PERFORMANCE OF FOUR-STAGE CASCADED FIBER OPTICAL PARAMETRIC AMPLIFIER (FOPA) USING OPTISYSTEM

FATIN NABILAH BINTI MOHAMAD SALLEH

UNIVERSITI TUN HUSSEIN ONN MALAYSIA
PERFORMANCE OF FOUR-STAGECASCADED FIBER OPTICAL PARAMETRIC AMPLIFIER (FOPA) USING OPTISYSTEM

FATIN NABILAH BINTI MOHAMAD SALLEH

A thesis submitted in fulfillment of the requirement for the award of the Master of Electrical Engineering

Faculty of Electrical and Electronic Engineering
Universiti Tun Hussein Onn Malaysia

JULY, 2017
To my beloved family
ACKNOWLEDGEMENT

Praise and thanks to Allah (SWT) who gave me the strength and courage to complete this project.

I would like to express sincere thanks to my supervisor Dr. Nor Shahida Binti Mohd Shah for her invaluable guidance throughout the course of this research. Her guidance, ideas, encouragement, affable nature, kindness and support were greatly helpful.

I would like to wish thanks to my mother Saidah Binti Hj Martan, for her daily prayers and giving me motivation and strength. I also want to thank my late father, Mohamad Salleh Bin Kassim for raising me up until his last breath. I will be ever grateful for his assistance, and am sorry that he has not lived to witness my achievements.

A special acknowledgment must be given to my brothers and sisters for their support and help during my academic period at UTHM.

Finally, sincere gratitude to my friends who inspired me by their courage and guidance throughout the period of my study.
ABSTRACT

An optical fiber plays a significant role to cater the increasing transmission capacity. In optical fiber, there is a few nonlinear effects. One of the nonlinear effects is four-wave mixing (FWM). In-depth analysis of FWM is conducted and it is found that one of the applications in the FWM is a fiber optical parametric amplifier (FOPA). An FOPA has an ability to achieve a high gain and bandwidth. One of the approaches is a cascaded FOPA. A cascaded FOPA is a FOPA with two or more active media, commonly known as a highly nonlinear fiber (HNLF). Previous experimental work shows that the improvement in gain and bandwidth of the cascaded FOPA depends on the passive or active devices inserted in between the HNLF. However, the results at each stage of the cascaded FOPA are not discussed. The result at each stage is crucial to ensure that the cascaded FOPA is amplifying power at the respective stage which is the essence of this work. The cascaded FOPA is demonstrated by using an OptiSystem software with four stages of HNLF with different parameters. Two research work related to the cascaded FOPA are presented in this thesis. The first work focusses on the effects of pump dithering to the cascaded FOPA, while the second work discusses the effects of passive components to cascaded FOPA. The passive components selected are isolator and optical bandpass filter (OBPF). The results show that the FOPA with pump dithering can achieved the gain up to 27 dB, while without pump dithering, only 9 dB gain is achieved. For the performance of the cascaded FOPA with isolators, a high gain of 30 dB is obtained, while the cascaded FOPA with OBPFs, a wider bandwidth of 36 nm is obtained. In conclusion, the pump dithering and isolator can be used to achieved a high gain of FOPA and OBPF can be used to obtain a wider bandwidth of FOPA.
ABSTRAK

# TABLE OF CONTENTS

<table>
<thead>
<tr>
<th>Section</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>DECLARATION</td>
<td>ii</td>
</tr>
<tr>
<td>DEDICATION</td>
<td>iii</td>
</tr>
<tr>
<td>ABSTRACT</td>
<td>v</td>
</tr>
<tr>
<td>ABSTRAK</td>
<td>vi</td>
</tr>
<tr>
<td>TABLE OF CONTENTS</td>
<td>vii</td>
</tr>
<tr>
<td>LIST OF TABLES</td>
<td>x</td>
</tr>
<tr>
<td>LIST OF FIGURES</td>
<td>xi</td>
</tr>
<tr>
<td>LIST OF SYMBOLS AND ABBREVIATIONS</td>
<td>xiii</td>
</tr>
<tr>
<td>LIST OF APPENDICES</td>
<td>xvi</td>
</tr>
<tr>
<td>LIST OF PUBLICATIONS</td>
<td>xvii</td>
</tr>
</tbody>
</table>

## CHAPTER 1 INTRODUCTION

1.1 Preamble ........................................ 1
1.2 Problem Background ................................ 2
1.3 Problem Statement ................................ 3
1.4 Research Objectives ................................ 3
1.5 Research Scopes .................................. 4
1.6 Report Outline .................................. 4

