding of a fiber</td>
</tr>
<tr>
<td>$n_{\text{core}}$</td>
<td>Refractive index of the core of a fiber</td>
</tr>
<tr>
<td>$n_{\text{clad}}^t$</td>
<td>Refractive index of the cladding of a tapered fiber</td>
</tr>
<tr>
<td>$n_{\text{core}}^t$</td>
<td>Refractive index of the core of a tapered fiber</td>
</tr>
<tr>
<td>$\nu$</td>
<td>Frequency</td>
</tr>
<tr>
<td>$\nu_{\text{CEO}}$</td>
<td>Carrier to envelope offset frequency</td>
</tr>
<tr>
<td>$\nu_N$</td>
<td>Carrier frequency in a frequency comb</td>
</tr>
<tr>
<td>$\nu_{\text{rt}}$</td>
<td>Repetition rate of a frequency comb</td>
</tr>
<tr>
<td>$\omega$</td>
<td>Angular optical frequency</td>
</tr>
<tr>
<td>$\Omega_r$</td>
<td>Angular velocity of a gyroscope</td>
</tr>
</tbody>
</table>
List of symbols

\[ P \quad \text{Cavity perimeter} \]
\[ \mathcal{P} \quad \text{Pump power} \]
\[ \mathcal{P}_0 \quad \text{Pump power at threshold of lasing} \]
\[ P_t \quad \text{Transmitted power} \]
\[ R \quad \text{Radius of a gyroscope} \]
\[ \text{rad} \quad \text{Radian} \]
\[ \tau_p \quad \text{Pulse duration} \]
\[ \tau_{rt} \quad \text{Round trip time of a mode-locked pulse within a cavity} \]
\[ v \quad \text{Pulse velocity} \]
# List of Acronyms

Presented in an alphabetical order

<table>
<thead>
<tr>
<th>Acronym</th>
<th>Definition</th>
</tr>
</thead>
<tbody>
<tr>
<td>AC</td>
<td>Autocorrelation</td>
</tr>
<tr>
<td>B</td>
<td>Birefringence</td>
</tr>
<tr>
<td>BS</td>
<td>Beam Splitter</td>
</tr>
<tr>
<td>CCW</td>
<td>CounterClockwise</td>
</tr>
<tr>
<td>CEO</td>
<td>Carrier to Envelope Offset</td>
</tr>
<tr>
<td>CEP</td>
<td>Carrier to Envelope Phase</td>
</tr>
<tr>
<td>Ch.</td>
<td>Chapter</td>
</tr>
<tr>
<td>CLEO</td>
<td>Conference on Laser and Electro Optics</td>
</tr>
<tr>
<td>CNT</td>
<td>Carbon Nanotube</td>
</tr>
<tr>
<td>Col</td>
<td>Collimator</td>
</tr>
<tr>
<td>CW</td>
<td>Clockwise</td>
</tr>
<tr>
<td>cw</td>
<td>Continuous Wave</td>
</tr>
<tr>
<td>D</td>
<td>Detector</td>
</tr>
<tr>
<td>DLT</td>
<td>Differential Luminescence Thermometry</td>
</tr>
<tr>
<td>Er</td>
<td>Erbium</td>
</tr>
<tr>
<td>Eq.</td>
<td>Equation</td>
</tr>
<tr>
<td>fm</td>
<td>Femtometer</td>
</tr>
<tr>
<td>Fig.</td>
<td>Figure</td>
</tr>
</tbody>
</table>
List of Acronyms

<table>
<thead>
<tr>
<th>Acronym</th>
<th>Definition</th>
</tr>
</thead>
<tbody>
<tr>
<td>FWHM</td>
<td>Full Width Half Maximum</td>
</tr>
<tr>
<td>G</td>
<td>Gain</td>
</tr>
<tr>
<td>GVD</td>
<td>Group Velocity Dispersion</td>
</tr>
<tr>
<td>He-Ne</td>
<td>Helium Neon</td>
</tr>
<tr>
<td>Hz</td>
<td>Hertz</td>
</tr>
<tr>
<td>IPI</td>
<td>Intracavity Phase Interferometry</td>
</tr>
<tr>
<td>kHz</td>
<td>Kilo-Hertz</td>
</tr>
<tr>
<td>M</td>
<td>Mirror</td>
</tr>
<tr>
<td>mg</td>
<td>Milli-gram</td>
</tr>
<tr>
<td>MHz</td>
<td>Mega-Hertz</td>
</tr>
<tr>
<td>MMF</td>
<td>Multi-Mode Fiber</td>
</tr>
<tr>
<td>MMI</td>
<td>Multi-Mode Interference</td>
</tr>
<tr>
<td>mW</td>
<td>milli-Watt</td>
</tr>
<tr>
<td>MW</td>
<td>Mega-Watt</td>
</tr>
<tr>
<td>MQW</td>
<td>Multiple Quantum Well</td>
</tr>
<tr>
<td>NALM</td>
<td>Nonlinear Amplifying Loop Mirror</td>
</tr>
<tr>
<td>NASA</td>
<td>National Aeronautics and Space Administration</td>
</tr>
<tr>
<td>nm</td>
<td>Nanometer</td>
</tr>
<tr>
<td>NOLM</td>
<td>Nonlinear Optical Loop Mirror</td>
</tr>
<tr>
<td>non-PP</td>
<td>non-Polarization Preserving</td>
</tr>
<tr>
<td>OC</td>
<td>Output Coupler</td>
</tr>
<tr>
<td>OPO</td>
<td>Optical Parametric Oscillator</td>
</tr>
<tr>
<td>PBS</td>
<td>Polarizing Beam Splitter</td>
</tr>
<tr>
<td>PDMS</td>
<td>Polydimethylsiloxane</td>
</tr>
<tr>
<td>PID</td>
<td>Proportional-Integral-Derivative</td>
</tr>
</tbody>
</table>
List of Acronyms

<table>
<thead>
<tr>
<th>Acronym</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>PM</td>
<td>Polarization Maintaining</td>
</tr>
<tr>
<td>PP</td>
<td>Polarization Preserving</td>
</tr>
<tr>
<td>ps</td>
<td>Picosecond</td>
</tr>
<tr>
<td>PTD</td>
<td>Photothermal Deflection</td>
</tr>
<tr>
<td>QWP</td>
<td>Quarter Wave Plate</td>
</tr>
<tr>
<td>Rep. rate</td>
<td>Repetition rate</td>
</tr>
<tr>
<td>RF</td>
<td>Radio Frequency</td>
</tr>
<tr>
<td>SA</td>
<td>Saturable Absorber</td>
</tr>
<tr>
<td>SEM</td>
<td>Scanning Electron Microscope</td>
</tr>
<tr>
<td>SESAM</td>
<td>Semiconductor Saturable Absorber Mirror</td>
</tr>
<tr>
<td>SMF</td>
<td>Single Mode Fiber</td>
</tr>
<tr>
<td>SNR</td>
<td>Signal-to-Noise Ratio</td>
</tr>
<tr>
<td>SOP</td>
<td>State Of Polarization</td>
</tr>
<tr>
<td>SPM</td>
<td>Self Phase Modulation</td>
</tr>
<tr>
<td>TC</td>
<td>Thermocouple</td>
</tr>
<tr>
<td>V</td>
<td>Volt</td>
</tr>
<tr>
<td>WDM</td>
<td>Wavelength Division Multiplexer</td>
</tr>
<tr>
<td>YVO$_4$</td>
<td>Yttrium Vanadate</td>
</tr>
</tbody>
</table>
Chapter 1

Introduction

1.1 Frequency Combs

Optical frequency combs, to be presented in chapter 2, have dramatically improved the accuracy of frequency metrology [1]. Various applications of frequency combs such as atomic clock [2], calibration of astronomical spectrographs [3], comb-based spectroscopy [4], distance measurement, and laser ranging are based on absolute frequency measurement. In all these applications relying on single frequency combs the absolute value of the carrier to envelope offset (CEO) frequency, a very important parameter in comb characterization, is required to achieve high-precision frequency metrology. The CEO of a single frequency comb is only a meaningful quantity if the frequency comb is stabilized\(^1\). Stabilization adds significantly to the price of a mode-locked laser. The optical frequency of a tooth of a stabilized frequency combs locked to frequency standards can be determined with an accuracy of 1 mHz [5]. With 1 mHz tooth bandwidth, these systems can detect a change in optical frequency with a resolution of \(1 : 10^{18}\). Such stabilization seems to be

\(^1\)In an unstabilized laser, the random fluctuations of the CEO frequency may exceed the mode spacing, making it totally undefined.
Chapter 1. Introduction

an overkill for most sensor applications that do not require absolute accuracy. Differential measurements between two unstabilized frequency combs issued from the same laser can achieve the same level of sensitivity as stabilized combs. We refer this differential comp interferometry as Intracavity Phase Interferometry (IPI), to be discussed in detail in chapter 4.

In IPI that was first realized in 1991 by Dennis, Lai and Diels [6, 7], a mode-locked laser with two intracavity counter-propagating pulses produces two correlated frequency combs interfering outside the laser cavity. The beat note frequency which measures the phase shift between combs (a phase shift that can be due to flow velocity, electric field, magnetic field, rotation, acceleration, and displacement) with the bandwidth as small as 0.2 Hz [8]. Because the combs are created in the same laser, their noise is correlated because they experience the same cavity fluctuations. The relative position of the teeth of the combs is fixed, even without cavity stabilization. Implementing IPI in fiber lasers make it attractive for commercial products which will be discussed in detail in chapter 4. An application as a deadband-free laser gyro will be presented in chapter 5.

1.2 Mode-Locking and Frequency Combs

Mode-locking is a popular method to generate a frequency combs. In a mode-locked laser, a short pulse is shaped at each round trip as a result of the balance between group velocity dispersion and self-phase modulation (SPM) in the cavity. The circulating intracavity pulse creates, through an output coupler, a train of pulses equally spaced in time, whose Fourier transform provides equally spaced teeth, which constitute a comb in frequency domain. There are various methods of mode-locking mainly categorized as active and passive. Passively mode-locked lasers have the advantage of not begin dependent of any electronics. There are variety of nonlinear materials and components to be used in as mode-locker in fiber lasers [9–11]. The focus of chapter 3 of this dissertation is on all-
Chapter 1. Introduction

fiber saturable absorbers, modified or developed for use in polarization maintaining (PM) fiber lasers.

1.3 IPI in Fiber Lasers

As mentioned in section 1.1, implementing IPI in fiber lasers is closer to commercial products in terms of simplicity and cost. In Chapter 4, IPI will be fully introduced and characterized. The challenge of creating a fiber laser with two intracavity circulating pulses will be addressed [12]. It is found that the main hurdle resides in the strong intensity dependence of group velocity inside a fiber laser, which leads to unequal repetition rate for the two circulating pulses. The solution for forcing the two pulses to circulate at the same cavity round-trip time was found in the design of a symmetric cavity, solution that also minimized the “bias beat note” (spurious response). It is shown (experimentally and theoretically) that the pulse velocity in the cavity is dominated by gain dynamics, and it is not simply equal to the group velocity [13, 14]. A similar conclusion has been found to apply — to a lesser extend, to free-space mode-locked lasers [15, 16].

A practical application of IPI is in inertial navigation systems comprising accelerometers (linear IPI) and laser gyros where the phase shift to be measured is the Sagnac phase shift. In Chapter 5, the Sagnac effect as the basic principal operation of optical gyroscopes and its formulation will be given. Because short pulses are circulating in the cavity, they can only scatter into each others at their crossing point. Therefore, a mode-locked gyroscope does not generally have a deadband [6], as its classical cw He-Ne counterpart. However, when the pulse crossing control is implemented with a non-moving saturable absorber, the scattering at that point causes injection locking of each beam into the other. As a result there is no response at low rotation rates which is called the deadband region. One of the advantages of using PM fiber lasers for IPI is the possibility of producing counter-circulating pulses orthogonally polarized. In this system counter-propagating pulses are
Chapter 1. Introduction

linearly polarized along slow and fast axes of the PM fiber, which minimizes the amount of coupling at the crossing point. An original method to create a ring laser where the counter-circulating pulses are cross-polarized was devised, and are the object of a patent application. Its successful implementation paves the way for the future development an all-fiber active laser gyro.

1.4 Nonlinear Transmission in PM Fibers

Polarization maintaining fibers are fabricated with two different refractive indices along two perpendicular axes (slow and fast axes). They can therefore be viewed as a very high order waveplate. The polarization of light is preserved when it is linearly polarized and launched along one of the principal axes of the fiber. Any other polarization state will be periodically modified propagating along the fiber. The state of polarization of light (circularly polarized, for instance) transmitted through the PM fiber is extremely sensitive to the environmental conditions (temperature, stress, magnetic field) or power variations of the propagating light [17–20]. Low-power nonlinear transmission will be demonstrated in Chapter 6 by terminating the PM fiber by an appropriately oriented polarizer. Different proposed applications of this property are experimentally demonstrated and discussed in Chapter 6.

References


Chapter 1. Introduction


Chapter 1. Introduction


Chapter 2

Frequency Combs

2.1 Introduction

The primary focus of this chapter is providing a short introduction on definition and characterization of frequency combs. Carrier to envelope offset frequency will be introduced as a very important parameter to characterize a comb. Then mode-locked fiber lasers will be discussed shortly as a source of generating frequency combs. Finally, a brief discussion will be provided on soliton mode-locking.

2.2 Fundamentals

An optical frequency comb is an optical spectrum consisting of a series of discrete, equally spaced frequency lines [1–3]. A frequency comb is usually associated with a train of ultrashort pulses emitted from a Mode-Locked (ML) laser at regular time intervals of $\tau_{rt} = \frac{P}{v_g}$ where $P$ is the cavity perimeter and $v_g$ is the group velocity of the pulse circulating in
Chapter 2. Frequency Combs

Figure 2.1: (a) An optical pulse train in time which is periodically repeated (sampled) in time intervals of $\tau_{rt}$. Carrier to Envelope Phase (CEP) of $\Delta \varphi$ defines the pulse to pulse change of optical oscillation with respect to pulse envelope. (b) The mode-locked operation in frequency domain provides a frequency comb with the carrier frequency of $\nu_N$. The optical spectrum consists of thousands to millions modes of frequency lines that are equally separated by repetition rate of $\nu_{rt} = 1/\tau_{rt}$. Due to the presence of CEP in time domain, the extension of the frequency comb to zero leads generally to a nonzero value of Carrier to Envelope Offset (CEO) frequency of $\nu_{CEO}$.

the cavity. Fig. 2.1(a) represents a series of pulses in time domain. The Fourier transform of this pulse train gives a frequency comb with repetition rate (teeth spacing) of $\nu_{rt} = 1/\tau_{rt}$ as shown in Fig. 2.1(b). As can be seen in Fig. 2.1(a), the carrier frequency of $\nu_N$, shown as a background oscillation in color gray, is not necessarily always at the same position with respect to the pulse envelope [4]. The Carrier to Envelope Phase (CEP) is defined as the value of the phase of the carrier frequency (somewhat arbitrary choice) at the location of the pulse peak. This parameter which is shown by $\Delta \varphi$ Fig. 2.1(a) results in a frequency comb that does not start from zero, but from a Carrier to Envelope Offset (CEO) frequency. The carrier to envelope offset frequency ($\nu_{CEO}$) shown in Fig. 2.1(b) is defined as the change in carrier to envelope phase divided by the pulse period ($\nu_{CEO} = \Delta \varphi/2\pi\tau_{rt}$). The
sharpness of the teeth is defined by the stability of the repetition rate and optical frequency. By active stabilization of two parameters (for instance cavity length and tilt of end mirror) controlling the optical frequency and the repetition rate, the bandwidth of an optical teeth can be reduced to as little as 1 Hz [5, 6]. This corresponds to a few femtometer (fm) change in the cavity length, which is $10^9$ times smaller than natural length vibration (a fraction of $\mu$m) of an unstabilized laser.

The constant teeth spacing across the comb [1] is a remarkable property which opens the way to new metrological applications such as optical frequency measurements, atomic clocks, high-precision spectroscopy, attosecond pulses, nonlinear optics, and more precise navigation. Much work has been devoted to the frequency combs, which was developed around the turn of the 21st century and ultimately led to one half of the Nobel Prize in Physics being shared by John L. Hall and Theodor W. Hänsch in 2005.

Fiber lasers have a number of qualities which make them very attractive for ultra-short pulse generation via active or passive mode-locking mechanisms. The large gain bandwidth (typically tens of nanometers) of rare-earth-doped fibers allows the generation of femtosecond pulses in fiber lasers. Also, Fiber lasers are very compact, low-cost, and free of alignment [7]. Among rare-earth elements, Erbium (Er) is one of the most popular candidates for gain medium in fibers. Erbium-doped fibers typically generate the wavelength of 1.55 $\mu$m which lies in eye-safe region of the optical spectrum, and is within the low loss window of silica fibers. Erbium-doped fiber lasers are therefore one of the most popular fiber lasers which have shown tremendous progress in recent years. In the next chapter, passive mode-locking of Erbium-doped fiber lasers is extensively covered.
2.3 Generating a Soliton Pulse

When a laser is operating in continuous regime, the cavity gain and losses are in equilibrium. In the case of femtosecond mode-locked lasers, the major pulse shaping mechanism comes from the combination of self-phase modulation (SPM) and group velocity dispersion (GVD) at each round trip. The self-phase modulation or Kerr effect occurs in a nonlinear medium with refractive index of \( n_0 + n_2 I \); \( n_0 \) is the linear index and \( n_2 I \) is the nonlinear term (\( I \) being the light intensity in \( \text{W cm}^{-2} \), \( n_2 \) being the nonlinear index in \( \text{cm}^2 \text{W}^{-1} \)). The phase introduced by Kerr effect for a wave traveling a distance \( z \) in a medium with optical Kerr coefficient \( n_2 > 0 \) will change the instantaneous frequency and results in up-chirping an optical pulse. The group velocity dispersion \( k'' \) (second derivative of the wave vector with respect to frequency) results from the frequency dependence of group velocity in a dispersive medium. In a medium with a positive (normal) dispersion (\( k'' > 0 \)) the red light (lower frequency) travels faster than the blue light (higher frequency) and the phase modulation is in the form of up-chirping (similar to SPM). In a negative (anomalous) dispersive medium (\( k'' < 0 \)) a propagating pulse will be down-chirped.

When the phase modulation induced by the Kerr effect (up-chirping) balances exactly the phase modulation resulting from dispersion (down-chirping) an ideal shape of pulse will be generated in the laser cavity that does not spread in time or frequency. This is the stationary solution of the nonlinear Schrödinger equation which is called “soliton” and its field has the form:

\[
\tilde{E} = \frac{1}{\tau_s} \sqrt{\frac{k''}{K}} \text{sech} \frac{t}{\tau_s} e^{-ik''z/2\tau_s^2} = \mathcal{E}_0 \text{sech} \frac{t}{\tau_s} e^{-ik''z/2\tau_s^2}
\]

(2.1)

where \( \tau_s \) is the pulse duration, \( t \) is the time, \( z \) is the distance, and \( K \) is the Kerr effect coefficient. In discrete component lasers the negative dispersion is usually achieved by using a pair of prisms. In fused silica, at a wavelength longer than 1.3 micron, the dispersion changes from positive to negative. Therefore, for erbium doped fibers operating at 1.55 \( \mu \text{m} \), the soliton condition is easily satisfied since the Kerr effect induces up-chirping. Fine
Chapter 2. Frequency Combs

Tuning of the dispersion is also possible in fibers by acting on the modal dispersion.

It has been shown [8] that the soliton condition (balance of phase modulation by the Kerr effect and dispersion) is same as the process that equalizes the tooth spacing in a frequency comb.
Chapter 2. Frequency Combs

References


Chapter 3

Passive Mode-Locking in Fiber Lasers

3.1 Introduction

As mentioned in Section 2.2, mode-locking is a method to obtain a train of ultrashort pulses (frequency comb) from a laser. Methods of mode-locking in a laser are classified as active and passive. An actively mode-locked laser typically involves an active element to induce the modulation of the intracavity light. The active element can be an acousto-optic modulator to generate the periodic modulation of the resonator losses or an electro-optic modulator to modulate the round trip phase change. Synchronized modulation with the resonator round trip in active mode-locking can lead to the generation of ultrashort (usually picosecond) pulses. In passive mode-locking a nonlinear passive element (saturable absorber) causes the light in the laser resonator to be amplitude modulated leading to the formation of an ultrashort pulse.

Passively mode-locked fiber lasers have the advantage of being entirely made of optical components as oppose to active mode-locking which requires external electrical components. Also, the mode-locking mechanism in the cavity is carried out automatically. Ultrafast Erbium-doped fiber lasers can be passively mode-locked using variety of nonlinear
Chapter 3. Passive Mode-Locking in Fiber Lasers

Materials and components such as semiconductor saturable absorber mirrors (SESAMs) [1], carbon nanotubes (CNTs) [2], graphene [3], topological insulators [4], and nonlinear optical/amplifying loop mirrors (NOLM/NALM) [5]. All these mode-locking techniques are well-established and widely used by the laser community.

Larger nonlinearities are generally associated with resonances, and are therefore slower (the speed being generally associated with the inverse of the resonance spectral width). A saturable absorber (SA) with lower nonlinearity is faster than the one with strong nonlinearity. A faster nonlinearity will lead to the shorter pulses, but will require the higher intensity. For instance, Kerr effect in glass is of the order of $10^{-16}$ cm$^2$/W, but it is fast (of the order of the light period) while micro-emulsions [6] have a nonlinearity of $10^{-8}$ cm$^2$/W, considerably larger, but with a response time of minutes.

In this chapter, three types of all-fiber saturable absorbers with different response times, modified or developed for use in polarization maintaining (PM) fiber lasers, will be discussed. First, the fastest SA based on Kerr effect on multi-mode interference in a tapered fiber will be presented. This type of SA has been entirely developed in our lab. Then two techniques of manufacturing saturable absorbers based on carbon nanotubes (CNTs) will be extensively discussed. This type of SA is based of interaction of propagating light with CNTs, a nonlinear material with recovery time $<1$ ps [7]. Finally, a highly nonlinear SA based on the birefringence of polarization maintaining fibers with response time of 125 µs will be proposed for applications with very low energy consumption where fast pulses are not required.
Chapter 3. Passive Mode-Locking in Fiber Lasers

3.2 Saturable Absorbers Based on Nonlinear Effect of Multi-Mode Interference in Tapered Fiber

In this section, we demonstrate a new all-fiber saturable absorber based on nonlinear effect on multi-mode interference (MMI) in a selected profile fiber taper. The principle of this nonlinear transmission is similar to the single mode–multi mode–single mode fiber (SMF-MMF-SMF) device studied numerically in 2013 [8] which is based on the Kerr effect of MMI in a multi-mode fiber (MMF). This component is schematically shown at the top of Fig. 3.1. Coupling the single mode light into the MMF excites different modes and the interference of the exited modes in the MMF results in creating self-imaging beat length \( L_b \) which takes place at very short (a few mm) periodic intervals. It is noted in [8] that by choosing the length of the MMF as the odd integer numbers of \( L_b/2 \) the relative power transmission is at its minimum value for low power signal (green lines in Fig. 3.1). By increasing the optical power (red lines in Fig. 3.1), the nonlinear effects such as self-phase and cross-phase modulations alter the refractive indices of the excited modes. Therefore, \( L_b \) in the MMF is also changed and consequently the relative power transmission is increased in nonlinear regime resulting in a power-dependent transmission which means the proposed configuration has the potential to operate as a saturable absorber.

A demonstration of such a SMF-MMF-SMF device for Q-switching was made in 2015 [9]. Besides the attractiveness of this technique such as high power damage threshold and wavelength independence, splicing the MMF between two single mode fibers (SMFs) within the accuracy of the half beat length is an issue. Recently, researchers use different tricks to overcome this issue which reduces the simplicity of this method [10–12]. Another limitation of this method is that it cannot be used in all-polarization maintaining fiber lasers as there is no PM multi-mode fiber to splice between PM single mode fibers. Also, due to the large diameter of MMF (usually 50 \( \mu \)m), a powerfull light is required to induce nonlinear effects. It will be demonstrated that by replacing the multi-mode fiber
Chapter 3. Passive Mode-Locking in Fiber Lasers

Figure 3.1: Demonstration of the saturable absorber based on nonlinear effect of multi-mode interference in a multi-mode fiber spliced between two pieces of single mode fibers (top) or in the tapered section of a single mode fiber (bottom). SMF: Single mode fiber, MMF: multi-mode fiber, \( L_b \): Self imaging distance, \( n_{clad}^t \) and \( n_{core}^t \): refractive indices of cladding and core of the tapered section, respectively.

with a tapered fiber, the above mentioned issues will be resolved.

The number of modes in a fiber is defined by \( M \approx V^2/2, V = 2\pi a \sqrt{n_{core}^2 - n_{clad}^2}/\lambda \) where \( a \) is the radius of the fiber core, \( \lambda \) is the wavelength of the propagating light, \( n_{core} \) and \( n_{clad} \) are the refractive indices of the fiber core and cladding, respectively. By increasing the core size or the difference of refractive indices, a fiber can support multiple modes for a given wavelength. For example, a fiber with the core diameter of 8 \( \mu \text{m} \), \( n_{core} = 1.4490 \), and \( n_{clad} = 1.4444 \) is considered single mode for the wavelength of 1550 nm. By tapering the single mode fiber (with initial diameter of 125 \( \mu \text{m} \)) down to the diameter of 5 \( \mu \text{m} \), the core of the fiber gets so narrow that the propagating light leaks to the cladding and will be guided through the tapered section surrounded by air. Therefore, the refractive indices of the core and cladding of the tapered section are \( n_{core}^t \approx n_{clad} = 1.4444 \) and \( n_{clad}^t \approx n_{air} = 1 \), respectively. The superscript \( t \) stands for “taper”. The V-number for the fiber taper shown at the bottom of Fig. 3.1 is calculated as \( V=10.6 \) (compare with \( V=12 \) for a 50/125 MMF) at the wavelength of 1550 nm. A micro taper made on a single mode fiber can be therefore viewed as a multi-mode fiber which is placed between two
Chapter 3. Passive Mode-Locking in Fiber Lasers

pieces of single mode fibers as shown in Fig. 3.1.

![Diagram of fiber laser setup]

**Figure 3.2:** a) Experimental setup for making SA based on nonlinear multi-mode interaction in a tapered fiber; WDM: wavelength division multiplexer, OC: output coupler. b) Actual fiber pulling station.

Fig. 3.2(a) is a schematic configuration of a fiber laser. A 90 cm of Er-doped fiber is pumped by a laser diode at 980 nm via a wavelength division multiplexer (WDM). An output coupler (OC) extracts 10% of the light from the fiber laser cavity and an isolator guarantees the unidirectional operation of the laser. The free portion of the fiber is placed on the pulling station (Fig. 3.2(b)) to make a taper while the output is being monitored on the oscilloscope to stop the pulling process once pulses appear. Q-switching was achieved for a tapered fiber with a waist diameter of 5 \(\mu\)m and the total length of 11 cm. It should be noted that slightly pulling the tapered fiber might help to let pulses appear after the pulling process is done. For more details on the tapering system please see Section 3.4.

Fig. 3.3 shows the transmission of light through the tapered fiber measured by sending a train of picosecond (ps) pulses (at different powers) at a repetition rate of 37 MHz. This measurement has to be done without moving the taper. The blue curve in this graph is the
Chapter 3. Passive Mode-Locking in Fiber Lasers

Figure 3.3: Power-dependent transmission through a SA based on nonlinear multi-mode interaction in a tapered fiber

The transmission is measured as the ratio of transmitted power of light to the input power, which is increased by 6% when the intensity of light increases from 25 to 250 MW/cm².

Figure 3.4: Typical pulse trains of a Q-switched fiber laser at different pump powers from 34.8 mW to 59.9 mW.

Fig. 3.4 shows the typical Q-switched pulse trains (taken with an oscilloscope) coming out of the fiber laser (Fig. 3.2(a)) at different pump powers from 34.8 mW to 59.9 mW.
Clearly, the pulse duration decreases with increased pump power. The optical spectrum of the Q-switched fiber laser measured by an optical spectrum analyzer is depicted in Fig. 3.5(a). Fig. 3.5(b) shows the radio-frequency (RF) spectrum of the Q-switched laser at the pump power of 39.5 mW. The inset shows the RF spectrum over a frequency range of 250 kHz at a pump power of 54.5 mW. The fundamental peak is at 13.7 kHz which corresponds to the repetition rate shown in Fig. 3.4(b).

![Figure 3.5: (a) Optical spectrum of the Q-switched fiber laser. (b) RF spectrum of the Q-switched fiber laser at the pump power of 39.5 mW; Bandwidth resolution: 10 Hz, inset: RF spectrum over a frequency range of 250 kHz.](image)

As shown in Fig. 3.6(a), the output power of the laser increases by increasing the pump power, giving 0.7 mW of output at the highest pump power of 59.9 mW. The measured repetition rate and the pulse duration at different pump powers are shown in Fig. 3.6(b).
Chapter 3. Passive Mode-Locking in Fiber Lasers

The repetition rate increases from 11.6 kHz to 20.5 kHz as the pump power increases from 34.8 mW to 59.9 mW. The Q-switched train is a manifestation of relaxation oscillations typical of solid state lasers with long lifetime $T_1$. As the pump rate $R$ of the upper state increases, the effective lifetime of the transition decreases as

$$T_{1,\text{eff}} = \frac{1}{R + \frac{1}{T_1}}.$$

As in all Q-switched operation, the pulse duration decreases with increased pump power to a minimum pulse duration of 4.1 $\mu$s at the highest pump power of 59.9 mW. The corresponding pulse energy and peak power of the Q-switched pulses are calculated and shown in Fig. 3.6(c). Both of these parameters increase monotonously as a function of pump power. The maximum pulse energy and peak power reach to 35.2 nJ and 7.3 mW, respectively.

Further theoretical and experimental studies and more reliable tapering machine are needed to generate mode-locked pulses using this technique.

3.3 Saturable Absorbers based on CNTs Squeezed Between Two Fiber Ferrules

Multi-wall and single-wall carbon nanotubes (CNTs) were first discovered by Sumio Iijima in 1991 [13] and 1993 [14], respectively. It was soon realized that single-wall CNTs can be either metallic or semiconducting depending on their structure (chirality) [7], and possess very fast ($<1$ ps) saturable absorption [15] being applied in mode-locking of fiber lasers [2]. CNT has therefore become a very popular nonlinear material for mode-locking of fiber lasers because of several advantages such as the possibility of making simple, compact, in-line, and fast saturable absorbers. Numerous reports have been published on unidirectional mode-locked fiber lasers using single mode fibers incorporating carbon
Chapter 3. Passive Mode-Locking in Fiber Lasers

nanotubes [16–21]. As the polarization of light propagating in a single mode fiber is very sensitive to external perturbations, there is a desire to apply this mode-locking technique to polarization maintaining fiber lasers. There are only a few reports on all-PM Erbium-doped fiber lasers mode-locked by CNTs. Nishizawa et al. demonstrated an all-PM Erbium-doped ultrashort-pulse fiber laser using a CNT-polyimide film as a saturable absorber [22]. An all-PM fiber ring laser reported by Jeong et al. [23] uses a side-polished (D-shaped) PM fiber coated with CNT/polymer composite.

Figure 3.7: Absorption spectrum of carbon nanotubes.

The characterized carbon nanotubes used in this work have tube diameters of 0.9 nm to 1.5 nm, and tube lengths of 0.3 µm to 4 µm. In Fig. 3.7, the absorption spectrum of CNTs shows a significant absorption of light at 1.55 µm which is usually the operating wavelength of Erbium-doped fiber lasers.

The easiest way to manufacture a CNT-based saturable absorber is by inserting CNTs between two fiber ferrules. CNTs can be directly deposited on the tip of a fiber ferrule or prepared as polymeric sheets to be placed between fiber ferrules. To deposit CNTs on the tip of a fiber ferrule (Fig. 3.8(a)) a CNT solution is prepared by mixing approximately 1 mg of CNTs with 8 ml of DI water and ultrasonically for 15 to 30 minutes. Then the fiber is dipped into the solution for a few minutes while a few milliwat power of a laser diode light at 1550 nm is passing through the fiber in order to absorb CNTs [18].
Fig. 3.8(b) shows deposited CNTs on the tip of the fiber ferrule. Then the fiber ferrules shown in Figures 3.8(a) and (b) are connected through an adaptor in Fig. 3.8(c) to form an in-line saturable absorber as can be seen in Fig. 3.8(d).

Figure 3.8: (a) Fiber ferrule before depositing CNTs. (b) Fiber ferrule after depositing CNTs. (c) Squeezing CNTs between two fiber ferrules through an adaptor. (d) Manufactured saturable absorber based on CNTs between two fiber ferrules. (e) CNT/PDMS layer prepared in a container. (f) 1mm by 1mm of the CNT/PDMS layer is placed on the tip of a fiber ferrule. (g) Thickness of CNT/PDMS layer measured by SEM is about 145 $\mu$m.

The other method to squeeze CNTs between fiber ferrules is placing a thin layer of CNT/polymer, as shown in Fig. 3.8(e), between two fiber ferrules. It can be done by mixing 0.5 mg of CNTs with 1 gram of a polymer which is polydimethylsiloxane (PDMS) in this study, ultrasonicating the solution for a few hours, degassing the solution in a vacuum chamber, pouring a small amount of the solution in a small container, and letting it cure for at least 12 hours. Then as shown in Fig. 3.8(f) a small piece (usually 1mm by 1mm) of the prepared layer is placed on the tip of the fiber ferrule to interact with the light passing through the finalized manufactured component shown in Fig. 3.8(d). Figure 3.8(g) shows the CNT/PDMS layer with the thickness of 145 $\mu$m which was measured using a scanning electron microscope (SEM).
Chapter 3. Passive Mode-Locking in Fiber Lasers

However, we have observed that this configuration has a lifetime ranging from a few hours (in the case of colliding pulse bidirectional lasers) to several months (in unidirectional lasers). The direct interaction of light with CNTs between two fiber ferrules burns the CNTs easily. The burned spot on the CNT/PDMS layer is pictured using a standard microscope at different magnifications of 15, 40, and 100 in Fig. 3.9(a) to (c), respectively. Fig. 3.9(d) is the zoomed version of the selected part in Fig. 3.9(c). As can be seen, the CNTs enclosed in a circle with radius of 20 µm centered at the core center of a fiber with core radius of 4 µm are affected by irradiation of light passing through the layer placed between two fiber ferrules.

Figure 3.9: The CNT/polymer layer as a SA between two fiber ferrules is burned due to direct interaction of light with CNTs. The burned spot is circled in the photos taken by a microscope at different magnifications of (a) 15, (b) 40, and (c) 100.

Saturable absorbers prepared by embedding a tapered section of fiber in a CNT/polymer composite have much more robust structure. However, there is always some challenges to make SAs based on tapered fibers which will be discussed in details in the next section.
3.4 Saturable Absorbers Based on Tapered Fiber Embedded in CNT/Polymer Composite

This section describes another method of fabricating a SA based on CNT. In this technique, a tapered fiber will be covered with a CNT/polymer composite which provides a more robust structure with longer lifetime than the one discussed in Section 3.3. It also has a higher saturation intensity since the light is only coupled via an evanescent wave distributed over several millimeters. A schematic of a tapered fiber is shown in Fig. 3.10. The evanescent field outside the fiber taper will interact with any medium in the vicinity of the taper, in our case the CNT/polymer composite.

There are different methods to fabricate optical fiber microwires [24–27]. A schematic of our experimental setup is shown in Fig. 3.11. This fiber-pulling station consists of an oscillating heat source (oxyhydrogen flame) which makes a uniform heated length of fiber and brings the glass to a temperature greater than its softening point (1585°C for fused silica) while two motorized translation stages, Thorlabs MTS50-Z8-50 mm, pull the fiber from both ends. The computer-controlled motors are mounted on the optical table with MTS50-Z8 adapters. Attached to each motor are optical fiber holders which clamp the fiber in their V-grooves by strong magnets. The V-grooves should be aligned for maximum transmission of light through a piece of fiber carrying the light from diode laser in Fig. 3.11 to the power meter. It can be done by monitoring the transmitted power using the power.
Chapter 3. Passive Mode-Locking in Fiber Lasers

Fig. 3.11: Fiber tapering station

As depicted in Fig. 3.11, the optical transmission of the taper is monitored during the pulling process using a diode laser at 1550 nm and a power meter connected to a computer.

Fig. 3.12(a) shows the original fiber and the tapered one under a microscope with magnification of 40. A tapered fiber with waist diameter of 5 µm, usually ideal for mode-locking, is shown in Fig. 3.12(b) taken by a microscope with magnification of 100. Fig. 3.12(c) is the zoomed version of the selected part in Fig. 3.12(b).

As depicted in Fig. 3.11, the optical transmission of the taper is monitored during the pulling process using a diode laser at 1550 nm and a power meter connected to a computer.
Fig. 3.13(a) shows the normalized transmission as a function of time during the pulling process. The transmission decreases dramatically at the initial pulling phase, and reaches a maximum of 96% at the end of the pulling process indicated by the red dashed line when a waist diameter of 15 $\mu$m is obtained. The tapered section is thereafter covered with a carbon nanotubes/polymer composite. We have used Polydimethylsiloxane (PDMS) as a polymer. The evanescent field outside the tapered fiber will interact the CNT/polymer composite. With a 5 $\mu$m tapered fiber, the evanescent field can be sufficiently intense to saturate the CNTs. The transmission of the saturable absorber to a train of pulses with repetition rate of 35 MHz and pulse duration of 0.6 ps is plotted in Fig. 3.13(b). A 2% increase in transmission of the SA is observed as the average input power is ramped from 100 $\mu$W to 1.6 mW (converted to intensity in Fig. 3.13(b)). The latter is the maximum average power of the home-made mode-locked fiber laser used to measure the transmission of the saturable absorber.

Figure 3.13: (a) Normalized transmission versus time as the fiber is pulled to a final waist diameter of 15 $\mu$m indicated by the red dashed line. (b) Transmission of a 5 $\mu$m tapered fiber embedded in CNT/PDMS as a function of the intensity of a home-made mode-locked fiber laser with repetition rate of 35 MHz and pulse duration of 0.6 ps propagating in PM fiber with core diameter of 8 $\mu$m.