## CHAPTER 2 LITERATURE REVIEW

2.1 Introduction ..................................... 5
2.2 Nonlinear Fiber Optics
   2.2.1 Stimulated Raman Scattering  6
   2.2.2 Stimulated Brillouin Scattering  7
   2.2.3 Self-Phase Modulation  8
   2.2.4 Cross-Phase Modulation  10
   2.2.5 Four-Wave Mixing  10

2.3 Dispersion
   2.3.1 Mode Dispersion  12
   2.3.2 Chromatic Dispersion  12
   2.3.3 Zero Dispersion Wavelength (ZDW)  13

2.4 Fiber Optical Parametric Amplifier (FOPA)
   2.4.1 Theory of FOPA  14
   2.4.2 Phase-Matching Condition  16
   2.4.3 Gain Spectrum of FOPA  17

2.5 Cascaded FOPA  19

CHAPTER 3 METHODOLOGY  23
3.1 Introduction  23
3.2 Simulations in Optisystem software  23
3.3 The Simulation Components  24
   3.3.1 Continuous-Wave Laser  24
   3.3.2 Polarization Controller  25
   3.3.3 Phase Modulator  25
   3.3.4 Sine Generator  25
   3.3.5 Erbium-Doped Fiber Amplifier  26
   3.3.6 Optical Bandpass Filter  26
   3.3.7 Pseudorandom Bit Sequences Generator  27
   3.3.8 Non-Return-To-Zero Pulse Generator  28
   3.3.9 Mach-Zehnder Modulator  28
   3.3.10 Isolator  29
   3.3.11 Highly Nonlinear Fiber  29
   3.3.12 Optical Spectrum Analyser  30
3.4 The Four Stage Cascaded FOPA Simulation Setup  30
   3.4.1 The Effects of Pump Dithering  31
### 3.4.2 The Effects of Components Inserted In Between The HNLF

3.5 Summary

### CHAPTER 4 RESULT AND ANALYSIS

<table>
<thead>
<tr>
<th>Section</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>4.1 Introduction</td>
<td>35</td>
</tr>
<tr>
<td>4.2 Simulation of FWM phenomenon</td>
<td>35</td>
</tr>
<tr>
<td>4.3 The effects of pump dithering</td>
<td>38</td>
</tr>
<tr>
<td>4.4 The effects of passive components</td>
<td>42</td>
</tr>
<tr>
<td>4.4.1 Isolators</td>
<td>42</td>
</tr>
<tr>
<td>4.4.2 Optical bandpass filter</td>
<td>45</td>
</tr>
<tr>
<td>4.4.3 Gain Comparison for isolators and OBPFs cases</td>
<td>47</td>
</tr>
</tbody>
</table>

### CHAPTER 5 CONCLUSION

<table>
<thead>
<tr>
<th>Section</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>5.1 Introduction</td>
<td>49</td>
</tr>
<tr>
<td>5.2 Conclusion</td>
<td>49</td>
</tr>
<tr>
<td>5.3 Main Contribution</td>
<td>50</td>
</tr>
<tr>
<td>5.4 Future Work</td>
<td>50</td>
</tr>
</tbody>
</table>

### REFERENCES

### APPENDIX
LIST OF TABLES

Table 2.1: Summary of nonlinear effects in optical fiber

Table 2.2 Comparison of previous work for cascaded FOPA

Table 3.1: Parameters of the CW laser

Table 3.2: The parameters of four HNLFs [40]

Table 4.1: Comparison of experimental and simulation results

Table 4.2: The value of signal power for with and without pump dithering at each stage

Table 4.3: The pump and idler power at each stage of with and without pump dithering cases

Table 4.4: The comparison of signal power for cascaded FOPA with and without isolator.

Table 4.5: Pump, signal and idler power at each stage.

Table 4.6: The pump, signal and idler power for cascaded FOPA with OBPF
**LIST OF FIGURES**