Fig. 3.14 shows a comparison between the saturation curves of a saturable absorber based on a tapered fiber covered with CNTs (blue dots) and the saturable absorber based on nonlinear multi-mode interaction in a tapered fiber (black dots). The blue curve in this
Chapter 3. Passive Mode-Locking in Fiber Lasers

Graph is the best fit to the experimental data. As can be seen, the saturation in the tapered fiber covered with CNTs happens at lower intensity than that in SA based on multi-mode interaction (MMI) in a tapered fiber (Section 3.2). It confirms that nonlinearity of CNTs is higher than that of the Kerr effect discussed in Section 3.2.

![Graph showing comparison between saturation intensities of SAs based on Kerr effect of multi-mode interaction (MMI) in tapered fiber (black dots) and tapered fiber covered with CNTs (blue dots).](image)

Figure 3.14: A comparison between saturation intensities of SAs based on Kerr effect of multi-mode interaction (MMI) in tapered fiber (black dots) and tapered fiber covered with CNTs (blue dots).

![Images of the final product for a SA based on tapered fiber covered with CNTs in (a) an Aluminum or (b) a plastic container. The tapered section of the fiber is covered by CNTs/PDMS and the sides are filled with PDMS.](image)

Figure 3.15: The final product for a SA based on tapered fiber covered with CNTs is shown in Fig. 3.15. CNTs/PDMS covers the tapered section of a fiber which is glued to the ends of...
Chapter 3. Passive Mode-Locking in Fiber Lasers

an Aluminum (Fig. 3.15(a)) or plastic (Fig. 3.15(b)) container. The sides of the tapered section are filled with PDMS which needs about 12 hours to cure.

In the rest of this section, a comprehensive study has been made to assess the environmental stability of CNT-based SAs, and in some cases power dependent loss of polarization of light passing through the SA.

3.4.1 Polarization Study on SAs Based on Tapered PM Fibers Covered with CNTs

The possibility of making a taper with a polarization maintaining fiber, down to a few micron, that preserves polarization has been demonstrated [28]. However, there is some randomness in the final characteristics of the taper, because of the difficulty in controlling some of the parameters, such as air currents, vibration, dust, instability of the flame etc. The uncontrollability of a taper is compounded when tapering PM fiber, because the stress rods are modified in the pulling process, and any small twist in the tapered section results in changing the polarization state of the light (see Appendix A for the properties of PM fibers).

Despite our low manufacturing yield, polarization preserving (PP) saturable absorbers are realized. Figure 3.16(a) and (b) shows the polarization measurement of the transmitted light at 1550 nm through a polarization preserving saturable absorber at different input powers. The light source is a fiber coupled continuous wave (cw) laser diode at 1550 nm, linearly polarized along the slow axis of the PM fiber. The polarization state of the transmitted light through the SA is measured using a rotating polarizing cube for a full 360° of rotation at different input powers from 1.2 mw to 17.1 mw. A detailed explanation on the polarization measurement procedure and its related set-up can be found in Appendix B [29].
Chapter 3. Passive Mode-Locking in Fiber Lasers

Figure 3.16: Polarization measurement of the transmitted light through the tapered section of a PM fiber covered with CNTs. Transmitted light passing through a rotating polarizing cube, for linearly polarized light at different input powers from 1.2 mW to 17.1 mW for (a) PP saturable absorber and (c) non-PP saturable absorber. Ellipticity and angle of the ellipses [corresponding to (a) and (c)] for (b) PP saturable absorber and (d) non-PP saturable absorber at different input powers. Inset in plot (a) is the cross section of the PM fiber showing the chosen coordinate system to measure the angle of ellipse.

The zero angle of the cube is chosen along the fast axis of the PM fiber which is indicated as $x$-axis in the inset of Fig. 3.16(a). As can be seen in this figure, the transmitted light is maximum at 90°, and reaches a minimum at zero angle. The ratio of the minimum to maximum transmitted light gives the ellipticity of the polarization state of the light, being zero for linear polarization and unity for circular polarization. Using a simple Matlab program, the polarization state of the light transmitted through a PP saturable absorber can be easily analyzed. The ellipticity and the angle of the ellipse with respect to the fast axis of the PM fiber ($x$-axis) are plotted in Fig. 3.16(b) for different input powers. The coordinates to which the ellipse is referenced are indicated on a cross-section of the PM
The ellipticity plotted in Fig. 3.16(b) is seen to depend on the input power, varying monotonically from 0.1 to 0.2 with increasing power. The first point corresponding to the lowest input power is however a (reproducible) anomaly. The polarization of the transmitted light is thus very close to linear, and the orientation of the polarization of the transmitted light is stable at different input powers. This saturable absorber preserves the polarization of the input linearly polarized light to a very good approximation.

<table>
<thead>
<tr>
<th>CNT-SA</th>
<th>$\epsilon_{\text{min}}$</th>
<th>$\epsilon_{\text{max}}$</th>
<th>$\Delta \epsilon$</th>
<th>$\Delta \theta$ (degree)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>0.2</td>
<td>0.4</td>
<td>0.2</td>
<td>14</td>
</tr>
<tr>
<td>2</td>
<td>0.3</td>
<td>0.8</td>
<td>0.5</td>
<td>90</td>
</tr>
<tr>
<td>3</td>
<td>0.2</td>
<td>0.4</td>
<td>0.2</td>
<td>30</td>
</tr>
<tr>
<td>4</td>
<td>0.2</td>
<td>0.7</td>
<td>0.5</td>
<td>60</td>
</tr>
<tr>
<td>5</td>
<td>0.1</td>
<td>0.2</td>
<td>0.1</td>
<td>8</td>
</tr>
<tr>
<td>6</td>
<td>0.1</td>
<td>0.2</td>
<td>0.1</td>
<td>7</td>
</tr>
<tr>
<td>7</td>
<td>0.0</td>
<td>0.4</td>
<td>0.4</td>
<td>32</td>
</tr>
<tr>
<td>8</td>
<td>0.3</td>
<td>0.5</td>
<td>0.2</td>
<td>103</td>
</tr>
<tr>
<td>9</td>
<td>0.2</td>
<td>0.4</td>
<td>0.2</td>
<td>30</td>
</tr>
<tr>
<td>10</td>
<td>0.1</td>
<td>0.2</td>
<td>0.1</td>
<td>3</td>
</tr>
</tbody>
</table>

Table 3.1: Measured polarization states of the transmitted light through ten different saturable absorbers. Polarization is measured at 30 different input powers for each SA but only the minimum and maximum values of the ellipticities and their difference ($\epsilon_{\text{min}}$, $\epsilon_{\text{max}}$, and $\Delta \epsilon$), and the maximum amount of change in the angle of ellipse ($\Delta \theta$) are reported in this table. Based on the defined criteria in the text, numbers 5, 6, and 10 preserve the polarization of light.

Ten different saturable absorbers with a very similar procedure and condition were fabricated. The measured polarization states of the transmitted light through all SAs are listed in Table 3.1. The polarization state is measured at 30 different input powers for each SA but only the minimum and maximum values of the ellipticities and their difference ($\epsilon_{\text{min}}$, $\epsilon_{\text{max}}$, and $\Delta \epsilon$) are listed. The maximum amount of change in the angle of ellipse ($\Delta \theta$) is also reported in this table. The values of $\epsilon_{\text{min}}$ and $\epsilon_{\text{max}}$ are not necessarily related to the lowest and highest input powers. We choose to define linear polarization here as ellipticity is less than 0.2. A PP saturable absorber should not change the polarization state of the input light at different powers. However, 10% change in ellipticity and angle...
of ellipse is acceptable. Therefore if \( \Delta \epsilon \leq 0.1 \) and at the same time \( \Delta \theta \leq 9^\circ \), the SA preserves the polarization of light at different powers. Based on these criteria it can be seen in Table 3.1 that only three attempts (number 5, 6 and 10) out of ten SAs are considered as PP saturable absorbers. A fabrication yield better than 30% requires a more sophisticated pulling, with more local heating (for instance electric heating) to accurately control the profile of the taper. The results shown in Fig. 3.16(a) and (b) are related to the saturable absorber number 6 in Table 3.1.

An example of polarization measurement of the transmitted light through an unsuccessful polarization preserving saturable absorber is shown in Fig. 3.16(c) and (d) which corresponds to the SA number 4 in Table 3.1. The raw measurement in Fig. 3.16(c) shows that indeed, the transmitted light is not linearly polarized anymore. Figure 3.16(d) shows that the ellipticity of the corresponding ellipse is changing between 0.2 and 0.7 and the angle of the ellipse changes between \( 83^\circ \) and \( 145^\circ \) by changing the input power. The power-dependent polarization state of light passing through the PM tapered fiber results from variations of fiber birefringence at different power of light. It will be shown in Section 3.5 of this chapter that a very small change of power of a cw light is sufficient to modify the birefringence of a PM fiber resulted in changing the beat length and consequently the polarization of light passing through a piece of PM fiber. In view of the short beat length (a few millimeters) of a PM fiber, the elliptically polarized light coming out of a non-PP saturable absorber leads to a completely unknown polarization state after an arbitrary length of PM fiber. Fortunately, as demonstrated in Section 3.4.2 of this chapter, in standard unidirectional all-PM mode-locked fiber lasers, polarization filtering by the isolator alleviates the demands on the tapered section.
3.4.2 Unidirectional Fiber Laser

To test the functionality of a SA, it has to be placed in a laser to be mode-locked. Fig. 3.17 is a schematic configuration of a unidirectional mode-locked all-PM fiber laser. This laser includes 91 cm of Er-doped polarization maintaining fiber as a gain medium, pumped by a laser diode at 980 nm via a PM wavelength division multiplexer. A polarization dependent isolator is added to the cavity to ensure unidirectional operation of the laser. This isolator passes the polarized light along the slow axis of the PM fiber and blocks any other polarization in the cavity. A PM output coupler extracts 30% of the light from the fiber laser cavity. The fabricated saturable absorber based on a tapered fiber embedded in CNT/PDMS composite leads to stable soliton mode-locking with Kelly sidebands [30, 31]. The perimeter of the cavity is about 551 cm including 91 cm of PM Er-doped fiber (Nufern PM-ESF-7/125) with the dispersion of 15.9 (ps/nm)/km at 1550 nm (group velocity dispersion of -0.0202 ps²/m) and 460 cm of Corning PM15-U25 fiber with the dispersion of 17.3 (ps/nm)/km at 1550 nm (group velocity dispersion of -0.0220 ps²/m). So the net round trip dispersion of the cavity is -0.12 ps² resulting in soliton mode-locking of the fiber laser.

![Figure 3.17: All-polarization maintaining unidirectional mode-locked fiber laser. WDM: Wavelength Division Multiplexer.](image)

Both PP and non-PP saturable absorbers have been tested in the ring cavity shown in
Chapter 3. Passive Mode-Locking in Fiber Lasers

Fig. 3.17. Soliton mode-locking is achieved using either pp or non-PP saturable absorber with a spectrum as shown in Fig. 3.18(a). In this figure, the central wavelength is blue-shifted by 3 nm using a non-PP saturable absorber. This usually happens in pulling the fiber when the modes start beating and finally a wavelength around 1560 nm or even at 1530 nm is picked as a central wavelength depending on the tapering condition [27].

Of concern is the output polarization states of the fiber laser (Fig. 3.17) using PP or non-PP saturable absorbers which are shown in Figs. 3.18(b) and (c), respectively. Both experimental data points and fitted curves are shown in these figures. As can be seen regardless of using PP or non-PP saturable absorber in the laser cavity, the output is linearly polarized along the slow axis of the PM fiber. The ellipticities of the fitted ellipses in both cases are same and equal to 0.2 which can be considered as linear polarization based on the criterium defined in the Section 3.4.1. One concludes that only the modes that are both resonant and linear survive.

![Figure 3.18: (a) Optical spectrum of the mode-locked fiber laser using PP (blue curve) and non-PP (red curve) saturable absorbers. The output of mode-locked all-PM fiber laser is linearly polarized along the slow axis of the PM fiber when using (b) PP or (c) non-PP saturable absorber.](image)

Fig. 3.19(a) and (b) show the intensity autocorrelation (AC) traces of the laser output of
Chapter 3. Passive Mode-Locking in Fiber Lasers

Figure 3.19: (a) Intensity autocorrelation trace of the laser output mode-locked with a PP saturable absorber. Fitting with a sech\(^2\) shaped pulse indicates a pulse duration of 0.67 ps. (b) Intensity autocorrelation trace of the laser output mode-locked with a non-PP saturable absorber. Fitting with a sech\(^2\) shaped pulse indicates a pulse duration of 0.70 ps. Insets: RF spectrum of the fundamental harmonic of the laser pulse train with Frequency span of 5 MHz and resolution bandwidth of 3 kHz.

the all-PM mode-locked fiber laser shown in Fig. 3.17 using PP saturable absorber (number 6 in Table 3.1) and non-PP saturable absorber (number 4 in Table 3.1), respectively. The AC traces are both fitted to the sech\(^2\) function (red curves), suggesting sech–shaped pulses of 0.67 ps and 0.70 ps durations at Full Width Half Maximums (FWHM) for PP and non-PP saturable absorbers, respectively. The sech\(^2\) function is expected to fit the intensity AC traces since a soliton pulse is given by Equation 2.3. The difference in pulse durations using PP and non-PP saturable absorbers is only 30 fs which lies within the measurement
uncertainty. The small side peaks in Fig. 3.19(b) usually appear at higher pump rates, when there is higher gain than that required to maintain the energy of the soliton of order 1.

The pulse repetition rate of 37.755 MHz corresponds to the measured cavity length of 551 cm and an average group velocity of \(2.08 \times 10^8\) m/s along the slow axis of the PM fiber. The output power of the ML laser, pumped at 65 mW, has been measured as 750 \(\mu\)W or 650 \(\mu\)W using PP or non-PP saturable absorbers, respectively. Less output power using a non-PP saturable absorber is expected because the polarization-dependent isolator passes the linearly polarized light along the slow axis of the PM fiber, and is lossy for any other polarization state of the light which reaches it. The stability of the mode-locked fiber laser is measured by a radio frequency (RF) spectrum analyzer. The fundamental peak is shown as insets of Figs. 3.19(a) and (b) at the repetition rate of a typical laser, with a signal-to-noise ratio (SNR) of about 70 dB which is an indication of stable mode-locking.

<table>
<thead>
<tr>
<th>Laser specification</th>
<th>PP</th>
<th>non-PP</th>
</tr>
</thead>
<tbody>
<tr>
<td>Laser power (mW) at pump power of 65 mW</td>
<td>0.75</td>
<td>0.65</td>
</tr>
<tr>
<td>SNR of the RF spectrum (dB)</td>
<td>70</td>
<td>70</td>
</tr>
<tr>
<td>Pulse width (ps)</td>
<td>0.67</td>
<td>0.70</td>
</tr>
<tr>
<td>Central wavelength (nm)</td>
<td>1559</td>
<td>1556</td>
</tr>
<tr>
<td>Output polarization</td>
<td>Linear</td>
<td>Linear</td>
</tr>
</tbody>
</table>

Table 3.2: Laser specifications mode-locked by polarization preserving (PP) and non-polarization preserving (non-PP) saturable absorbers.

A summary of laser specifications comparing the use of a polarization preserving saturable absorber versus a non-polarization preserving saturable absorber is provided in table 3.2. As can be seen, the operation of the mode-locked fiber laser is very similar using either one. However, there are situations where it is desirable to operate the laser with two orthogonally polarized intracavity pulses, such that there be no coupling between them (see Section 4.5). This is also the case in laser gyro applications, where two pulses circulate in opposite directions in a ring laser [32–36]. Any coupling between the counter
circulating pulses results in a deadband, which will be explained in Section 4.4.

### 3.4.3 Thermal Effect

Thermal damage threshold of carbon nanotubes in CNT-based saturable absorbers is always a concern for the researchers in this area. It was claimed that a saturable absorber based on tapered fiber covered with CNTs has a higher damage threshold since the light is only coupled via an evanescent wave distributed over several millimeters along the tapered section. However, there is no study on the stability and temperature sensitivity of mode-locking using this kind of saturable absorbers except our work published in CLEO 2018 [37].

![Figure 3.20](image)

Figure 3.20: (a) Temperature dependence of the transmitted light through a saturable absorber based on tapered fiber covered with CNTs. (b) The output power of a fiber laser mode-locked by the SA in (a) at different temperatures.

Fig. 3.20(a) shows the transmission of the fabricated polarization preserving SA (number 6 in the Table 3.1) at different temperatures. In this measurement, the SA is placed on a temperature-controlled plate (Peltier cooler) and a cw laser diode light at 1550 nm is transmitted through the SA at different temperatures from 0°C to 30°C. First, the temperature
of the Peltier cooler stays at 0°C for about 50 seconds and the transmission of light through the SA is recorded as being nearly zero. Then, the temperature is set at 30°C (maximum achievable temperature) and the transmission of light is measured while the temperature of the SA is increasing towards the set temperature of 30°C. This heating process, which take about 150 s, is shown in Fig. 3.20(a) by the red rectangular shadow. As can be seen, the SA is more transparent at higher temperatures and the rate of changing transmission from 0°C to 5°C (1.5 %/°C) is 7.5 times faster than that from 5°C to 30°C (0.2 %/°C). The temperature of SA is kept at 30°C for about 100 s and cooled back to 0°C in the cooling process (blue rectangular shadow in Fig. 3.20(a)) more slowly than heating.

Figure 3.20(b) shows the output power of the mode-locked fiber laser (Fig. 3.17) while the SA is placed on the temperature-controlled plate at different temperatures from 0°C to 30°C. The figure shows the output of the laser being tunable by changing the temperature of the SA or the ambient temperature. Having a very smooth pattern without any abrupt drop in output power demonstrates the stable mode-locking at different temperatures for about 10 minutes (Fig. 3.20(b)).

In order to check the stability of mode-locking, the operation of the mode-locked laser at room temperature is monitored for 22 hours by recording the output power of the laser as shown in Fig. 3.21(a). The drastic changes in the power of light in Fig. 3.21(a) is an indication of unstable mode-locking at room temperature in long-term. In this experiment the SA is in contact with the surface of the optical table at room temperature. The mode-locked pulses appear directly after turning the pump laser on, and the output power is monitored and recorded by a power meter. The mode-locking operation of the laser depicted as blue spikes in Fig. 3.21(a) stays stable for time intervals of duration ≈22 minutes separated by intervals of ≈18 minutes in which the laser stops mode-locking. Fig. 3.21(b) magnifies these intervals of operation. These time durations are approximate, and vary over the whole measurement of 22 hours. Such a behavior can be explained considering the temperature-dependent SA transmission and the plot of laser output of Fig. 3.20(a).
Chapter 3. Passive Mode-Locking in Fiber Lasers

and (b), respectively. For a better understanding, an explanation is provided starting from point “a” in Fig. 3.21(b) to point “e” in this figure. Continuous ML laser operation starting from point “a” in Fig. 3.21(b) will increase the local temperature of CNTs and result in an increase of SA transmission. Consequently the laser output reaches the maximum at point “b”. At this point, the SA has maximum transmission (minimum absorption), which helps it cooling down. The laser output power is thereafter reduced from point “b” to “d”. The mode-locking operation stops at point “c” because of the SA being lossy (stronger absorber). After a few minutes from point “c” (cw laser operation) the absorption of light by the SA reaches its maximum at point “d” (minimum transmission), and heating of the absorber starts. Finally, mode-locking is back at point “e” when the SA is heated up sufficiently to overcome the threshold of mode-locking. Such a periodic behavior in Fig. 3.21(a) is therefore the outcome of a dynamic balance between temperature of the SA and its transmission.

![Figure 3.21](image)

Figure 3.21: Monitored laser output for 22 hours with the saturable absorber at the (a) unstabilized room temperature and (c) stabilized temperature of 21.7 °C. (b) Looking at a time interval of 2 hours from (a).

By stabilizing the temperature of SA at 21.7°C using a Peltier cooler, the operation of mode-locking becomes more stable with less variation in the laser output as shown in Fig. 3.21(c). In this experiment, the saturable absorber is placed on the surface of a Peltier cooler whose temperature is controlled by adjusting the PID (Proportional-Integral-Derivative) parameters of a temperature controller. As can be seen in Fig. 3.21(c), the
stable mode-locking (blue oscillation) stays for about 4 hours from its initiation. The inset is the magnified scale of a portion of this graph which indicates the short time intervals that laser stops mode-locking (red data points). The double blue curves in the inset comes from small variation of temperature around the set point of 21.7°C as the temperature controller is slightly overcorrecting.

3.5 Saturable Absorbers Based on Power-Dependent Birefringence of PM Fibers

A polarization maintaining fiber can be seen as extremely high order waveplate. As a result, if circularly polarized light is sent through such a fiber, the polarization of the transmitted light is extremely sensitive to the fiber environment. Background to this section is a review of fundamental birefringence properties in PM fibers provided in Appendix A. Our technique of polarization measurement is explained in detail in Appendix B. These properties result in extremely sensitive nonlinear loss (saturable absorption), but much slower than the two mechanisms discussed in the preceding sections.

It has been reported that small variations of beat length of a PM fiber can take place by changing the environmental conditions such as temperature [38, 39] (see Section 6.2) and stress [40]. It will be demonstrated here that power variations of a weak beam sent through a piece of PM fiber will also affect its beat length [39]. Accumulating beat length variations over only a few centimeters of a PM fiber results in a considerable change in the state of polarization (SOP) of the propagating light. This nonlinear effect is quite different from the intensity-dependent polarization rotation due to Kerr effect, exploited for mode-locking through polarization rotation [41]. The nonlinear index in silica being of the order of $10^{-16}$ cm$^2$/W, Kerr-induced mode-locking by polarization rotation involves peak powers of the order of tens of watts. As will be shown in this section, the polarization rotation that
Chapter 3. Passive Mode-Locking in Fiber Lasers

we observe involves peak powers of only tens of mW, hence an equivalent nonlinear index of the order of $10^{-12}$ cm$^2$/W.

![Figure 3.22: Experimental setup to study power induced birefringence in PM fibers. Light from a 1550 nm diode laser is made circularly polarized before being sent through the PM fiber. QWP: quarter wave plate.](image)

To make a comprehensive determination of the polarization modification of light passing through a PM fiber, the complete polarization ellipse is measured at different powers of light. As shown in Fig. 3.22, a cw laser diode at 1550 nm generates low power linearly polarized light which is sent through a quarter-wave plate at 45° to create circularly polarized light, to excite both polarization modes of the PM fiber independently of the orientation of the input end of the PM fiber. The transmitted light passing through the PM fiber is collimated and sent to a home-made Labview-controlled polarimeter to extract the actual polarization ellipse of light coming out of the PM fiber in Fig. 3.22. This method of polarimetry is explained in detail in Appendix B of this dissertation.
Chapter 3. Passive Mode-Locking in Fiber Lasers

As mentioned in Appendix A, the polarization of a linearly polarized light input to a PM fiber along one of its principal axes is maintained while propagating in the fiber. Any other input polarization will be periodically modified along the PM fiber. As shown in Appendix A, the phase shift between two polarization modes (for a particular $\lambda$) propagating in a PM fiber is directly proportional to the birefringence ($B$) and the length ($L$) of the PM fiber. As shown in Fig. 3.22, a circularly polarized light at 1550 nm sent to 17.5 cm of a PANDA PM fiber with birefringence of 0.0005 will become elliptical, with power-dependent output polarization measured by the polarimeter.

![Figure 3.23](image)

Figure 3.23: (a) Projection patterns of the transmitted circularly polarized laser light at different powers through a 17.5 cm PM fiber (at room temperature) followed by a rotating polarizer. (b) Ellipticities and angles of the polarization ellipses associated to (a).

Figure 3.23 shows the polarization modification as the power of light is incremented from 0.7 mW to 35 mW. The data presented in Fig. 3.23(a) show a rotating polarization ellipse, when circularly polarized light at different powers is input to the PM fiber. The change in ellipticity and angle of the ellipse are plotted as a function of input power in Fig. 3.23(b). Even with such a short fiber section, the polarization state is sensitive to a mW change in the power of cw light.

Figure 3.24(a) is a 2D color-coded representation of Fig. 3.23(a). This graph shows the normalized transmission through the PM fiber followed by a polarizer at different
angles, as a function of input power. The shaded regions in Figs. 3.23(a) and 3.24(a) correspond to the range of polarizer angles (from 15° to 90°) for which the transmission of light is increasing with light power. As illustrated in Fig. 3.24(b), at the optimal polarizer angle of 58°, the change in transmission with increasing power reaches to a maximum of 86%. Therefore a short piece of PM fiber can be used as a saturable absorber of very low saturation intensity compared to that of other SAs shown in Fig. 3.14. As mentioned earlier, this amount of intensity is not sufficient to induce the Kerr effect. The phase shift induced by Kerr effect is given by,

$$\Delta \varphi = \frac{2\pi n_2 I}{\lambda} L$$

(3.1)

where \(n_2 = 2.7 \times 10^{-16}\) is the nonlinear index of silica-core fiber, \(I\) is the intensity and \(\lambda\) is the wavelength of propagating light, and \(L\) is the length of the fiber. For the calculated range of intensity in this work (Fig. 3.24(b)), Kerr effect induced phase shift is in the order of \(10^{-7}\) radians which is too small to modify the input polarization. The origin of this huge change of polarization results in other novel applications of PM fibers which will be discussed in more details in Chapter 6.
Chapter 3. Passive Mode-Locking in Fiber Lasers

References


Chapter 3. Passive Mode-Locking in Fiber Lasers


Chapter 3. Passive Mode-Locking in Fiber Lasers


Chapter 3. Passive Mode-Locking in Fiber Lasers


Chapter 4

Intracavity Phase Interferometry

4.1 Introduction

Intracavity Phase Interferometry (IPI) is a frequency comb metrology technique in which two mode-locked pulses (frequency combs) are generated in the same cavity in opposite directions (in the case of ring cavity) with the same repetition rates. A sensing element in the cavity imparts a phase shift to one pulse, which alters the CEO\(^1\) of the corresponding frequency comb and not the teeth spacing. The measurement is conducted outside the laser cavity by interfering the shifted comb with the other one taken as reference. The measured parameter is the beat-note frequency which can be used to directly calculate the phase difference between pulses.

In this chapter, IPI will be introduced, and compared with traditional interferometers such as the Michelson. Two different laser designs for IPI applications are linear and ring to measure different physical parameters. Linear lasers based on polarization maintaining fibers provide the possibility of generating two orthogonally polarized pulses in the laser cavity to overcome deadband in IPI. The possibility of having mode-locked linear fiber

\(^{1}\)Carrier to Envelope Offset
Chapter 4. Intracavity Phase Interferometry

laser with cross-polarized pulses will be investigated.

4.2 Fundamentals of IPI

Interferometry has been a tool for precision measurement long before the invention of lasers. It involves comparing two paths (sample and reference) of single frequency or multi color light. In classical or passive interferometry, the phase difference between a sample and reference beam is measured by recording the amplitude of the overlapping (interfering) fields. For instance, in the Michelson interferometer shown in Fig. 4.1(a), an external laser source is used to measure the phase variation ($\Delta \phi$) introduced by an optical element. The laser beam is split into two beams (sample and reference) using a beam splitter (BS). The phase difference $\Delta \phi$ can be measured by interfering the sampling beam which passes through the optical element with the reference beam of the same frequency. As depicted in Fig. 4.1(b), the phase difference is therefore measured by counting the number of fringes (destructive interference) of the interfering pattern on the detector as,

$$\Delta \phi = k \Delta L,$$

where $k = 2\pi/\lambda$ and $\Delta L = (m + \epsilon)\lambda/2$ in which $m = 0, 1, 2, ...$ is the number of fringes and $\epsilon$ indicates the fractional fringe\(^2\). $\Delta L$ is the difference in distances traveled by the sample and reference beams, and $\lambda$ is the wavelength of light. As a result, the sensitivity of this method is in the order of a fraction of wavelength or 1 $\mu$m for the near infrared region.

A considerable increase in sensitivity can be achieved by inserting the sample (physical parameter to be measured) inside an active laser cavity. Active interferometry or intracavity phase interferometry is realized as a cross breeding of “frequency combs”, “interferometer” and “resonator based laser sensors”. Since the invention of the laser and realization

\(^2\)The accuracy with which $\epsilon$ (hence $\Delta L$) can be measured is determined by the amplitude noise.
of coherent light, there had been various ways of tailoring laser sources for precision measurements [1]. In the case of a continuous laser, utmost stretching of the coherence time leads to a precisely defined single frequency. Comparable precision is achieved through the mode-locking mechanism, creating a train of equally spaced pulses, of which the spectrum is a frequency comb. The group velocity of the intracavity pulse defines the teeth spacing, while the phase velocity determines the absolute position of this comb or “carrier to envelope frequency offset” (CEO). CEO is defined in Section 2.2 (Chapter 2) as the position (in frequency) of the first tooth of an extended comb with respect to 0 Hz, and extremely sensitive to any phase perturbation inside the laser cavity. Stabilization of CEO in femtosecond lasers is a complicated process which has been extensively studied (see for instance [2]).

In IPI, a mode-locked laser with two intracavity pulses produces two frequency combs, correlated without need of stabilization. The noise of the two combs is correlated because
Chapter 4. Intracavity Phase Interferometry

the reference and sampling pulses are part of the same laser cavity with a shared gain medium.

By interfering the two correlated combs outside the laser cavity, the phase shift between combs (due to a physical parameter to be measured) will be measured as a beat note frequency. Since the IPI response is measured in frequency, the resolution of this method can be seven to eight orders of magnitude better than that of a traditional interferometer which is based on measuring the intensity of interference fringes. Intracavity phase interferometry was first realized in 1991 by Dennis, Lai and Diels [3, 4]. Many advances were investigated over decades of extensive work on this technique by this research group [5–11] and by others (for instance [12, 13]).

4.3 Mode-Locked Lasers For IPI

The main concern in IPI design is generating two uncoupled pulse trains with the same repetition rate in a laser cavity. Two methods are possible: (i) gating the gain, as in Optical Parametric Oscillators (OPO), or (ii) gating through the losses, as with saturable absorbers. We have chosen here this second method, where amplitude coupling mechanism at a saturable absorber forces pulses to cross at the same point (SA in Fig. 4.2) at each round trip. However, this mechanism should exclude any phase coupling between the circulating pulses to avoid deadband a problem that will be discussed later in this chapter. Whether to use a ring or linear cavity for IPI depends on the quantity to be measured. The principle of the measurement is the same in both laser designs. The case of a linear cavity is sketched in Fig. 4.2(a) and that of a ring cavity in Fig. 4.2(b). The corresponding traditional interferometers are Michelson for the linear design and Mach-Zender for the ring cavity. Two short pulses in each laser cavity propagate in opposite sense, and share almost all of the optical elements with only one exception: the red pulse is affected by the “sample”, while the blue is not. Please note that the mirrors M2 and M3 in the linear cavity (Fig. 4.2(a))
Chapter 4. Intracavity Phase Interferometry

Figure 4.2: Sketch of (a) a linear and (b) a ring ML laser for IPI generating two pulses with the same rep. rates to interfere outside the laser cavity which is shown in green dashed lines. (c) The interference pattern (yellow) of the interfering pulse trains in time. The frequency of the envelope (red sinusoidal curve) is measured as the beat note. (d) Frequency shift between two combs as a function of phase shift \( \Delta \phi \) due to a physical parameter such as a change of \( \Delta P \) in cavity perimeter of \( P \) (twice the cavity length in the case of a linear cavity). SA: Saturable Absorber, M: Mirror, BS: Beam Splitter, D: Detector.

have to be identical. A fraction of each of the two intracavity pulses is extracted from the cavity through a beam splitter (BS2 in linear and BS1 in ring cavities), and made to combine by a set of mirrors and beam splitters on a detector (D) in Figs. 4.2(a) and (b). The physical quantity to be measured (flow velocity [4], electric field [14, 15], magnetic field [16], rotation [3], acceleration [11] and displacement [17]) imparts a phase shift \( \Delta \phi \)
between the two intracavity pulses per round trip, which results in a frequency shift of [11]:

\[
\Delta \nu = \frac{\Delta \phi}{2\pi \tau_{rt}} = \nu \frac{\Delta P}{P},
\]

(4.2)

where \( \tau_{rt} \) is the cavity round-trip time at the phases velocity, \( \nu \) is the frequency of light, \( P \) is the optical perimeter of the ring laser cavity (twice the cavity length in the case of a linear cavity), and \( \Delta P \) is the difference in optical path length that would correspond to the phase shift \( \Delta \phi \). The frequency change of \( \Delta \nu \) is measured as a beat note by interfering two pulse trains (frequency combs) outside the laser cavity. The interference pattern of pulse trains is shown in yellow in Fig. 4.2(c) which is taken by an oscilloscope. The oscillation frequency of the red sinusoidal curve, the envelope of the modulated pulse train, is measured as the beat note frequency which is proportional to \( \Delta \phi \) as plotted in Fig. 4.2(d).

As can be seen in Fig. 4.3(a), the beat note frequency \( \Delta \nu \) is equal to the difference in CEOs of the two combs with the same repetition rates \( \nu_{rt} = 1/\tau_{rt} \). In this figure, \( \Delta \phi \) is the phase difference between two frequency combs, and is different from the carrier to envelope phase (CEP) \( \Delta \varphi \) which was defined in Ch.2. A typical measured beat note is plotted in Fig. 4.3(b) using a slow detector to eliminate high frequency pulse train.

The bandwidth of the beat note can be as small as 0.2 Hz [18], even though each comb has a bandwidth larger than 1 MHz, again indicating the correlation between combs. This amount of bandwidth corresponds to a phase shift of \( \approx 10^{-8} \) rad or optical path length change of a few fm. The sensitivity of the intracavity measurement is thus typically seven to eight orders of magnitude better than that of the passive interferometer.

IPI has many advantages over other comb sensing methods mentioned in Chapter 2. First, as the sensing method is based on detecting a frequency shift between two combs, the measurement does not depend on the pulse amplitude, which implies that the cavity output power can be relatively low for accurate measurements and IPI is not affected by amplitude noise. Second, the mechanical noise is nearly completely washed out\(^3\). This

\(^3\)In the ns time difference that the pulses hit a cavity mirror, its position may have moved by
Chapter 4. Intracavity Phase Interferometry

Figure 4.3: (a) Interfering two frequency combs with different CEOs and same rep. rates $\nu_{rt} = 1/\tau_{rt}$. $\Delta\phi$ is the phase difference between frequency combs. (b) The beat note frequency is measured as the difference in CEOs of the two combs.

is because the pulses are generated in the same cavity, meaning that all phases imparted to one pulse are automatically given to the other, except for the sensing element, which is specifically designed to give a different phase to each pulse [9]. Finally, and most importantly, unlike in other comb metrology, stabilization of the carrier to envelop offset is completely waived. It is because the measured beat note equals to the difference between CEOs of two correlated frequency combs and the absolute values of CEOs are not relevant in IPI. However, the phase coupling between pulses due to the back-scattering from SA where pulses meet is a main issue which creates a deadband in IPI response. This topic will be briefly covered in Section 4.4.

4.4 Deadband in IPI

As explained in Section 4.3, a mode-locked laser for IPI has to generate two pulses with a few fm, resulting in a broadening of the beat note bandwidth. This effect is minimized in some cavity geometries [11].
Chapter 4. Intracavity Phase Interferometry

the same repetition rate. This condition comes true only if pulses meet at the same location in the cavity at each round trip. The mutual saturation of the saturable absorber forces two pulses propagating in the cavity to cross at a predetermined location of the SA [11]. This causes phase coupling with the back-scattered light from the SA to create a deadband region in the characteristic plot of IPI response shown in Fig. 4.4. The deadband is a range of phase differences between two pulses in a cavity, for which there is no beat note. In other words, the deadband in IPI limits the smallest measurable phase shift between pulses which is caused by a physical parameter to be measured.

Figure 4.4: Beat note frequency as a function of phase shift between two frequency combs in a laser for IPI. A virtual phase shift (bias) in the laser cavity moves the operating point away from deadband. Small frequency shift $\Delta \nu$ associated to phase shift $\Delta \phi$ can be measured by subtracting the known bias from the IPI response.

In Fig. 4.4 the amount of phase shift $\Delta \phi$ is within the deadband of the IPI sensor for which there is no response. The deadband region could be avoided by introducing an artificial phase shift with larger magnitude than the deadband. For instance, it can be done
Chapter 4. Intracavity Phase Interferometry

by placing an electro-optic phase modulator driven by an electrical signal at the round-trip time of a ring cavity [19]. Such biasing moves the operating point of the IPI sensor away from deadband as shown with blue dashed lines in Fig. 4.4. The actual phase shift $\Delta \phi$ can therefore be measured by merely subtracting the known bias from the IPI response as depicted in Fig. 4.4.

Mechanical dithering has been used in commercial laser gyroscopes for decades. this partially defeats the purpose of a laser gyro to be an instrument without moving part! The mode-locked laser offers the possibility of electro-optic dithering [19], hence no moving part. It is however preferable to eliminate the deadband by suppressing any phase coupling between the two circulating pulses in a mode-locked laser. There are two disadvantages in the dithering technique: (i) the dithering introduces noise, thus a broadening of the beat note bandwidth and a decreased sensitivity, and (ii) the dithering does not eliminate totally the nonlinearity of response associated with the deadband.

One possible solution to avoid phase coupling between pulses at the saturable absorber is to generate orthogonally polarized pulses in the laser cavity. Mode-locked polarization maintaining (PM) fiber lasers are the most promising lasers towards deadband-free IPI, because the two pulses can be made to propagate along the slow axis and the fast axis; two orthogonally polarized, non interacting, cavities. This proposed solution to remove the deadband in IPI will be discussed briefly in next section. In Chapter 5, the experimental results on ring fiber laser will be elaborated.