<table>
<thead>
<tr>
<th>Figure</th>
<th>Description</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>2.1</td>
<td>The optical power transfer (a) before and (b) after the SRS effects [8].</td>
<td>7</td>
</tr>
<tr>
<td>2.2</td>
<td>The SBS power depletion from the original signals [8].</td>
<td>7</td>
</tr>
<tr>
<td>2.3</td>
<td>Optical pulse as it propagates into the fiber [8].</td>
<td>9</td>
</tr>
<tr>
<td>2.4</td>
<td>The optical pulse experience spectral broadening due to SPM [8].</td>
<td>10</td>
</tr>
<tr>
<td>2.5</td>
<td>Two channel pump wave</td>
<td>11</td>
</tr>
<tr>
<td>2.6</td>
<td>One channel pump wave (degenerate FWM)</td>
<td>12</td>
</tr>
<tr>
<td>2.7</td>
<td>The gain spectrum of FOPA [24]</td>
<td>19</td>
</tr>
<tr>
<td>3.1</td>
<td>The CW laser block diagram</td>
<td>24</td>
</tr>
<tr>
<td>3.2</td>
<td>The polarization controller.</td>
<td>25</td>
</tr>
<tr>
<td>3.3</td>
<td>The phase modulator</td>
<td>25</td>
</tr>
<tr>
<td>3.4</td>
<td>The sine generator</td>
<td>26</td>
</tr>
<tr>
<td>3.5</td>
<td>The EDFA</td>
<td>26</td>
</tr>
<tr>
<td>3.6</td>
<td>The OBPF</td>
<td>26</td>
</tr>
<tr>
<td>3.7</td>
<td>The PRBS Generator</td>
<td>27</td>
</tr>
<tr>
<td>3.8</td>
<td>The NRZ pulse generator</td>
<td>28</td>
</tr>
<tr>
<td>3.9</td>
<td>The Mach-Zehnder modulator</td>
<td>28</td>
</tr>
<tr>
<td>3.10</td>
<td>The isolator</td>
<td>29</td>
</tr>
<tr>
<td>3.11</td>
<td>The HNLF</td>
<td>29</td>
</tr>
<tr>
<td>3.12</td>
<td>The OSA</td>
<td>30</td>
</tr>
<tr>
<td>3.13</td>
<td>The simulation setup for cascaded FOPA</td>
<td>31</td>
</tr>
<tr>
<td>3.14</td>
<td>Simulation setup of cascaded FOPA with OBPF</td>
<td>33</td>
</tr>
<tr>
<td>4.1</td>
<td>The pump wavelength spectrum</td>
<td>36</td>
</tr>
</tbody>
</table>
Figure 4.2: The pump and signal wavelength after injected into fiber
Figure 4.3: The FWM phenomenon inside the optical fiber
Figure 4.4: The gain spectrum for simulation done and experimental from [40]
Figure 4.5: The signal powers at each stage of cascaded FOPA without pump dithering
Figure 4.6: The signal power at each stage of cascaded FOPA with a pump dithering
Figure 4.7: The gain spectrum for cascaded with and without isolator.
Figure 4.8: The signal power at each stage of cascaded FOPA without isolator
Figure 4.9: Output spectrum for each HNLFs of cascaded FOPA with OBPFs
Figure 4.10: Gain spectrum for cascaded FOPA with isolators and OBPFs.
LIST OF SYMBOLS AND ABBREVIATIONS