4.5 IPI in Mode-Locked Linear Fiber Lasers

Fiber technology is traditionally used for sensing applications, where a phase shift is measured either in a resonator or through evanescent wave coupling in a tapered fiber. For instance, Sagnac interference in an optical system consisting of a fiber loop with counter-
Chapter 4. Intracavity Phase Interferometry

propagating light beams can be used for rotation, temperature, tension, magnetic field sensing [20–22] and medical applications [23]. Michelson and Fabry-Perot interferometers are also used for temperature sensing [24, 25]. A simple structure based on non-adiabatic tapered optical fiber utilizes the evanescent field of an optical microfiber to enhance the light-biomaterial interaction for biosensing applications [26, 27]. Intracavity Phase Interferometry can be applied to all these applications, with the benefit of orders of magnitude enhanced sensitivity.

The IPI technique has successfully made measurements of nonlinear index, gas flow, electro-optic coefficients, and rotation [3, 4, 15, 18] using both ring and linear cavities. These demonstrations used free-space component lasers which do not lend themselves to field applications. Mode-locked fiber lasers are the most promising media to implement IPI due to their ability to produce ultrashort pulses in a robust, compact system that does not require overwhelming alignment.

There is abundant literature on unidirectional mode-locked fiber lasers in the form of ring [28–33] or linear cavities [34, 35]. However, achieving colliding pulse mode-locking in bidirectional fiber lasers to realize correlated frequency combs is surprisingly challenging. The difficulties stem from the high gain and loss and large nonlinearities of fiber optics. Pulses circulating in opposite directions in a bidirectional laser traverse the optical components in a different order creating an asymmetry in the cavity. This asymmetry, at the worst, leads to the tendency of the two circulating pulses to unlock from crossing at the saturable absorber. This results in having different repetition rates (pulse velocities) and wavelengths (frequencies); a mode of operation totally inadequate for IPI [36–38]. Remarkably successful implementations of IPI in passively mode-locked bidirectional (ring) fiber lasers, have been demonstrated by Kieu et al [39], and more recently by Krylov et al [12]. However, a large bias beat note is measured as a result of the asymmetry in phase velocities and large amount of nonlinearity in single mode fibers, which doesn’t let to measure the actual deadband of the IPI sensor. A nearly symmetric
design of a ring fiber laser to lower the intrinsic bias of the sensor will be presented in Chapter 5.

Figure 4.5: The fiber laser is terminated by an intracavity Michelson interferometer through a PBS which separates two polarization modes of the PM fiber. The mode-locked pulse linearly polarized along the fast axis of the PM fiber (“blue” pulse) propagates in the “reference” cavity. Simultaneously and independently, the “red” pulse (linearly polarized normal to the plane) propagates along the slow axis of the fiber and is separated through the PBS and sent to the sample arm of the Michelson. The sample can be anything that creates a phase shift between two pulses. The frequency combs corresponding to the fast and slow axis are extracted by output couplers (OC1 and OC2) and made to interfere on a detector D, where a beat note of frequency proportional to the phase shift is recorded. WDM: Wavelength Division Multiplexer, PBS: Polarizing Beam Splitter, OC: Output Coupler, M: Mirror, D: Detector.

A linear PM fiber laser for IPI provides the opportunity of generating orthogonally polarized pulses to remove deadband. A similar idea has been experimentally tested for a cw laser [40]. However, the lock-in effect (phase coupling) is much stronger in cw lasers since the beams overlap over the whole length of the cavity. In mode-locked lasers, the two propagating pulses do not occupy the same region of space at the same time. The lock-in effect is therefore limited to the crossing points in the cavity in which pulses meet and have a small chance of being locked together. Fig. 4.5 is a sketch illustrating the implementation of IPI in a linear fiber laser. The key element in this dual pulse mode-locked fiber laser is the saturable absorber based on tapered fiber embedded in Carbon Nanotubes (CNT),
Chapter 4. Intracavity Phase Interferometry

which initiates the mode-locking and establishes the crossing point of the two circulating pulses. It is essential that the CNT imposes strong amplitude coupling between the two circulating intracavity pulses, and that there be no phase coupling. To ensure the absence of phase coupling, the polarization has to be conserved through the tapered section as affected by the CNTs (see Section 3.4). An in-line polarization beam splitter (PBS) separates two polarization modes, one along slow axis and the other one along fast axis of the PM fiber. All the fibers and components are polarization maintaining, so the two polarization modes will be preserved along the principal axis of the PM fiber. In this laser, a piece of Er-doped fiber from Nufern (PM ESF-7/125) is pumped by a diode laser at 980 nm thorough a Wavelength Division Multiplexer (WDM). Three mirrors (M1, M2, and M3) are required to oscillate light in the cavity. M1 and M2 are made fiber coupled (alignment-free) while M3 is a discrete component which reflects collimated light back to the fiber. This helps to adjust the optical length of the laser for the red pulse to have the same repetition rate as the blue pulse, which is essential for IPI application. Please note that cross-polarized pulses oscillate along slow and fast axes of the fiber with different refractive indices or phase velocities (see Appendix A for properties of PM fibers.) Also, a sample can be easily placed in the air gap provided in the sampling arm of the laser. 10% of light from each arm of the laser is coupled out using output couplers (OC1 and OC2) and sent to a 50/50 combiner to overlap the pulse trains on the beat note detector (D).

Although the linear fiber laser appears straightforward to generate cross-polarized pulses, the experiment was not successful and mode-locking was not achieved for this design. One of the main hurdle is to have equal losses for the two polarization modes. We came to the realization that the in-line polarization beam splitter has very different loss in transmission and reflection. In fact, no commercially available polarizing beam splitter could be found that does not have large loss either in transmission or reflection. Solution to this problem was only found in the course of the later development of a ring laser, and is detailed in Section 5.5.1. Losses for either polarization of less than 1% were achieved by using total transmission through an optically contacted interface in p-polarization, and
Chapter 4. Intracavity Phase Interferometry

total internal reflection in s-polarization (see Fig. 5.10). Another problem associated with
the design of Fig. 4.5 is the extreme sensitivity of IPI, which requires that the two arms
of the interferometer be stable within at least a few pm, an impossibility with the in-line
polarization beam splitter and the fiber interferometer. One possible solution which might
be implemented in the future is to have the two branches of the interferometer in air (or
vacuum), as short as possible, and rigidly fixed on a zero expansion plate (zerodur for
instance). Finally, the saturable absorber based on tapered fiber embedded in CNT does
not provide sufficient localization of the pulses. Experiments with the ring fiber laser have
shown that the solution is to squeeze the CNTs between two fiber ferrules (see Section 3.3).
More details will be provided in Section 5.4.

References

[2] R. J. Jones and J. C. Diels. Stabilization of femtosecond lasers for optical frequency metrol-
[5] Ladan Arissian and Jean-Claude Diels. Mode-locked laser applied to coherent interactions
In Jun Ye and Stephen Cundiff, editors, *Femtosecond Optical Frequency Comb: Principle,
American Scientific Publishers (USA), 2009.
[8] Scott Diddams, Briggs Atherton, and Jean-Claude Diels. Frequency locking and unlocking
in a femtosecond ring laser with the application to intracavity phase measurements. *Applied
Chapter 4. Intracavity Phase Interferometry


Chapter 4. Intracavity Phase Interferometry


Chapter 4. Intracavity Phase Interferometry


Chapter 5

Implementation of IPI in Mode-Locked Ring Fiber Lasers

5.1 Introduction

As mentioned in Chapter 4, bidirectional mode-locked lasers are very promising for implementation of highly sensitive Intracavity Phase Interferometry (IPI) for high precision sensing. Examples of applications are detection of small displacement, linear and nonlinear refractive indices, magnetic field, scattering, rotation, and acceleration. Rotation sensors or optical gyroscopes are of great interest to develop modern navigation systems.

The primary focus of this chapter is on implementing IPI in ring PM fiber lasers (gyroscopes) to overcome the deadband introduced by the phase coupling between two pulses in the cavity. In this chapter, the Sagnac effect as the basic principal operation of optical gyroscopes and its formulation will be given. Then the importance of having a symmetric ring fiber laser cavity to minimize the bias beat note will be investigated. It will also be shown that the pulse velocity in the cavity is dominated by gain dynamics, and it is not simply equal to the group velocity. This remarkable investigation is surprisingly consistent with a theory from 1960s. Finally, a novel design of a ring fiber laser with orthogonally polarized pulses will be presented and experimentally tested to be a
deadband-free IPI sensor.

## 5.2 Sagnac Effect

Optical gyroscopes operate by sensing the difference in optical path length between two counter-propagating beams traveling in opposite directions of a loop. A rotation-induced change in the path lengths generates a phase difference between the counter-propagating beams. This is the basic principle of almost all optical gyroscopes which was discovered in 1913 by George Marc Sagnac [1, 2].

![Sagnac Principle Diagram](image)

\[
L_{CCW} = 2\pi R + \Delta S \\
L_{CW} = 2\pi R - \Delta S \\
\Delta P = L_{CCW} - L_{CW} = 2\Delta S
\]

Figure 5.1: A rotating ring (green circle) with a counter-clockwise angular velocity $\Omega_r$ induces different optical paths for the clockwise (red) and counter-clockwise optical (blue) beams, $L_{CW}$ and $L_{CCW}$, respectively; $R$: Radius of the ring, $\Delta S$: Displacement of the start point due to the ring rotation, $\Delta P$: Optical path difference between counter-propagating beams.

Sagnac principle states that two optical beams counter-propagating in a rotating ring structure (Fig. 5.1) travel different optical lengths ($L_{CCW}$ and $L_{CW}$ for counter-clockwise and clockwise, respectively) resulting in a relative phase change between the two light beams. The phase shift can be measured by interfering the beams outside the loop and measuring the interference fringes. Thus, in a Sagnac interferometer, it is possible to relate the phase change $\Delta \phi$ to the angular speed
Chapter 5. Implementation of IPI in Mode-Locked Ring Fiber Lasers

Ω_r of the ring through the following equation:

\[ \Delta \phi = \frac{8\pi A}{\lambda c} \Omega_r, \]  

(5.1)

where \( \lambda \) and \( c \) are wavelength and speed of light, and \( A \) is the surface enclosed by the perimeter \( P = 2\pi R \). The difference in optical path lengths of counter propagating beams can be written as:

\[ \Delta P = \frac{\Delta \phi}{2\pi} \frac{\lambda}{c} = \frac{4A}{c} \Omega_r = \frac{2RP}{c} \Omega_r, \]  

(5.2)

in which \( \Delta \phi \) is substituted by Eq. 5.1 and \( A = RP/2 \).

5.3 Implementing IPI in Laser Gyroscopes

Based on the measurement technique of the Sagnac effect, the optical gyroscopes can be classified as passive and active gyros. In passive architecture, the optical source is external to the ring cavity while the optical source in an active gyroscope is part of the optical loop forming a laser resonator. The focus of this work is on laser gyroscopes with enhanced sensitivity. The ring laser can be either continuous-wave (cw), which is the case for the conventional He-Ne laser gyros or pulsed [3–5]. The commercial laser gyroscope is a cw, single-mode He-Ne ring laser. It can be seen as a particular case of IPI, discussed in Chapter 4, in which the pulse duration fills the whole cavity, and therefore the counter-propagating beams cannot be distinguished by their position at a given time. Rotation of the ring laser about an axis orthogonal to its plane results in a frequency difference between the outputs corresponding to each sense of circulation. This frequency change in the rotating ring laser is proportional to the rotation rate through the following equation:

\[ \Delta \nu = \frac{2R}{\lambda} \Omega_r, \]  

(5.3)

which is extracted from combining Equations 4.3 and 5.2 and knowing that \( \lambda = c/\nu \). \( \Delta \nu \) can be measured by beating the two outputs on a detector. The frequencies of two counter-circulating beams in a laser gyro would lock together due to back-scattering from components within the cavity and phase coupling happens, which is responsible for a deadband in the gyro characteristic. Since 1967 [6] it was recognized that the deadband region could be avoided by introducing an artificial
rotation rate with larger magnitude than the deadband. In a cw He-Ne laser, the virtual rotation can be accomplished by mechanically shaking the laser gyro (successive rotations switched between clockwise and counter-clockwise). In mode-locked ring dye lasers nearly zero deadband has been achieved [3]. There is also no need for a mechanical solution to avoid deadband in mode-locked laser gyros. An electro-optic intracavity phase modulator will create virtual rotation which has been analyzed in detail and demonstrated experimentally for a ring laser [7].

Although gyroscopic response was successfully realized in discrete element bidirectional mode-locked dye lasers [3, 8, 9], it is impractical in commercial systems due to the extensive need of alignments. Fiber lasers are the most promising laser media to implement IPI owing to the possibility of producing ultrashort pulses with a compact and low-cost design [5, 10–12]. However, there are numerous challenges associated with the implementation of IPI in fiber lasers. Since a typical fiber laser operates with large gain and losses, the pulses circulating in opposite direction in a ring laser traverse the optical components (gain, output coupling, saturable absorption) in a different order. The resulting asymmetry of the counter-circulating pulses makes a huge bias beat note. Therefore, as a first step to reduce the bias of the system, a bidirectional mode-locked fiber laser has been engineered with the ability to control the energy of two counter-propagating pulses by tuning the pump powers. The measurements confirm the conclusion of prior results obtained with free-space component lasers [13], that the pulse velocity in the cavity is dominated by gain dynamics and it is not simply equal to $\frac{d\Omega}{dk}$, generally referred to as group velocity, where $k$ is the wave vector and $\Omega$ is the optical frequency [4, 14].

### 5.4 IPI in Mode-Locked Ring Fiber Laser;
Parallel Polarization

An all-polarization maintaining bidirectional fiber laser is constructed and shown in Fig. 5.2. Passive Mode-locking is achieved by sandwiching carbon nanotubes between two FC/APC fiber connectors [15] creating two correlated counter-propagating frequency combs. The laser cavity elements are arranged as symmetrically as possible with respect to the saturable absorber (SA), to
ensure that counter-circulating pulses of near equal intensities are generated. The SA establishes the crossing point of the counter-circulating pulses. A tapered fiber covered with CNTs fails to stabilize the crossing point possibly because the taper is longer than the pulse length, resulting in the mutual saturation being applied to only a small fraction of the total absorption. An important contribution to minimize the asymmetries in the cavity is to use two portions of Er-doped fibers from Nufern (PM-ESF-7/125) pumped through two wavelength division multiplexers (WDM) [Fig. 5.2]. Using WDMs in reflection helps to protect the saturable absorber from overheating by filtering out the extra power from the pump lasers, which also makes the mode-locking more stable [16]. A 2 by 2 output coupler extracts 10% of the light from either direction. The output pulse trains from clockwise (CW) and counter-clockwise (CCW) directions combine through a 50/50 combiner to measure the beat note. As can be seen in the setup, the output coupler is not placed in exactly equal distances from SA, creating some asymmetries which can be compensated by tuning the pump powers of the two gain sections. The near symmetric operation reduces the bias beat note by equalizing the intensities of the counter-circulating pulses, hence reducing the differences between phase velocities of the circulating pulses.

An adjustable delay line ensures temporal overlap of the counter-propagating pulses on the detector. The delay line is made of two collimating lenses with adjustable collimated optical length. 1% of the output coupler (OC) in either direction is split out and monitored for extra measurements such as output power, optical spectrum and pulse train.

### 5.4.1 Experimental Results

Colliding pulse mode-locking in a bidirectional ring fiber laser creates two counter-propagating pulses which meet at the same location established by the saturable absorber at each round trip. Fig. 5.3(a) to (c) pictures the pulse trains in each direction taken by an oscilloscope at different time scales of 10 ns, 50 ns, and 1 μs, respectively. As shown in this figure, the pulse trains have the same round trip time of $\tau_{rt}$, and a comparable amplitude.

The soliton spectra in clockwise (CW) and counter-clockwise (CCW) directions are shown in Fig. 5.4(a) with the same central wavelength of 1565 nm for both directions. Each pulse of intensity
Figure 5.2: Experimental setup of an all-polarization maintaining bidirectional fiber laser with minimized asymmetries using two sections of Er-doped fibers; WDM: Wavelength Division Multiplexer, OC: Output Coupler. Saturable absorber is a thin layer of carbon nanotubes between two fiber ferrules which establishes the crossing point of pulses. The other crossing point is located at the opposite side of the ring marked by a cross (×). Placed at that location, OC would cause back scattering that injection locks the two counter-circulating pulses. To avoid the large resulting deadband, OC is moved away from ×. An adjustable delay line images the crossing point × onto the beat note detector.

Figure 5.3: Counter-propagating pulse trains of a bidirectional fiber laser at different time scales of (a) 10 ns, (b) 50 ns, and (c) 1 µs. \( \tau_{rt} \): round trip time, CW: clockwise, CCW: counter-clockwise.

\( I \) circulating in the cavity of perimeter \( P \) accumulates a large amount of nonlinear phase \( \phi_{nl} \) along the core of the fiber given by:

\[
\phi_{nl} = \frac{2\pi}{\lambda} n_2 IP, \tag{5.4}
\]
where \( n_2 \) is the nonlinear refractive index of the fiber core, and \( \lambda \) is the operating wavelength. The difference between the accumulated phase in either direction (\( \Delta \phi \)) per cavity round-trip results in a beat note measured by interfering the frequency combs. The frequency \( \Delta \nu \) of that beat note which is defined as Eq. 4.3 can be also written as:

\[
\Delta \nu = \nu \frac{\Delta \phi}{P k_{av}}
\]

(5.5)

where \( \nu \) is the optical frequency, \( \Delta \phi \) is the induced phase shift to be measured, \( P \) is the perimeter of the laser, and \( k_{av} = 2\pi\tau_r\nu/P \) is the averaged \( k \) vector over the cavity. By combining Eqs. 5.4 and 5.5, the beat note frequency is found as:

\[
\Delta \nu = \nu \frac{n_2}{n_{av}} \Delta I,
\]

(5.6)

where \( n_{av} \) is the average linear phase index. As can be seen, the beat note frequency is directly proportional to the difference of pulse intensities of \( \Delta I \). Thanks to the symmetric design of the laser cavity (Fig. 5.2), each pulse sees the components in the same order starting from the crossing point in the CNT saturable absorber, resulting in a small difference in accumulated nonlinear phase. Therefore, one expects to measure a very small bias beat note (nonzero beat note for zero applied phase shift) for a perfectly symmetric cavity. Unfortunately, making a perfect symmetric cavity is not practical as it needs the \( 2 \times 2 \) output coupler (OC) placed at the crossing point (\( \times \) in Fig. 5.2) opposite to the saturable absorber. This introduces a large coupling between the counter-circulating pulses, resulting in a large deadband (mutual injection locking). Therefore, the symmetry had to be broken by locating the \( 2 \times 2 \) output coupler away from the pulse crossing point (\( \times \)), as shown in

![Figure 5.4](image.png)

Figure 5.4: Experimental results; (a) Spectra of the pulse train for each direction of circulation. (b) Beat note measurement in time. (c) Beat note measurement in frequency. BW: Bandwidth.
Chapter 5. Implementation of IPI in Mode-Locked Ring Fiber Lasers

Fig. 5.2. As a result, a bias beat note of a few MHz is measured. Fig. 5.4(b) shows the modulation in overlapping pulse trains due to the presence of $\Delta I$. The beat note frequency can be directly measured as 1.554 MHz by a radio frequency (RF) spectrum analyzer (Fig. 5.4(c)) which is the Fourier transform of Fig. 5.4(b).