\( f_i \) - First optical frequency
\( f_j \) - Second optical frequency
\( f_k \) - Third optical frequency
\( f_{ijk} \) - Fourth intermodulation product
\( \chi_{1111} \) - Third-order nonlinear susceptibility
\( \eta \) - Channel spacing
\( n \) - Fiber refractive index
\( D \) - Degeneracy factor
\( L_{\text{eff}} \) - Effective length
\( A_{\text{eff}} \) - Effective area
\( \alpha \) - Attenuation
\( L \) - Length
\( P_i \) - Input power at \( f_i \)
\( P_j \) - Input power at \( f_j \)
\( P_k \) - Input power at \( f_k \)
\( P_{ijk} \) - Power generated at \( f_{ijk} \)
\( \omega_{p_1} \) - Angular frequency of pump one
\( \omega_{p_2} \) - Angular frequency of pump two
\( \omega_i \) - Angular frequency of idler
<table>
<thead>
<tr>
<th>Symbol</th>
<th>Definition</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\omega_s$</td>
<td>Angular frequency of signal</td>
</tr>
<tr>
<td>$\omega_c$</td>
<td>Center angular frequency</td>
</tr>
<tr>
<td>$P_p$</td>
<td>Pump power</td>
</tr>
<tr>
<td>$P_s$</td>
<td>Signal power</td>
</tr>
<tr>
<td>$P_i$</td>
<td>Idler power</td>
</tr>
<tr>
<td>$\gamma$</td>
<td>Nonlinear coefficient</td>
</tr>
<tr>
<td>$\Delta \beta$</td>
<td>Low propagation mismatch</td>
</tr>
<tr>
<td>$\beta_p$</td>
<td>Propagation constant of pump</td>
</tr>
<tr>
<td>$\beta_s$</td>
<td>Propagation constant of signal</td>
</tr>
<tr>
<td>$\beta_i$</td>
<td>Propagation constant of idler</td>
</tr>
<tr>
<td>$c$</td>
<td>Speed of light</td>
</tr>
<tr>
<td>$\lambda_o$</td>
<td>Zero dispersion wavelength</td>
</tr>
<tr>
<td>$\lambda_p$</td>
<td>Pump wavelength</td>
</tr>
<tr>
<td>$\lambda_s$</td>
<td>Signal wavelength</td>
</tr>
<tr>
<td>$\lambda_i$</td>
<td>Idler wavelength</td>
</tr>
<tr>
<td>$\frac{dD}{d\lambda}$</td>
<td>Slope of dispersion at zero dispersion wavelength</td>
</tr>
<tr>
<td>$\beta_4$</td>
<td>Fourth-order dispersion coefficient</td>
</tr>
<tr>
<td>$\phi_p$</td>
<td>Phase of the pump</td>
</tr>
<tr>
<td>$\phi_s$</td>
<td>Phase of the signal</td>
</tr>
<tr>
<td>$\phi_i$</td>
<td>Phase of the idler</td>
</tr>
<tr>
<td>$\theta$</td>
<td>Relative phase difference</td>
</tr>
<tr>
<td>$\kappa$</td>
<td>Phase-matching condition</td>
</tr>
<tr>
<td>$\kappa_M$</td>
<td>Material dispersion</td>
</tr>
<tr>
<td>$\kappa_W$</td>
<td>Waveguide dispersion</td>
</tr>
</tbody>
</table>
$\kappa_{\text{NL}}$ - Nonlinear dispersion
$G$ - Gain
$G_{\text{exp}}$ - Exponential gain
$G_{\text{quad}}$ - Quadratic gain
DCF - Dispersion Compensation Fiber
DSF - Dispersion-Shifted Fiber
EDFA - Erbium Doped Fiber Amplifier
FBG - Fiber-Bragg Grating
FOPA - Fiber Optical Parametric Amplifier
FWM - Four-Wave Mixing
HNLF - Highly Nonlinear Fiber
OBPF - Optical Bandpass Filter
OOK - On-Off Keying
OSA - Optical Spectrum Analyzer
PC - Polarization Controller
PCF - Photonic Crystal Fiber
PIA - Phase-Insensitive Amplifier
PM - Phase Modulator
PSA - Phase-Sensitive Amplifier
QPM - Quasi-Phase Matching
RF - Radio Frequency
SBS - Stimulated Brillouin Scattering
SPM - Self-Phase Modulation
SRS - Stimulated Raman Scattering
SSMF - Standard Single-Mode Fiber
WDM - Wavelength Division Multiplexing
XPM - Cross-Phase Modulation
ZDW - Zero-Dispersion Wavelength
<table>
<thead>
<tr>
<th>Appendix</th>
<th>Description</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>The cascaded FOPA with pump dithering setup</td>
<td>57</td>
</tr>
<tr>
<td>B</td>
<td>The cascaded FOPA without pump dithering setup</td>
<td>58</td>
</tr>
<tr>
<td>C</td>
<td>Optisystem software setup for cascaded FOPA without isolators</td>
<td>59</td>
</tr>
<tr>
<td>D</td>
<td>Optisystem software setup for cascaded FOPA with OBPFs</td>
<td>60</td>
</tr>
</tbody>
</table>
LIST OF PUBLICATIONS

Journal:


Proceeding:


CHAPTER 1

INTRODUCTION

1.1 Preamble

In the past, the way people communicate with each other is different from what that have been practiced today. Back then, most of the communication were realized via voice, writing and signals.

The technology keeps evolving from the increasing demands. One of them is the transfer of the information within the considerable distance. From the historical point of view, the rapid growth of the electrical communication is the result of the invention of the telegraph by Samuel F. B. Morse. The Morse code is represented by letters and numbers with a series of dots and dashes. The major invention in communication history is the discovery of the telephone in 1876 by Alexander Graham Bell [1].

As time goes by, the increasing portion of the electromagnetic spectrum has enhanced the medium of communication to be more reliable and has the ability to cater the high capacity to convey messages from one place to another. Optical fiber is one of the approaches to send messages via long distance transmission. The long-haul transmission of data is not a problem to optical fiber because of the lower transmission loss. Besides that, the low operation cost can be achieved by reducing the number of repeaters. At the same time, the reduction of elements will reduce the complexity of the systems. The optical fiber is also immune from the electromagnetic interference since
it is made from dielectric materials. The demanding factor of high data rate application is the reason wider bandwidth is needed. The optical fiber is the medium that can realize that purpose.

The optical fiber itself experiences nonlinear effects that start to appear at the increasing level of optical power. The nonlinear effects in an optical fiber are four-wave mixing (FWM), cross-phase modulation (XPM), self-phase modulation (SPM), stimulated Brillouin scattering (SBS) and stimulated Raman Scattering (SRS). In this work, the focus is on the FWM nonlinearities.

Basically, FWM occurs when a light of two or more with different wavelengths is launched into the optical fiber. When the lights are fed into the fiber, a new wavelength will appear which is known as an idler [2]. The idler has a different wavelength as compared to the light that is launched into the fiber. When the two pumps of FWM have the same frequency, it is known as the degenerated FWM.