The difference in intensity $\Delta I$ between counter-circulating pulses can be modified by tuning the power of the two pump lasers in Fig. 5.2, resulting in a change of beat note indicated by Eq. (5.6). Figure 5.5 shows the position of the beat note spectrum on the RF spectrum analyzer, as the difference between the pump powers ($\Delta P$) is increased. In this figure, the beat note frequency taken from the RF spectrum analyzer shows an increase from 1.1 MHz to 3.9 MHz by increasing the asymmetry in the cavity through changes in pump powers $\Delta P$ from 23 mW to 160 mW. While increasing $\Delta P$, the delay line in Fig. 5.2 has also to be adjusted (stretched) to get the maximum modulation (visibility) in the measured beat note of Fig. 5.4(b).

![Figure 5.5: Radio frequency spectra recorded for different pump power differences ranging from 23 mW to 160 mW.](image)

Figure 5.6 illustrates the power dependence of the beat note (representative of the phase velocity) and the delay adjustment (representative of the pulse velocity) to achieve optimum beat note visibility. The RF bias beat note is plotted in Fig. 5.6(a) as a function of the difference in pump powers ($\Delta P$) applied to the two erbium doped fibers. The difference in pump powers is

70
calculated as $\Delta P = P_{\text{cw}} - P_{\text{ccw}}$ where $P_{\text{cw}}$ and $P_{\text{ccw}}$ are the pump powers in CW and CCW directions, respectively and $P_{\text{cw}} > P_{\text{ccw}}$. The change of the bias beat note as a function of intensity can be easily calculated from Eq. (5.6). A simple one to one correspondence between pump power and peak intensity can be established, under the assumption that the laser generates only a single pulse/cavity round-trip, and that the pump power dependence of the pulse duration can be neglected. The measured pulse width of 0.7 ps, repetition rate $c/(n_{av}P)$ of 37.255 MHz, and fiber core area of $8.659 \times 10^{-7} \text{ cm}^2$ (corresponding to mode field diameter of 10.5 $\mu\text{m}$) have been used for both pulses, as well as a linear dependence of the intracavity power on the pump power to calculate the intensities in either direction. The nonlinear refractive index of $n_2 = 3 \times 10^{-16} \text{ cm}^2/\text{W}$ at a wavelength of $\lambda=1565 \text{ nm}$ is used to calculate the beat note frequency. The calculated power dependence of the bias beat note under these assumptions is plotted as a red line in Fig. 5.6(a) adding a fixed bias of 1 MHz to fit the experimental data. A linear fit of the experimental data is shown as dashed line in this figure. The large scatter of the experimental data is a clear indication that the assumptions are not accurate. Indeed, satellite pulses are observed for some values of pump powers proving that the energy of the most intense pulse is less than the ratio of the average power to the repetition rate.

Figure 5.6: Experimental and theoretical results; (a) pump power dependence of the beat note frequency in experiment (red triangles) and theory (solid red line), (b) Displacement in delay line to achieve the maximum visibility when changing the pump powers in experiment (blue circles) and based on the theory of Basov [17] (solid blue line). For comparison, the amount of displacement based on the Kerr effect is shown as a dotted red line. (c) Magnified scale of the Kerr effect in graph (b) to emphasize the actual behavior of displacement based on the Kerr effect. *Pump power difference = (Pump power in the CW direction)-( Pump power in the CCW direction).*
Chapter 5. Implementation of IPI in Mode-Locked Ring Fiber Lasers

If the pulses circulating in opposite directions experience a different index of refraction, one would also expect a change in position of the second crossing point (× in Fig. 5.2), requiring an adjustment of the detection delay line for maximum beat note visibility. Blue circles in Fig. 5.6(b) show that indeed, the change in delay depends on the pump power difference (ΔP) applied to the gain fibers. These data were obtained by adjusting the delay line for maximum contrast in the beat note pattern shown in Fig. 5.4(b) at each pump power setting. It should be noted that the plot refers to changes in the delay line which is placed in the CW direction. Here again, we attribute the apparently scattered pattern of the pump power dependence to the fact that an increase in pump power does not imply a proportional pulse intensity increase. The presence of satellite pulses results in an erroneous estimate of the main pulse intensity.

If the observed changes in delay line were solely due to the Kerr effect, the more intense pulse would be delayed by (assuming group index and phase index are close to each other):

$$\Delta L = n_2(I_{cw}\ell_{cw} - I_{ccw}\ell_{ccw}),$$  \hspace{1cm} (5.7)

where $I_{cw}$ and $I_{ccw}$ are the pulse intensities, each going through the length of fiber from the saturable absorber (crossing point) to the 10% output coupler in clockwise ($\ell_{cw} = 2.856$ m) and counter-clockwise ($\ell_{ccw} = 2.566$ m) directions, respectively. The dotted red line in Fig. 5.6(b) and its magnified version in Fig. 5.6(c) shows the amount of delay between counter-circulating pulses due to the Kerr effect. This delay is considerably smaller than the experimental observation, and of opposite sign. Therefore, it can be concluded that the changes in index do not explain the intensity dependence of the pulse velocity. Instead, the much larger delay observed between two pulses can be explained by the fact that the power dependence of the group velocity in an active laser is dominated by gain dynamics [9, 13].

The surprising observation is that the ratio of the beat note to the change in delay follows a linear dependence depicted as black circles in Fig. 5.7, even though the dependency of the beat note frequency and delay to pump powers are rather scattered. The fact that the bias beat note and the change in delay are so correlated is an indication that both are proportional to the intensity of the two pulses interfering on the detector. The change in delay line is about 370 µm for a 3.1 MHz change in beat note. It is also shown that the theory (black line in Fig. 5.7 which is the ratio of the theory lines in Figs. 5.6(a) and 5.6(b)) perfectly fits the experiment.
Chapter 5. Implementation of IPI in Mode-Locked Ring Fiber Lasers

Figure 5.7: A tight correlation between beat note frequency and displacement in delay line is illustrated experimentally (black circles) and theoretically (black line).

The phase velocity intensity dependence is well explained by the Kerr effect [Eq. (5.7)]. It is shown below that propagation in a saturated gain medium explains the sign and magnitude of the intensity dependence of the pulse velocity.

5.4.2 Group Velocity Modification Through Gain Dynamics

Basov et al [17] showed that the velocity of a pulse (v) in a saturable gain medium fits the expression:

\[
\frac{v}{c} = 1 + \frac{cT_P}{2}(\alpha - \gamma),
\]

where \( c \) is the velocity of light in the medium, \( T_P \) is the pulse duration, \( \alpha \) is the small signal gain coefficient, and \( \gamma \) the loss coefficient (per unit length). We adapt the very simple model of Basov to calculate the asymptotic pulse velocity in our fiber laser. To this effect, circulation of a pulse in a ring fiber laser of perimeter \( P \) is replaced by pulse propagation through a distributed amplifier of gain \( \alpha = \alpha_0 \mathcal{P}/P_0 \) and distributed loss of \( \gamma \). \( \mathcal{P} \) is the pump power, equal to \( P_0 \) at threshold, where the gain \( \alpha_0 \) is calculated from the threshold condition of \( R \exp(\alpha_0 \ell_g) = 1; R \) being the total survival factor per round-trip, and \( \ell_g \) the length of the erbium doped fiber. The distributed loss \( \gamma \) per unit length is calculated from \( R = \exp(-\gamma P) \). For our fiber laser, we have \( \alpha_0 = 2.5 \text{ m}^{-1} \) and
Chapter 5. Implementation of IPI in Mode-Locked Ring Fiber Lasers

\( \gamma = 0.48 \text{ m}^{-1} \). Modifying the expression from Basov [Eq. (5.8)], the superluminal pulse velocity in the fiber is given by:

\[
v = c + \frac{\tau_p c^2}{2} (\alpha_0 \frac{P}{P_0} - \gamma).
\] (5.9)

The calculated delay versus pump power difference based on the theory of Basov is plotted as a solid blue line in Fig. 5.6(b) which is consistent with the experiment. It should also be mentioned that the zero displacement in the delay line is defined as the position for which the beat note is measured for the minimum difference in pump powers (\( \Delta P \)). Due to the large deadband in the cavity, smaller beat note cannot be measured by lowering \( \Delta P \).

5.4.3 Comparison of Theory and Experiment

The theoretical curves of Figs. 5.6(a) and (b) are assuming an ideal case in which the pulse intensity varies monotonically and proportionally to the pump power. In Fig. 5.7, the experimental beat note plotted as a function of the displacement (black dots) is compared to the theory (black line). The beat note is proportional to the variation of phase delay in the fiber laser, while the displacement is proportional to the variation of pulse delay. The agreement between theory and experiment in Fig. 5.7 is quite remarkable, considering that there are no adjustable parameters, and given the coarse assumptions (uniform intensity through the fiber and modeling of the ring laser as a uniform amplifier medium). The calculated plot of beat note versus delay adjustment [solid line in Fig. 5.7] match exactly the best fit line of the experimental data [dashed black line in Fig. 5.7]. It is often claimed that the pulse velocity is given simply by \( 1/(dk/d\Omega) \) where \( k \) is the wave vector and \( \Omega \) the optical frequency. The measurements presented here clearly demonstrate that this definition applies only to transparent dielectrics. Inside a laser cavity, the pulse velocity differs from this definition by orders of magnitude, as has been shown for free-space component lasers [9].
Chapter 5. Implementation of IPI in Mode-Locked Ring Fiber Lasers

5.5 IPI in Mode-Locked Ring Fiber Laser; Orthogonal Polarization

Unless extreme care was taken to design a rigorously symmetric structure of a bidirectional fiber laser (Fig. 5.2) and defining a very thin layer of saturable absorber, the smallest measurable beat note was about 1 MHz at specific pump powers. The symmetry of the cavity could be controlled by changing the powers of two pump lasers symmetrically located on the sides of the saturable absorber. A huge deadband in the cavity didn’t let us measuring the low beat frequencies when the two sections of gain fiber were equally pumped. So, a difference of 23 mW was needed between pump powers to measure the lowest beat frequency as shown in Fig. 5.5.

The mechanism by which the saturable absorber forces the pulses circulating in the cavity to cross at a predetermined location is mutual saturation. Through mutual saturation, the effective saturation energy is 3x less than self saturation in a standing wave configuration [18]. Therefore, the threshold for mode-locked operation is reduced if the pulses cross in the saturable absorber (configuration of minimum loss). Saturable absorption also adjusts dynamically the average group velocity in the cavity to force and maintain the crossing point of the intracavity pulses at the location of the absorber. A robust saturable absorption is required, to force the pulses to meet at the same point at each cavity round-trip. however, a dense absorber may cause backscattering of one direction into the other, resulting in mutual injection locking; the origin of the deadband in IPI sensors.

Coupling by backscattering has to be prevented or minimized in the saturable absorber where the pulses cross. One solution used in discrete component lasers [9], is to have a moving saturable absorber, resulting in a randomization of the backscattered phase. This is generally implemented by having a flowing dye jet, a solution not prone to miniaturization, nor easily implemented in airplane or car. However, in a fiber laser the amount of coupling between pulses at the crossing point can be reduced by making pulses cross-polarized. This solution which is implemented in a ring fiber laser, will be described and experimentally tested in the reminder of this chapter.

The cavity configuration having two circulating pulses orthogonally polarized is shown in
Chapter 5. Implementation of IPI in Mode-Locked Ring Fiber Lasers

Figure 5.8: Schematic of the PM fiber laser cavity generating two cross-polarized counter-circulating pulses. WDM: wavelength division multiplexer, G: gain fiber, OC: output coupler, Col: collimator, PBS: polarizing beam splitter, s: s-polarized, p: p-polarized.

Fig. 5.8. The all-PM fiber laser has two portions of Er-doped gain fibers (G1 and G2) pumped through WDM1 and WDM2 by laser diodes at 980 nm labeled as Pump1 and Pump2 in Fig. 5.8. The other two WDMs (WDM3 and WDM4) are used to trap the radiation of pumps in the region of gain fibers to isolate the rest of the laser from 980 nm radiation. The saturable absorber is based on the interaction of light with a thin layer of CNTs between two fiber ferrules (Section 3.3) resulting in colliding pulse mode-locking. A combination of a 3-port circulator and a lossless polarizing beam splitter (PBS) forces unidirectional operation of s-polarized light in CCW direction and p-polarized light in CW direction. In CCW direction the light is polarized along the slow axis of the PM fiber while in the CW direction the light is polarized along the fast axis, as shown in the inset of the Fig. 5.8.

The PBS is designed and made to reflect the s-component of the light in the CCW direction.
Chapter 5. Implementation of IPI in Mode-Locked Ring Fiber Lasers

and to transmit the p-component in the CW direction. The pair of collimators (Col1 and Col2 in the CW direction and Col2 and Col3 in the CCW direction) with a remarkable overall transmission factor above 95% are responsible to make collimated beams in air for transmission/reflection at the PBS. The alignment of the free-space part is extremely critical to achieve bidirectional mode-locking. The 3-port circulator (1→2→3) guarantees the unidirectional operation of cross-polarized beams. s-polarized light is guided through port 1 to port 2 of the circulator and p-polarized light in CW direction is transmitted from port 2 to port 3 of the circulator.

Each of the three collimators is mounted on a separate 6-axis positioner including rotation to adjust the orientation of PM fibers at the three collimators. The cavity length in either direction is controlled by translating Col1 to ensure that the optical cavity length is equal in both directions. The path of light in either direction, starting from the saturable absorber, is explained at the bottom of Fig. 5.8. Figure 5.9(a) shows the actual setup of the free-space part of the laser in Fig. 5.8. The paths of light in CW and CCW directions are sketched in blue and red, respectively. The magnified picture of the PBS is shown in Fig. 5.9(a) with the faces labeled. The 10% output couplers (OC1 and OC2) are placed symmetrically with respect to the saturable absorber to extract 10% of light in either direction. Therefore, the gain and losses at both sides of the absorber can be equal (in the case of pumping the same lengths of gain fibers equally) and result in comparable output powers.

Figure 5.9: (a) The experimental setup of the free-space part of the orthogonally polarized ring fiber laser to separate the two orthogonal polarizations. Col: collimator, PBS: polarizing beam splitter. (b) The magnified picture of the PBS with the 3 optical faces labeled.
This design of bidirectional fiber laser not only generates two orthogonally polarized pulses, but also reduces the number of crossing points to only one at the saturable absorber. This helps to decrease the coupling between pulses in the cavity. The other advantage of this laser is the possibility of being used as a sensor to measure any physical parameter, by introducing a sample in one of the free space arms. That function as a sensor makes this ring sensor equivalent to the linear sensor presented in Section 4.5. It is however a “tour de force” to realize and maintain the equality of the perimeter for the two polarization within less than one fraction of micron. In the case of the linear laser, the path length equality and stability requirement applies only for the small distance from polarizer to end mirrors.

5.5.1 Polarizing Beam Splitter

Figure 5.10: The operation of the lossless polarizing beam splitter used in the setup of Fig. 5.8 for the (a) CW and (b) CCW directions of light. It consists of two YVO₄ prisms optically contacted. (a) The blue beam is incident parallel to the optic axis at 25° from the interface. The upper prism has its optic axis normal to the plane of the figure. The solid blue beam, p-polarized, traverses the interface without loss, being an ordinary ray in both prisms. The dashed blue ray, s-polarized, is deflected being extraordinary in upper prism. (b) The s-component of the red beam is totally reflected on the interface being an extraordinary ray in the upper prism. The p-component (red dashed lined) is transmitted through the PBS without loss being an ordinary ray in both prisms.

Despite a thorough search through suppliers and requests for custom optics, no polarizing beam splitter could be found that does not have large loss either in transmission or reflection. We designed
the PBS sketched in Fig. 5.10, based on a positive uniaxial crystal (extraordinary index > ordinary index). Two YVO$_4$ crystals with optic axis as indicated in the figure are optically contacted. The optical contact is needed, because there is no index matching gel or liquid at the high index of YVO$_4$. When the polarization of light is perpendicular to the optical axis of the crystal it is called ordinary, with lower refractive index. The light polarized along the optic axis is an extraordinary wave, seeing a higher index of refraction. The p-component of the beam entered from surface 1 in Fig. 5.10(a) is an ordinary ray for both prisms, and thus is transmitted without loss in the absence of interface (which is the case for a good optical contact). The s-component shown is blue dashed line is refracted at the interface of the prisms being ordinary (lower index) in the lower crystal and extraordinary (higher index) in the upper one. As a result, the s-component does not reach Col2 in Fig. 5.8. In Fig. 5.10(b), the s-component of the beam incident to the surface 2 undergoes total internal reflection at the interface, being extraordinary ray (higher index) in the upper prism, and thus does not suffer any loss. The p-component is transmitted, being an ordinary ray for both prisms. In this case, the p-component reaches the Col1 in Fig. 5.8, but the port 3 of the circulator is terminated and doesn’t let the p-polarized light oscillates in wrong direction in the cavity. It should be mentioned that faces 1, 2, and 3 of the PBS (Fig. 5.10) are anti-reflection coated at 1550 nm. Of all the optics Co contacted, only Princeton Applied Research took on the challenge of manufacturing such a PBS. The loss in p-transmission and s-reflection were both less than 1%.

### 5.5.2 Beat-note Measurement

The two outputs of the laser in CW and CCW directions are orthogonally polarized as expected. In order to measure the beat note, the two directions of circulation should have exactly equal round trip time. Since the indices of refraction along the fast (CW direction) and slow axes (CCW direction) of the PM fiber are different the optical length is not measured as purely geometrical length. The position adjustment of the collimators (Col1, Col2, and Col3 in Fig. 5.8) is therefore very critical to have the same repetition rate in each direction.

First, all collimators should be set for the best coupling ratio in each direction, then by translating the Col1 (while maintaining alignment) the equal repetition rate condition may be found.
Chapter 5. Implementation of IPI in Mode-Locked Ring Fiber Lasers

Figure 5.11: Radio frequency spectrum of the pulse trains in opposite directions of the cross-polarized fiber laser with (a) different and (b) same repetition rates. The scales on x and y axes are same in both graphs. CW: clockwise, CCW: counter-clockwise, Bandwidth resolution: 100 Hz.

Fig. 5.11(a) shows the radio frequency (RF) spectra of pulse trains in CW and CCW directions, when the repetition rates are not equal, and pulses in CW direction have lower repetition rate. \( \delta \nu_{rt} \) in this figure shows the difference between repetition rates. To match the rates, the Col1 in Fig. 5.8 has to be moved to the left to shorten the cavity length, and increase the repetition rate of pulses in CW direction by \( \delta \nu_{rt} \). This method helps to learn which direction the collimator (Col1) should be moved to. Once the equal repetition rates are achieved, the RF spectrum changes to the modulated pattern shown in Fig. 5.11(b). The latter figure could be understood as a kind of RF spectral interferometry. The optical field on the detector is:

\[
E = E_1 + E_2 = \sum_p E_1 e^{i(\omega + p\nu_{rt,1})t} + \sum_q E_1 e^{i(\omega + q\nu_{rt,2})t}, \tag{5.10}
\]

where \( \omega \) is the optical frequency, \( \nu_{rt,1} \) the mode spacing of comb 1 and \( \nu_{rt,2} = \nu_{rt,1} + \epsilon \) the mode spacing of comb 2. The detector records a signal proportional to \( |E|^2 \). The RF spectrum analyzer zooming in the region close to \( \nu_{rt,1} \) records the signal \( |E_1 E_2^*| \) with frequencies at \( \nu_{rt,1} + (q - p)\epsilon \).