In the transmission of the wavelength-division multiplexing (WDM), FWM is commonly avoided because it can cause crosstalk in the signal that is transmitted through the optical fiber [3][4]. However, FWM is a practical technological basis for certain applications. There are many applications for the FWM such as phase conjugation, parametric amplification, wavelength conversion, ultrafast optical sampling, optical switching and all-optical regeneration. In this research, attention is diverted to the fiber optical parametric amplifier (FOPA). FOPA is an amplifier that can have an amplification bandwidth outside Erbium Doped Fiber Amplifier (EDFA). FOPA has a potential for amplification and wavelength conversion in multi-terabit/s dense wavelength division multiplexing (DWDM). There are two types of FOPA which are one-pump FOPA and two-pumps FOPA [5][6]. In this study, the one-pump FOPA is chosen because of its simplicity. Besides that, FOPA can offer high gain and low noise. However, narrow bandwidth of FOPA is the problem. Thus, in this work, a method to obtain high gain with a wider bandwidth of FOPA is investigated.

1.2 Problem Background

The currents trends of FOPA demand a high gain and bandwidth. One of the technique to achieved a high gain and wider bandwidth is by using a cascaded FOPA. Cascaded FOPA is a concatenation technique of a few fibers that had been cut into
short pieces and been splice together. The cascaded FOPA is chosen due to its ability to achieve a high gain or wider bandwidth depending on the components inserted in between the two fibers. The latest trend involved a four-stage of cascaded FOPA and show a reliable gain and bandwidth despite it splice loss [7].

However, the result at each stage is not presented. The result at each stage is an added contribution towards the analysis. The spectrum at each stage of four-stage cascaded FOPA is observed where the spectrum of pump, signal and idler light is shown. The observation is focussed on the signal power due to it is related to the gain and bandwidth. The observation at each stage of cascaded FOPA is quite complicated to apply in the experimental work. This is one of the reason to conduct a simulation and observing a spectrum at each stage of cascaded FOPA.

1.3 Problem Statement

The cascaded FOPA can increased the gain and bandwidth with an in-line of highly nonlinear fiber (HNLF) configurations. A previous work has been conducted which discussed the effects of passive devices that are added in between the HNLF. However, the results at each stage of cascaded FOPA is not presented. The results at each stage is crucial to ensure the cascaded FOPA runs successfully.

This work investigates the effects of components inserted at each stage on the gain and bandwidth of cascaded FOPA. The in-depth study is also conducted at each stage to observe the output spectrum of the cascaded FOPA.

1.4 Research Objectives

The objectives of this work are:
(i) To perform four-stage cascaded FOPA configurations.
(ii) To investigate the effects of pump dithering and inserted components towards cascaded FOPA.
(iii) To analyse the signal power at each stage of the four-stage cascaded FOPA and the gain and bandwidth of the whole system.
1.5 Research Scopes

This research is conducted by using an Optisystem software. This four-stage cascaded FOPA is only focused on the Non-Return to Zero-On Off Keying (NRZ-OOK) modulation. Besides that, the inserted passive components chosen in this research are isolators and optical bandpass filter (OBPF). However, there is a limitation in the characterization at each stage of the four-stage cascaded FOPA. The analysis only involves the value of signal powers at each stage because it related to the gain and bandwidth. The bandwidth range involve in this research are from 1535 nm until 1570 nm.

This research is not considering the splice loss of the four-stage concatenation fiber. It also neglected the polarization and the phase of the pump and signal light.

1.6 Report Outline

This thesis consists of five (5) chapters. The introduction of this research is discussed in Chapter 1. The literature review is elaborated in detail in Chapter 2. Next, the methodology is being examined in Chapter 3. It described the method conducted to achieve the objective in this study. Subsequently, the results of this study are presented in Chapter 4 and the analysis towards the cascaded performance is discussed. Lastly, the study is concluded in Chapter 5.
CHAPTER 2

LITERATURE REVIEW

2.1 Introduction

This chapter describes the theoretical background of nonlinear effects and FWM phenomenon. In addition, this chapter discusses the nonlinear fiber optics, dispersion, phase matching, zero dispersion wavelength, fiber optic parametric amplifier (FOPA) and cascaded FOPA.