In the case of Fig. 5.11(b), \( \nu_{rt,1} = 22.820 \text{ MHz} \) and \( \epsilon \approx 0.000030 \text{ MHz} \). This indicates that we are within 10 \( \mu \text{m} \) of equal perimeter for both directions.

An external delay line is also manufactured to compensate the time delay \( \delta t \) (Fig. 5.12(a)) between output pulses in opposite directions in order to measure the beat note frequency. The operation of this system is the same as what was explained for adjusting length loop in Fig. 5.2.
Chapter 5. Implementation of IPI in Mode-Locked Ring Fiber Lasers

Figure 5.12: (a) Oscilloscope trace of the clockwise (upper) and counter-clockwise (lower) pulse trains in cross-polarized fiber laser. (b) The envelope of the modulated pulse train due to the asymmetry in the ring cavity.

The only difference here is that a RF low pass filter has been used to filter the high frequency pulses keeping the low frequency envelope of the modulated pulse train as illustrated in Fig. 5.12(b). By taking the inverse of modulation period (≈ 32 µs) in this figure, the beat note frequency is calculated as ≈ 31 kHz. With a cavity perimeter of \( c/n_{rt} (\nu_{rt} = 22.82 \text{ MHz and } n = 1.44) \) or ≈ 9 m, we find from Eq (4.3) that the difference in cavity length for the two polarizations is only 1.5 nm! Obviously, considerably more elaborate mechanical isolation/rigidity is needed to exploit the sensitivity of this method. This results is most likely also applicable to linear IPI, where the geometry is more amenable to a rigid interferometer.

This is an initial measurement without optimizing pump powers to lower the amount of measured beat frequency like what was done in Fig. 5.5. However, a beat note of 31 kHz is measurable in cross-polarized ring fiber laser, which is almost 32x less than the lowest measurable beat frequency (≈ 1 MHz) presented in Fig. 5.5. It means that cross-polarized pulses in the ring fiber laser has lowered the phase coupling significantly at the crossing point (saturable absorber).

5.5.3 Summary

It has been demonstrated that the ratio of the counter-circulating pulse intensities, an important parameter to generate the bias beat note, can be fine-tuned by changing the pump powers in the two gain sections [14]. We have further measured a beat note of only 31 kHz, which implies
Chapter 5. Implementation of IPI in Mode-Locked Ring Fiber Lasers

that we were able to adjust the cavity lengths in both directions to be equal within 2 nm. This is a remarkable result, given that the free-space part of the laser pictured in Fig. 5.9 is extremely sensitive to the environmental conditions such as vibration, temperature, air current etc.
Chapter 5. Implementation of IPI in Mode-Locked Ring Fiber Lasers

References


Chapter 5. Implementation of IPI in Mode-Locked Ring Fiber Lasers


Chapter 6

New Fiber Development Enabling IPI

Whether intra or extra-cavity, fibers offer the prospects of becoming sensors of minimum power consumption. Energy frugality is not only important for space applications, such as for inertial navigation for spacecrafts, but also for ordinary applications on earth. Since the research presented here involves propagation of light in PM fibers, it is important to understand how environmental perturbations will affect the light. In studying the transmission of circularly polarized light through relatively short sections (10 to 20 cm) of PM fibers, we came to the realization that the state of polarization of the fiber output is extremely sensitive to temperature, laser power, and even to magnetic fields. Straightforward applications discussed in this chapter are temperature sensing and non-invasive measurements of transmitted power. A more subtle implication is that nonlinear transmission can be made at extremely low power levels, as will be demonstrated. Finally, it is shown that the combined power and temperature sensitivity can be exploited for optical length stabilization. This is an important application for all Michelson type interferometer, and in particular essential for the linear intracavity Phase interferometer which is terminated by a reference and signal arm. The accuracy of IPI in this case is only as good as the optical length of the reference can be maintained stable.
Chapter 6. New Fiber Development Enabling IPI

6.1 Introduction

Fiber sensors can, in principle, provide the same quality features as their free-space counterparts while being cheaper, more compact, and easier to use. Passive fiber sensors are usually implemented as Sagnac interferometer [1, 2], Michelson interferometers [3], Fabry-Perot interferometers [4], or microfibers [5] to measure magnetic fields, strain, torsion, and temperature.

It is shown here that simply monitoring the polarization of initially circularly polarized light transmitted through a PM fiber leads not only to new sensing methods, but also to power control, saturable absorption, magnetometry, and possibility of optical path stabilization. Even at peak power levels not exceeding a few mW, nonlinear transmission is detected, with time constants in the microsecond range. All effects related to the Kerr nonlinear index can be neglected in the range of powers considered here.

Single mode fibers exhibit some birefringence, typically stress induced, such that the polarization of a beam sent through the fiber varies with positioning and bending of the fiber. This effect has been exploited for generating short pulses through polarization mode-locking [6]. PM fibers were introduced in order to maintain linear polarization along a preferred axis. As a very high order waveplate, it is designed with different indices of refraction along two orthogonal axes (the “slow axis” for the higher index, the “fast axis” along the direction of lower index). One defines the “beat length” (typically a few millimeters) as the distance over which the retardation between slow and fast lights equals $2\pi$. Any input polarization except linearly polarized light along a principal axis of a PM fiber will be periodically modified propagating along the fiber. While the beat length is considered to be a constant, small variations can take place because of environmental conditions (temperature, stress, magnetic field) or power variations of the propagating light. By accumulating beat length variations over long distances, we demonstrate extreme sensitivity in the measurement of many parameters affecting the fiber birefringence. More information about the properties of PM fibers can be found in Appendix A.

To make a comprehensive determination of the polarization modification, the polarization ellipse is measured for each value of a given parameter affecting the beat length. The method of extracting polarization ellipse through measurements is explained in Appendix B. As mentioned in
Section 3.5, because of the power dependent birefringence of PM fibers, saturable absorption can be applied to pulsing fiber lasers. A study on this effect revealed very interesting novel applications of PM fibers for which a patent is being applied for [7].

6.2 Temperature-Dependent Birefringence of PM Fibers

6.2.1 Method of Measurement

There is no theoretical study quantifying thermal effects in low loss undoped silica PM fiber in the mW powers investigated in Sec. 3.5. It is experimentally shown that a few mW change in the power of light sent through a PM fiber raises the temperature of the core sufficiently to modify the fiber birefringence. To verify that the same temperature sensitivity is involved in the power measurements of Section 3.5, we used the same fiber at a constant power of 30.4 mW, and varied the temperature. Fig. 6.1(a) shows the setup to measure the polarization changes of the light passing through a piece of Corning fused silica PM fiber which is exposed to temperature changes. A combination of a laser diode linearly polarized at 1550 nm and a quarter waveplate (QWP) at 45° generates circularly polarized light that equally excites two polarization modes of the PM fiber. The QWP can be simply replaced by a 45° splice between the PM fiber coming out of the 1550 nm diode laser and the sensing PM fiber in order to excite two polarization modes of the fiber through sending linearly polarized light oriented at 45° to the slow axis of the PM fiber. A FC/APC connectorized PM fiber of the PANDA type (Fig. A.1(c)) from Corning (PM15U25) with the birefringence of $\Delta n = 0.0005$ is used in this experiment. About 6 cm of the PM fiber is attached to an object whose temperature is being measured. In the actual experimental setup illustrated in Fig. 6.1(b), the object is replaced by a temperature-controlled plate (Peltier cooler) whose temperature can vary from 0 to 30℃.

Due to the birefringence of the PM fiber the initially circular polarization will rotate along the PM fiber. Knowing the birefringence and length of the PM fiber the output polarization can be predicted. However, the output polarization changes when temperature variations are applied to the
Chapter 6. New Fiber Development Enabling IPI

Figure 6.1: (a) Schematic setup to monitor temperature changes of an object attached to the PM fiber; QWP: Quarter Wave plate. (b) Actual temperature measurement setup.

6 cm of the PM fiber through the Peltier cooler. The transmitted light is collimated and sent through the home-made polarimeter (Fig. 6.1(a)) and the polarization ellipse is determined as described in Appendix B.

The birefringence of the PM fiber of $\Delta n = 0.0005$ results in a beat length of 3.1 mm at 1550 nm. As shown in Fig. 6.2(a), the polarization state of the transmitted light gradually changes by increasing the temperature from 2 to 30°C. The interpretation of the transmitted patterns shown in this figure can be found in Appendix B. The calculated ellipticities and angles of the polarization ellipses associated with Fig. 6.2(a) are depicted in Fig. 6.2(b) as a function of temperature. As can be seen in Fig. 6.2(b), a phase shift of $\pi$ occurs between two modes of polarization by increasing the temperature from 10°C to 29°C. It means that the birefringence of the fiber is changed by $1.3 \times 10^{-5}$ using the phase shift $\Delta \varphi = 2\pi \Delta n L / \lambda$ in which $L$ is the length of the PM fiber exposed to the heating/cooling source (6 cm in this experiment) and $\lambda$ is the wavelength of light. Therefore, a change of 4.1 $\mu$m/°C is expected in the beat length of the PM fiber. The results are comparable with those of reference [8]. In Fig. 6.2(b), the discontinuity in the angle of ellipse at
Chapter 6. New Fiber Development Enabling IPI

Figure 6.2: Projection patterns of the transmitted circularly polarized laser light (at 30.4 mW) through a 17.5 cm PM fiber whose 6 cm is exposed to different temperatures from 2 to 30°C. (b) Ellipticities and angles of the polarization ellipses associated to (a) as a function of temperature.

Temperature 20°C arises from the transition of polarization from circularly to rotated elliptically polarized light. The fitting algorithm only defines angles from 0 to 180° to the slow axis of the PM fiber and does not unwrap the curve so that a discontinuity appears when the ellipse rotates past 180 degrees.

6.2.2 Adjusting Parameters for Optimum Sensitivity

Figure 6.3: Projection patterns of the transmitted circularly polarized laser light (at 30.4 mW) through a 17.5 cm PM fiber whose 6 cm is exposed to different temperatures from 20 to 20.8°C. (b) Ellipticities and angles of the polarization ellipses associated to (a). (c) Resolving 20 mK change in temperature.

To extract the highest sensitivity from the arrangement of Fig. 6.1, the system is placed at the
transition point identified in the previous paragraph by tuning the fiber length. The sensitivity at the turning point is experimentally measured by increasing the temperature from 20°C to 20.8°C in very small increments as shown in Fig. 6.3(a). As can be seen, a significant transition of the polarization state of light is occurred for only 0.8°C change in temperature of the fiber. The ellipticities and the angles of polarization ellipses at different temperatures from 20 to 20.8°C are depicted in Fig. 6.3(b). The selected part of this figure is magnified in Fig. 6.3(c). As can be seen, a temperature change as small as 20 mK can be resolved by increasing the temperature of 6 cm of a PM fiber from 20.68°C to 20.70°C. This sensitivity is limited by accuracy of the temperature controller as well as the variation of environmental condition. The length of the fiber under test is also critical to define the sensitivity of this sensor. A longer fiber under test accumulates more phase shift for the same temperature change results in more sensitive sensor for a specified range of temperatures.

This whole calibration measurement which takes a few hours has to be done once in order to characterize the sensor. Then, one can simply measure the transmission of light through the polarizer shown in Fig. 6.1(a) at a fixed orientation. There is an optimum polarizer angle for a given temperature range. In this experiment, the optimum angles to get the maximum change in transmission at different temperatures are 46 and 136 degrees as illustrated in figures 6.2(a) and 6.3(a) by the dashed lines.

Figure 6.4(a) shows a color-coded normalized transmission of light through the PM fiber followed by a polarizer at different angles, for the temperatures from 20.2°C to 20.8°C. As shown in Fig. 6.4(b), the sensor can instantly measure the temperature variations by setting the polarizer at the angle for maximum modulation in transmission (either 46° or 136° in this work).

The direct measurement of the transmitted circularly polarized light through the PM fiber at different temperatures followed by a polarizer at 46° is plotted in Fig. 6.5. The response \( r \) to temperature change of \( \Delta T \) is a relative transmitted power change of \( \Delta P_t/P_{in} \), proportional to the fiber length of \( L \):

\[
r = \frac{\Delta P_t}{P_{in}} \frac{1}{\Delta T L},
\]

(6.1)

where \( P_{in} \) is the input power of light. Considering the transmitted powers related to the data points
Figure 6.4: (a) Color-coded transmission of circularly polarized light sent through a piece of PM fiber followed by a polarizer at different angles as a function of temperature. (b) Transmission of light through a polarizer oriented at 46 and 136 degrees for different temperatures from 20.27°C to 20.8°C.

Figure 6.5: Transmission of circularly polarized light at 30.4 mW sent to the PM fiber at different temperatures followed by a polarizer oriented at 46 degrees which is shown by the dashed lines located at 46° in Fig. 6.2(a) and Fig. 6.3(a). Temperature determination is ambiguous in the highlighted regions. Inset: enlarged scale to show the sensitivity of the temperature sensor.

at 20.65°C and 20.68°C shown in the inset of Fig. 6.5 and for L=0.6 dm, the response $r$ to the temperature change is calculated $0.73 \degree C^{-1}dm^{-1}$ for the input power of 30.4 mW. It means that for a given resolution of $\Delta P_t/P_m$ of 0.1%, we can resolve a temperature change of $\Delta T=0.001 \degree C$. 

91
for 10 cm (1 dm) of fiber.

There is a compromise to make between sensitivity and dynamic range. The longer the fiber, the higher the sensitivity, and the shorter the dynamic range. For the 6 cm PM fiber length, by increasing the temperature from 2 to 30 °C, the transmission changes periodically (Fig. 6.5) [9]. This makes the sensor impractical for temperatures below 10°C in this case. In Fig. 6.5, the transmission of light through the PM fiber at temperatures below 10°C (highlighted pink region) is very similar to that of temperatures above 10°C (highlighted green region). This ambiguity could be avoided by shortening the exposed length of the PM fiber which also results in reducing the sensitivity of the sensor.

### 6.3 Power-Dependent Polarization Changes

Instead of varying the temperature of a section of fiber in the setup of Fig. 6.1, we operated at constant temperature and analyzed the transmitted polarization as a function of input power. The result (Fig. 3.23) is surprisingly similar to that of Fig. 6.2, which lead us to conclude that the observed polarization change in Section 3.5 is simply the same thermal effect. We can thus establish a temperature-power calibration curve as plotted in Figure 6.6(b) for the given values in Fig. 6.6(a). As the exposed length of the fiber is different in Sections 3.5 and 6.2 (the whole 17.5 cm PM fiber is heated by the power of light passing through it while 6 cm of fiber is attached to the temperature-controlled plate), we have to normalize the results to the exposed lengths. Considering the exposed length of the PM fiber in Section 6.2 is almost one-third of that in Section 3.5, the temperature changes in Fig. 6.6(b) is divided by 3 to keep the response $r$ and relative transmission of $\Delta P_t/P_{in}$ in Eq. 6.1 unchanged.

As shown by black dots in Fig. 6.6(b), 13 mW change in the power of light passing through the PM fiber corresponds to about 2.3°C of change in temperature of the fiber. In other words, a slope of 0.18 °C/mW given by the linear fit in Fig. 6.6(b) shows that 1 mW change in the power of a CW laser light passing through a 17.5 cm of PM fiber heats the fiber core by 0.18 °C. Considering 4.1 µm/°C change in beat length and the measured correlation between power and temperature...
Chapter 6. New Fiber Development Enabling IPI

Figure 6.6: (a) Transmission of circularly polarized light at the power of 30.4 mW through the PM fiber at specific temperatures (solid lines) and transmission of circularly polarized light at specific powers through the PM fiber at temperature of 19°C (circles). (b) Changes in temperature of the PM fiber versus changes in power of light passing through the fiber calculated from the legend of (a).

(0.18 °C/mW), a value of 0.7 µm/mW is calculated for the change of beat length by changing the power of light at 1550 nm. Any change in the wavelength of light or type of PM fiber results in different amount of beat length and it has to be taken into account. This method is accurate enough to measure the changes of temperature/power, however the length of the fiber under test should be measured within a few µm accuracy to give you the absolute value of temperature/power. The accuracy of measuring length in this work is a millimeter. It is therefore recommended to calibrate the system to find the reference polarization.

6.3.1 Response Time of Power/Temperature Changes

The response time of the fiber core temperature to changes in optical power passing through the fiber is measured by analyzing the step function response of the polarization change. The power meter in Fig. 6.9 is replaced by a fast detector connected to an oscilloscope as shown in Fig 6.7(a). The power of the measuring beam is unchanged while the power of the heating source (980 nm laser) is modulated to create square pulses from 0 to 40 mW. Red square symbols in Fig. 6.7(b)
show a normalized step function for the heating source. The response curve of the sensor to this step function is measured by recording the transmission of the 1550 nm laser light through a polarizer at an optimized angle [green dots in Fig. 6.7(b)]. Best fit to this curve is with two exponentials of 1/e values of 0.009 and 0.125 ms corresponding to cut-off frequencies of 111.1 and 8 kHz, respectively. The lower time constant corresponds to the conduction from core to cladding. The higher time constant corresponds to the conduction from the fiber to the surroundings. The fast response, extreme sensitivity, and the simplicity of this potentially in-line sensor make it competitive with other techniques [10] for specific applications, such as radiation-balanced lasers.

6.4 Fiber Core Temperature Measurement

This section presents an application that exploits the results of Sections 6.2 and 6.3.

Temperature measurements in optical fibers is crucial in some experiments such as high-power lasers and amplifiers in which fiber temperature should remain in a specific range. There are different methods for temperature measurement such as using thermal camera, differential luminescence thermometry (DLT), photothermal deflection (PTD), and thermocouple (TC). However, in order
to measure the small changes of temperature in optically thin materials like Single-Mode Fibers (SMFs) many of the aforementioned methods fail to work. For example, thermal cameras lack image resolution; or in DLT of the SMFs the lack of fluorescence power leads to a very low signal to noise ratio. One of the most reliable methods to measure the fiber temperature is sensors utilizing optical fibers [11]. Radiation-balancing is a technique that can mitigate the generated heat in lasers and amplifiers using solid-state laser cooling. To detect the effect of radiation-balancing in fiber amplifiers or lasers, especially single-mode fiber amplifiers or lasers, one needs to measure the minuscule changes in temperature of fiber core. The temperature sensor presented in Sec. 6.2 can overcome some of the limitations by combining simplicity, robustness, high sensitivity, fast response, and possibility of direct fiber core temperature measurement.

Figure 6.8: Different methods to measure fiber core temperature variations using the sensor based on birefringence of PM fiber.

Fig. 6.8 shows different methods to measure the fiber core temperature using the presented temperature sensor in Sec. 6.2. In Fig. 6.8(a) the sensor is attached to the fiber under test and using thermal compound a better thermal conductivity can be achieved. However, 250 μm spacing between the fiber cores doesn’t guarantee the same temperature in the fiber under test as what is measured by the sensor. Although removing the fiber jackets in Fig. 6.8(b) helps to have a better thermal conductivity there is always a risk of having heat load at the physical contact of the fibers. By intentionally inducing a uniform birefringence along the fiber under test, it can be used as a temperature sensor based on the birefringence of the fiber (Fig. 6.8(c)), which guarantees direct
measurement of temperature changes of the fiber core.