2.2 Nonlinear Fiber Optics

Transmission of data in the optical fiber is a challenging process. One of the factors that need to be considered is the nonlinear effects in the optical fiber. In the next section, the nonlinear effects are discussed that include Stimulated Raman Scattering (SRS), Stimulated Brillouin Scattering (SBS), Self-Phase Modulation (SPM), Cross-Phase Modulation (XPM) and Four-Wave Mixing (FWM). The nonlinearities can be divided into two categories, which are summarized in Table 2.1 [8].
Table 2.1: Summary of nonlinear effects in optical fiber

<table>
<thead>
<tr>
<th>Nonlinearity category</th>
<th>Single Channel</th>
<th>Multiple Channel</th>
</tr>
</thead>
<tbody>
<tr>
<td>Index related</td>
<td>Self-phase modulation</td>
<td>Cross-phase modulation</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Four-wave mixing</td>
</tr>
<tr>
<td>Scattering related</td>
<td>Stimulated Brillouin scattering</td>
<td>Stimulated Raman scattering</td>
</tr>
</tbody>
</table>

From the table, the first group arises from intensity-dependent variations in the refractive index in silica fiber. It is known as *Kerr effect*. These are SPM, XPM and FWM. The second group is scattering related which comprises of nonlinear inelastic scattering processes. These are SRS and SBS. The SBS, SRS and FWM results in gain or losses in a wavelength channel. The power variations, on the other hand, depend on the optical signal intensity.

### 2.2.1 Stimulated Raman Scattering

Stimulated Raman Scattering is an interaction between light waves and vibrational modes of silica molecules [9]. The SRS process generates scattered light at a wavelength longer than the incident light. If there is a light present in this longer wavelength, the SRS light will amplify it. This will reduce the power of the pump wavelength. Consequently, SRS can severely limit the performance of a multichannel optical communication system by transferring energy from short-wavelength channels to neighboring higher-wavelength channels.

Figure 2.1 demonstrates the effect. Figure 2.1 (a) illustrates the lights launched into the fiber before its experience SRS effects. Figure 2.1 (b) shows the light experience the SRS effects and it scattered the wavelength longer than incident light up to 125 nm. SRS amplify the signal at the longer wavelength. The pump-wavelength limiting the power of the signal.
Stimulated Brillouin Scattering

Stimulated Brillouin Scattering (SBS) occurs when the high optical signal generated an acoustic wave that produces differences in the refractive index. It will cause the depletion of signal power because the backscattered light receives the gain from the forward propagating signals. The backscattered light exists when there are variations in the refractive index. The lightwave will scatter in the backward direction of the transmitter. Figure 2.2 illustrates the power depletion of SBS.

SBS is limiting the maximum amount of optical power that can be coupled into a waveguide [10]. SBS implies a strict limit to the power that will be delivered into the
fiber due to the generated backward propagating wave due to the material properties. This input is known as SBS threshold and can be define as equation 2.1.

\[ P_{th} \sim \frac{21kA_{eff} \Delta v_p}{g_o L_{eff} \Delta v_B} \]  

(2.1)

where:

- \( k \) is the polarization state,
- \( A_{eff} \) is the effective modal area,
- \( L_{eff} \) is an effective interaction length,
- \( g_o \) is the Brillouin gain parameter,
- \( \Delta v_B \) is the Brillouin gain bandwidth,
- \( \Delta v_p \) is the incident pump linewidths

Most of the fiber that useful for FOPA systems is expected having an extremely small value of the SBS threshold. Because of this limitation, the SBS suppression methods must be employed to create a FOPA with net gain.

### 2.2.2.1 Pump Dithering Method

One of the method to suppress the SBS is by using a pump dithering. In the pump dithering, the phase or frequency of the pump dithering manipulates the incident pump linewidth, \( \Delta v_p \) to minimize the spectral overlap between the incident laser and the Brillouin bandwidth [11]. Usually, the pump is modulated by using several RF signals to broaden the linewidth of the pump. It results a limited gain experienced by the back-reflection.

### 2.2.3 Self-Phase Modulation

Self-phase modulation (SPM) refers to the phenomenon in which the laser beam propagating in a medium interacts with the medium and imposes a phase modulation itself. The nonlinearity in the refractive index is known as Kerr nonlinearity. The nonlinearity produces a carrier-induced phase modulation of the propagating signal
which is known as *Kerr effect*. It will convert optical power fluctuations to spurious phase fluctuations in the same waves.

Figure 2.3 indicates the optical pulse propagates in a fiber. Here the time axis is normalized to the parameter $t_0$, which is the pulse half-width at the 1/e-intensity point. The edges of the pulse represent a time-varying intensity, which rises rapidly from zero to a maximum value, and then returns to zero. In a medium having an intensity-dependent refractive index, a time-varying signal intensity produces a time-varying refractive index. Thus, the index at the peak of the pulse is slightly different than the value in the wings of the pulse. The leading edges is at positive $dn/dt$, whereas the trailing edge is at negative $dn/dt$.

This temporally varying index change results in a temporally varying phase change, shown by $d\varphi/dt$ in Figure 2.4. The consequence is that the instantaneous optical frequency differs from its initial value across the phase. That is, since the phase fluctuations are intensity-dependent, different parts of the pulse undergo different phase shifts. This leads to what is known as *frequency chirping*. Frequency chirping is the rising edge of the pulse (red shift in frequency) which means that the shifting towards the lower frequencies or longer wavelengths. The trailing edge will experience a blue shift which is the shifting of the pulse towards the higher frequencies.