Figure 6.9: Experimental setup to measure the temperature changes of a fiber core.

Here, in order to prove the viability of this measurement, a very simple setup is used as shown in Fig. 6.9. A 1550 nm laser diode is used as a measuring beam to monitor the polarization changes induced by power variations of a 980 nm laser diode as a heating source. A PM wavelength division multiplexer (WDM) combines the light from the two sources and sends it to a QWP followed by the same 17.5 cm PM fiber. Actual laser cooling in fiber is not attempted here and a regular PANDA PM fiber from Corning has been used. Changing the power of the 980 nm laser will affect the beat length of the PM fiber [12] resulting in polarization changes of 1550 nm laser light passing through the fiber. The 980 nm laser light is filtered out just before the polarimeter and the polarization measurement is solely done on 1550 nm laser light.

Fig. 6.10 (a) indicates how the polarization of light changes when increasing the power of 980 nm laser from 0.183 mW to 4.37 mW. As can be seen in Fig. 6.10(b), by plotting the color-coded transmission of the measuring beam (1550 nm laser) at different power of 980 nm laser through the polarizer at different angles, the maximum modulation depth is measured at the polarizer angle of 46°. Fig. 6.10(c) indicates a modulation depth of 22% in transmission of 1550 nm laser light through the polarizer at 46° for a 4.19 mW change in the power of 980 nm laser light. The change of birefringence of the PM fiber by changing power can be attributed to the temperature changes
Figure 6.10: The results taken from the setup shown in Fig. 6.9. (a) Polarization state of a 1550 nm circularly polarized light passing through a piece of PM fiber at different powers of 980 nm light passing through the same PM fiber. (b) Normalized transmission of 1550 nm laser light at different powers of 980 nm laser passing through the PM fiber followed by a polarizer at different angles. (c) Normalized transmission versus power of 980 nm laser light at a polarizer angle of 46° with a modulation depth of 22%.

of the fiber core. The correlated temperature change which results in the same amount of change in the birefringence of the fiber can be extracted from the temperature-power calibration curve. As shown in Fig. 6.6 the blue square symbols indicate the temperature change of 0.75°C for the power change of 4.19 mW.

### 6.5 Optical Length Stabilization

An optical interferometer compares a sample optical path to be measured with a reference optical path, by interfering it on a detector. This applies as well to extra-cavity interferometry as to intra-cavity interferometry as sketched in Fig. 4.5. For the purpose of illustration, we choose as example the passive Michelson interferometer sketched in Fig. 6.11, of which the optical path is shown in red. The beam at frequency $\omega_1$ is linearly polarized, along the axis of the PM fibers, and is split into two branches by a beam splitter. The beams from either branch recombine on a detector ($D_1$)
Chapter 6. New Fiber Development Enabling IPI

at the port 3 of the circulator. The interference signal on the detector is a measure of the optical path difference between the two branches of the interferometer. The change in optical path length can be due to anything that changes either the length or the index of refraction of the sample arm. That could be the position of end mirror, temperature, stress, magnetic field, electric field or any material placed in the sample arm which changes the index of refraction. The reference arm should however have a constant optical path length, or the interference is meaningless.

Figure 6.11: Stabilization of the reference branch of a Michelson interferometer, by monitoring the polarization of a circularly polarized beam injected into the branch; A:amplifier, D: detector, WDM: Wavelength division multiplexer.

A very simple and sensitive fiber optical length stabilization can be devised based on the birefringence properties of PM fibers and the fast thermal response of the fiber core. It can be done through the feedback loop shown as a green path in Fig. 6.11. A cw laser beam at a different wavelength $\omega_2$ (not to interfere with the operation of the interferometer) is sent to the reference arm through the WDM$_1$. The source at $\omega_2$ is linearly polarized. The beam is made circularly polarized just before being launched into the reference arm using a quarter waveplate in order to excite two polarization modes of PM fiber between two WDMs. The polarization of light at $\omega_2$ rotates along the PM fiber between two WDMs and the light is extracted from the reference arm by the WDM$_2$. 

98
Chapter 6. New Fiber Development Enabling IPI

The transmitted power of the extracted beam through the polarizer depends critically on the optical path length between the two WDMs. This optical length can be affected by environmental conditions as well as by the power of light at $\omega_2$. Any change of the environmental conditions can be compensated through changing the power of $\omega_2$ laser. A detector ($D_2$) placed after the polarizer looks at the transmission of $\omega_2$. The signal from that detector is amplified, and used to control the power of light at $\omega_2$ through controlling the current of the semiconductor laser. With proper adjustment of the gain and phase of the feedback loop, any perturbation of optical path of the reference arm could be compensated. The whole interferometer shown in Fig. 6.11 can be part of a laser cavity made of PM fibers as a highly sensitive sensor implementing the technique of intracavity phase interferometry discussed in Chapter 4.

References


[7] Hanieh Afkhamiardakani and J.-C. Diels. Fast power and temperature monitoring, saturable absorption, magnetometry, optical length control and laser stabilization based on birefrin-


Chapter 7

Conclusion and Future Work

This dissertation has demonstrated the implementation of intracavity phase interferometry (IPI) in mode-locked fiber lasers, as a high-precision tool for metrology. In order to prevent environmental conditions to affect the operation of the fiber laser, polarization maintaining (PM) fibers were used in this research. PM fibers open the possibility of having the two pulses circulating in the cavity to be orthogonally polarized. This is an important property to reduce or even prevent phase coupling between the intracavity circulating pulses. In addition, it makes it possible to separate by polarization a “sample beam” from a reference beam.

7.1 Mode-Locking

Mode-locking is required to produce frequency combs for IPI measurements. Two different methods of passive mode-locking using carbon nanotubes that were previously reported in the literature have been modified and characterized to be adapted for use in PM fiber lasers. Seeking for a more long-lasting saturable absorber, two novel techniques of fabricating all-PM fiber absorbers have been created and investigated. A very promising method is based on nonlinear multi-mode transmission of light through a tapered PM fiber with diameter of 5 µm and a total length (including transition parts on both sides of the tapered section) of ≈ 11 cm, surrounded by air. This method
has been successfully tested to Q-switch a fiber laser.

**Future Work** → To achieve mode-locking incorporating this method a numerical simulation could be done to extract the exact dimension of the fiber taper. Then a CO$_2$ tapering machine is required to pull the fiber to the calculated dimension. This machine would be much more sophisticated, reliable and expensive than the home-made tapering system used in this dissertation (Fig. 3.2 (b)). A few centers in the USA own a CO$_2$ machine that could be asked to collaborate for providing tapers. It tried once a collaboration with the College of Optics and Photonics (CREOL) at the University of Central Florida. After a week of working unsuccessfully with the machine, it turned out the micro-tapering module was missing.

The other proposed method of mode-locking is the result of nonlinear transmission of circularly polarized light passing through a PM fiber terminated by an appropriately oriented polarizer. This method has been demonstrated and characterized as a potential all-PM fiber saturable absorber.

**Future Work** → It is my hope that this new method of mode-locking could be tested in a fiber laser to generate short pulses of very low average power and low repetition rate. The practical saturable absorber that could be placed in a fiber laser is shown in Fig. 7.1 in blue from point 1 to point 2. A piece of PM fiber (from b to c) should be spliced at 45° to the fiber laser at location 1 ($\times$) to excite two polarization modes of the PM fiber at location b. Power-dependent polarization rotation at location c could be used to find the optimum angle (A) of the polarizer for the maximum change of transmission. The polarizer transmission axis is along the slow axis of the collimator at location d and both rotate together using the rotational mount they are attached to. The blue box at location 2 contains a rotational mount to rotate polarizer and collimator simultaneously.

### 7.2 IPI and Applications

Mode-locked fiber lasers are the most promising media to implement IPI due to their ability to produce ultrashort pulses in a robust, compact system that does not require difficult alignment, and has the potential of producing compact arrays of sensors. Fiber laser gyro (ring cavity) is a particular example of IPI in which the physical parameter to be measured is angular rotation.
Chapter 7. Conclusion and Future Work

Figure 7.1: Sketch of a unidirectional Er-doped fiber laser to be mode-locked by a novel method of mode-locking based on nonlinear transmission in PM fibers. The laser part shown in blue indicates the mechanism of mode-locking in this method. The polarization of light with respect to the axis of the fiber is indicated at different locations as a, b, c, and d. The power-dependent polarization states at location c is an example to show the mechanism. A: angle of polarizer with respect to fast axis, WDM: wavelength division multiplexer.

A nearly symmetric design of bidirectional mode-locked fiber ring laser has been presented that has the ability to control the asymmetry of the cavity by tuning two symmetrically located pump powers. Due to the asymmetry of the cavity a bias beat note has been measured although no physical parameter (induced phase shift) has been introduced to the system. The measured bias beat note has been therefore demonstrated to be variable by tuning two pump powers. The measured beat note frequency has shown an increase from 1.1 MHz to 3.9 MHz by increasing the asymmetry in the cavity through changes in pump powers difference from 23 mW to 160 mW.

**Future Work** → The possibility of monitoring very small and slow changes in biological samples is a potential project implementing IPI technique. It could be done by interacting one circulating pulse in the cavity through evanescent wave coupling to a biological sample, by tapering the fiber or creating an air gap in the bidirectional fiber laser (Fig. 5.2). Any small changes in the
Chapter 7. Conclusion and Future Work

refractive index of the sample would change the phase of the propagating pulse resulting in an extra phase shift between combs.

The presence of phase coupling between two counter-circulating pulses at the saturable absorber, where pulses cross, has created a dead–band which limits the smallest measurable value of the beat note to about 1 MHz for the laser shown in Fig. 5.2. The dead–band has been reduced — possibly removed – by making the two circulating pulses orthogonally polarized. PM fibers provide the possibility of circulating two pulses linearly polarized, one along the slow axis and the other one along the fast axis of the PM fiber. A reduced bias beat note of 31 kHz was measured with the unique design of Fig. 5.8 with cross-polarized pulses. This is considerably less than previously recorded beat note frequencies in fiber lasers [1–3]. Mechanical instabilities prevented the tuning of the beat note to lower value and determine whether the dead–band has been completely eliminated.

Future Work → With a reduced path in air and enhanced mechanical stability, the laser of Fig. 5.8 promises to become the most performant gyroscope. Applying the same technique to the linear IPI as sketched in Fig. 4.5 with shorter air path and enhanced stability (using for instance zerodur glass support) would enable the continuous monitoring of optical paths with fm precision.

7.3 Fiber Sensor Based on Birefringence of PM Fibers

It has been shown that a piece of PM fiber can be used as a sensor to stabilize the environmental conditions. Low-power nonlinear transmission through a PM fiber has been demonstrated by sending a circularly polarized light to the fiber terminating with an appropriately oriented polarizer. The polarization rotation at different powers of light and various temperatures of the fiber has been investigated. A comprehensive characterization of the sensor has shown the possibility of having a robust, all-fiber saturable absorber as already mentioned in section 7.1. The application of this sensor in monitoring small temperature changes (20 mK) has been demonstrated. A strong correlation between power-dependent and temperature-dependent polarization rotation has been discovered. The response time of the sensor to the change of power has been measured as 125 µs.
Chapter 7. Conclusion and Future Work

**Future Work** → One of the very practical application of power/temperature sensor could be optical length stabilization in interferometers which has been elaborated in section 6.5.
Chapter 7. Conclusion and Future Work

References


Appendix A

Polarization Maintaining Fibers

This appendix is included to provide some fundamental information regarding polarization maintaining (PM) fibers. The work in this dissertation utilized the properties of PM fibers to propose a novel all-fiber saturable absorber to mode-lock fiber lasers presented in Chapter 3. Other applications such as temperature sensor and optical length stabilization are presented in Chapter 6.

A single mode optical fiber has a circular core which is covered by cladding of another material with lower refractive index. Theoretically speaking, an optical fiber with a circular core has no birefringence, and the polarization state of light does not change during propagation in such an optical fiber. In reality, however, there is always a small amount of birefringence, typically stress induced, such that the polarization of a beam sent through the fiber varies with positioning and bending of the fiber. This effect has been exploited for generating short pulses through polarization mode-locking [1]. Such birefringence is inherently random which causes random power coupling between two polarization modes propagating in an optical fiber. The output polarization state of light, therefore, becomes unpredictable and also varies with environmental conditions. By intentionally inducing uniform birefringence along the entire fiber length, random power coupling between two polarization modes will be prohibited. Today, Birefringent fibers are fabricated for the purpose of preserving two polarization modes of the propagating light. Polarization maintaining fibers are designed such that there are two well defined polarization modes which propagate along
Appendix A. Polarization Maintaining Fibers

Figure A.1: Two different methods of making PM fibers through shaping the fiber core in a) form-birefringent fibers or by introducing mechanical stress rods of another material within the cladding with different shapes as b) bow-tie, c) PANDA, or d) elliptical cladding.

As can be seen in Fig. A.1, there are two different methods to induce birefringence in PM fibers known as form-birefringent and stress-birefringent fibers. The form-birefringent fiber which is shown in Fig. A.1 (a), is based on elliptical shape of the fiber core. However, it will affect the propagating modes in the fiber, and also reduce the efficiency of coupling light to or from fibers with circular cores. Alternatively, some mechanical stress can be applied by introducing different shapes of stress rods of another material within the cladding [see Fig. A.1(b) and (c) for Bow-Tie and PANDA fibers) or by using an elliptical cladding as shown in Fig. A.1(d). In this work, PANDA PM fiber has been used.

By exciting two polarization modes of a PM fiber through sending off-axis linearly polarized light or by sending circularly or elliptically polarized light, a phase shift of \( \Delta \varphi \) appears between the polarization modes propagating along the PM fiber which is defined as,

\[
\Delta \varphi = \frac{2\pi B}{\lambda} L \quad \text{(A.1)}
\]
Appendix A. Polarization Maintaining Fibers

where $B$ is the birefringence of the PM fiber defined as the difference between refractive indices along slow and fast axes ($B = n_{\text{slow}} - n_{\text{fast}}$), $\lambda$ is the wavelength of the propagating light, and $L$ is the length of the PM fiber.

![Image of PANDA fiber with polarization modes]

Figure A.2: a) linearly polarized light at 45° to the slow axis of a PM fiber. Polarization rotation along a PM fiber with b) high birefringence and c) low birefringence.

In Fig. A.2 a linearly polarized light at 45° to the fast axis of a PM fiber excites two polarization modes of a PM fiber equally. Fig.A.2 (b) shows that the initial input polarization rotates along the PM fiber and is repeating itself once $\Delta \varphi = 2\pi$. The corresponding traveling distance (typically a few millimeters) is called beat length over which the wave in one polarization mode will experience an additional delay of $\lambda$ compared to the other mode, since the modes travel at different phase velocities [2]. Therefore half a beat length of a PM fiber is equivalent to a half-wave plate and a PM fiber can be seen as the fiber version of a very high order waveplate. From equation A and considering $\Delta \varphi = 2\pi$, the beat length of a PM fiber is inversely proportional to the birefringence of the PM fiber through $L_B = \frac{\lambda}{B}$. For a PM fiber with a lower amount of birefrigence, the beat length is therefore longer for a particular wavelength of the propagating light as shown in Fig. A.2 (c).
Appendix A. Polarization Maintaining Fibers

References


Appendix B

Polarization Ellipse Measurement

This appendix is included to provide a method for polarization measurement. The work in this dissertation utilizes the polarization modification of initially circularly polarized light propagating in a piece of polarization maintaining (PM) fiber to propose a novel all-PM fiber saturable absorber presented in Chapter 3.

![Figure B.1: A simple home-made polarimeter to measure the polarization ellipse.](image)

The polarization ellipse of the light is measured using a simple home-made polarimeter shown in Fig. B.1. A collimator collects and collimates the unknown polarized light and sends it through a rotating polarizer. Polarization measurements are performed at angular increments of 2° for a full
Appendix B. Polarization Ellipse Measurement

rotation of 360°. The projection of the polarization along the transmission axis of the polarizer is given by \[ \begin{pmatrix} E \\ F \end{pmatrix} = M \begin{pmatrix} A \\ B \end{pmatrix} \] in which \( \begin{pmatrix} A \\ B \end{pmatrix} \) is the actual polarization ellipse to be measured and M is the transfer function of the polarizer of the form of a Jones matrix

\[
M = \begin{bmatrix}
\cos^2 \theta & \sin \theta \cos \theta \\
\sin \theta \cos \theta & \sin^2 \theta
\end{bmatrix}
\]

where \( \theta \) is the angle between the transmission axis of the polarizer and the slow axis of the PM fiber shown in Fig. B.2(a).

![Figure B.2: (a) The angle \( \theta \) between transmission axis of a polarizer and the slow axis of a PANDA PM fiber. The transmitted power through a rotating polarizer for (b) linearly, (c) circularly, (d) and (e) elliptically polarized light.](image)

As the polarizer rotates from 0 to 360 degrees, a power meter measures the transmitted power through the rotating polarizer at each angle as \( |E|^2 + |F|^2 \). The different patterns of the measured transmitted power for a full rotation of polarizer from zero to 360 degrees for different polarization...
Appendix B. Polarization Ellipse Measurement

states are depicted in Fig. B.2 (b) to (e). Figures B.2 (b) and (c) illustrate the patterns of transmitted light through the rotating polarizer for linear and circular polarizations, respectively. As can be seen in Fig. B.2 (b), the transmitted light is maximum at zero angle and reaches to the minimum (ideally zero for linear polarization) at 90°. For the elliptically polarized light with major axis along the slow axis of the PM fiber, the transmitted light through the polarizer is shown in Fig. B.2 (d), and Fig. B.2 (e) illustrates the transmitted pattern for an elliptically polarized light with an arbitrary orientation of the ellipse.

Figure B.3: An example of elliptically polarized light with ellipticity of 0.37 and angle of 135° with respect to the slow axis of the PM fiber.

The transmitted pattern is used to reconstruct the actual polarization ellipse \( \begin{bmatrix} A \\ B \end{bmatrix} \) of the transmitted light using a simple MATLAB program. The ratio of minor to major axes of the retrieved ellipse gives the ellipticity of the polarization state of the light, being zero for linear polarization and unity for circular polarization. The angle of ellipse can also be found using the orientation of the major axis of the retrieved ellipse. The accuracy of the reconstruction of the polarization state is demonstrated by comparing the normalized experimental data and the fitted ellipse projection in Fig. B.3. The experimental data is taken by the polarimeter shown in Fig. B.1 for an elliptically polarized light with ellipticity of 0.37 and angle of 135° with respect to the slow axis of the PM fiber depicted in Fig. B.2 (a).
Appendix B. Polarization Ellipse Measurement

This is the procedure that was followed in order to find the polarization of light in Chapter 3 of this dissertation. I have also written a MatLab© function that I can make available if requested.
Chapter 1


References


References


Chapter 2


Chapter 3

References


References


References


References


Chapter 4


References


References


References


Chapter 5


References


Chapter 6


References


Chapter 7


References

Appendix A