![Figure 2.3: Optical pulse as it propagates into the fiber [8].](image-url)
2.2.4 Cross-Phase Modulation

Cross-Phase Modulation (XPM) exists in WDM systems and has a similar origin as SPM. Since the refractive index seen by a particular wavelength is influenced by both optical intensity, SPM is always present when XPM occurs. However, XPM only arises when two interacting light beams overlap in space and time. But if the light travels in different group velocities because of the dispersion, the slide past each other and the XPM effect reduces. The XPM effect is reduced as the polarization of light is not identically polarized.

2.2.5 Four-Wave Mixing

Four-Wave Mixing (FWM) is a phenomenon when two or more light is pumped into the optical fiber. In this case, a new light will arise which is called an idler. As mentioned before, FWM is a third-order nonlinearity in optical fibers that is analogous to intermodulation distortion in electrical system. When the pumped wavelength is near zero dispersion wavelength, three optical frequencies mix together to produce the fourth-order intermodulation product. Figure 2.5 and Figure 2.6 illustrate the two channel pump wave and one channel pump wave (degenerate FWM), respectively. The light $f_i, f_j$ and $f_k$ (i, j ≠ k) will interact with each other inside the optical fiber and generate a new frequency, $f_{ijk}$.
\[ f_{ijk} = f_i + f_j - f_k \]  

(2.2)

For the 1-channel pump wave cases, the equation is changes to Equation 2.3, where \( i = j \)

\[ f_{ijk} = 2f_i - f_k \]  

(2.3)

These idlers will travel with the first wave and will grow at the expense of the signal-strength depletion. The efficiency of four-wave mixing depends on the fiber dispersion and channel spacing. The pump light must be near zero-dispersion wavelength to achieve the phase-matching condition. The idler power will decrease as the channel spacing become wider. The idler power can be calculated by Equation 2.4.

\[ P_{ijk}(L) = \eta(D\kappa)^2 P_i(0)P_j(0)P_k(0)\exp(-\alpha L) \]  

(2.4)

where the nonlinear interaction constant, \( \kappa \) is:

\[ \kappa = \frac{32\pi^3}{n^2\lambda^3} \frac{L_{\text{eff}}}{A_{\text{eff}}} \]  

(2.5)

From Equation 2.5, \( \chi_{\text{eff}} \) is the third-order nonlinear susceptibility, \( \eta \) is the efficiency of the four-wave mixing, \( n \) is the refractive index of the fiber, and \( D \) is the degeneracy factor which has the value 3 or 6 for two waves mixing or three waves mixing, respectively. \( L_{\text{eff}} \) and \( A_{\text{eff}} \) are the effective length and effective area in optical fiber. \( \alpha \) is the attenuation in the fiber and \( L \) is the length of the fiber.

Figure 2.5: Two channel pump wave
2.3 Dispersion

Dispersion plays a significant role in optical fiber. Dispersion is the phase velocity that depends on the optical frequency. In telecommunication, the dispersion is used to explain the phenomenon where the signals carried by the electromagnetic wave will have some degradation. The degradation occurs because radiations have various frequencies and velocities. The dispersion can be divided into two types which are mode dispersion and chromatic dispersion.

2.3.1 Mode Dispersion

Mode dispersion appears only in multimode. Mode dispersion is a result of each mode having different values of group velocity at a single frequency. It exists only in multimode because of the core is larger as compared to the single mode and the rays can travel to different paths.

2.3.2 Chromatic Dispersion

Chromatic dispersion is a pulse spreading within a single mode. Since the dispersion depends on the wavelength, it also affects the signal distortion as the signal distortion increases with the increasing spectral width. The two leading causes of the chromatic dispersion are:
2.3.2.1 Material dispersion

Material dispersion is the variations of the refractive index of the core material as a function of wavelength. Material dispersion is also known as chromatic dispersion in which a prism spreads out the spectrum.

2.3.2.2 Waveguide dispersion

Waveguide dispersion effects pulse spreading because of the optical power propagation is confined to the core. The wavelength will vary the distribution of the light because of the cross-sectional of the core. It is the reason why the shorter wavelengths are more confined to the center. The longer wavelengths will propagate in the cladding. Waveguide dispersion can usually be ignored in multi-mode fibers, but it is crucial in a single-mode fiber.

2.3.3 Zero Dispersion Wavelength (ZDW)

Zero dispersion wavelengths are the wavelength at which material dispersion and chromatic dispersion will cancel each other and is equal to zero. The wavelength is 1300 nm for all silica-based optical fiber. For the dispersion shifted fibers, the zero dispersion wavelengths are 1550 nm.

The phase matching is satisfied when the zero-dispersion wavelength is positioned at the middle between the two lights. The phased match frequency bandwidth is narrower for larger wavelength difference [2].

2.4 Fiber Optical Parametric Amplifier (FOPA)

Fiber optical parametric amplifier (FOPA) is one of the applications that is based on the FWM. FOPA builds on the third-order Kerr nonlinearity of the optical fiber itself. The higher value of nonlinearity coefficient, γ (about 5-10 times than conventional fiber [12]) and high power of the input source are necessary to achieve the amplification outside the Erbium Doped Fiber Amplifier (EDFA). Historically, the
first FOPA was demonstrated in 1976 by using low-loss fiber [13]. The discovery of EDFA in late 1980s has sparked the interest on FOPA. It has also contributed to the development of dispersion-shifted fiber (DSF) with the zero-dispersion wavelength (ZDW) at 1550 nm in the C-band area. The DSF with the highest value of $\gamma$ has been discovered in 1995 by increasing the germanium concentration and decreasing the core diameter [14].

FOPA has been chosen as an amplifier because of its various advantages. One of the benefits is it can avoid the degradation due to the chromatic dispersion since it operates in the ZDW region. It also has low noise figure that can enhance the signal amplification for long-haul communication. The most important factor is FOPA offers wider bandwidth and high gain in phase-matching condition. The phase-matching condition will be described later in this chapter. The research of FOPA has gained more interest because of the adjustable center wavelength. This is due to the fact that the Kerr nonlinearity varies slowly with wavelength. Thus, the parametric gain can achieve the arbitrary wavelength. It also has the advantages of operating on the (S-C-L) band wavelength [15]. Many features can be applied by using FOPA such as wavelength conversion, phase conjugation and supercontinuum generation [16]. However, it has limited bandwidth and the methods to widen it have become a significant interest.

**2.4.1 Theory of FOPA**

There are two types of FOPA which are One-Pump FOPA and Two-Pump FOPA. One pump FOPA has a simple configuration as compared to the two-pump. However, two-pump FOPA offers a wider bandwidth than one-pump FOPA[17].

As mentioned before, FOPA consists of one or two high power waves at angular frequencies of $\omega_{p1}$ and $\omega_{p2}$ that will serve as the pump light sources. The new wave at angular frequency, $\omega_i$ will give rise to an idler. $\omega_i$ will be generated at the mirror image of the signal angular frequency, $\omega_s$ where the signal input is the weak signal that has been interacting with the pump light. Idler will be located at the center wavelength, $\omega_c$ which can be calculated by using Equation 2.6:
\[ \omega_c = \frac{\omega_{p_1} + \omega_{p_2}}{2}, \]  
\[ \omega_q + \omega_l = 2\omega_c \]  
(2.6)

where \( \omega_c \) is located at the halfway of pump 1 and pump 2 and can be simplified using Equation 2.7:

\[ \omega_q + \omega_l = 2\omega_c \]  
(2.7)

For one-pump FOPA, \( \omega_c \) is equal to the angular frequency of pump source, \( \omega_p \). One pump FOPA is also known as degenerate FWM while the two-pump is known as non-degenerate FWM [18].

The basic equations in describing the process of FOPA by neglecting the fiber losses with respect to optical power and phases are as follows [19][20]:

\[ \frac{dP_p}{dz} = -4\gamma \left( P_p^2 P_s P_i \right)^{1/2} \sin \theta; \]  
(2.8)

\[ \frac{dP_s}{dz} = 2\gamma \left( P_p^2 P_s P_i \right)^{1/2} \sin \theta; \]  
(2.9)

\[ \frac{dP_i}{dz} = 2\gamma \left( P_p^2 P_s P_i \right)^{1/2} \sin \theta; \]  
(2.10)

\[ \frac{d\theta}{dz} = \Delta\beta + \gamma \left( 2P_p - P_s - P_i \right) + \gamma \left[ \left( P_p^2 P_s P_i \right)^{1/2} + \left( P_p^2 P_s / P_i \right)^{1/2} - 4 \left( P_p \right)^{1/2} \right] \cos \theta; \]  
(2.11)

where \( P_p, P_s \) and \( P_i \) are the powers of the pump, signal, and idler waves, respectively. \( \gamma \) is the nonlinearity of the fiber. The linear phase mismatch, \( \Delta\beta \) can be calculated by using the formula in Equation 2.12:

\[ \Delta\beta = \beta_s + \beta_i - 2\beta_p \]  
(2.12)

where the longitudinal propagation constant of \( \beta_p, \beta_s \) and \( \beta_i \) are expanded by using Taylor series around ZDW. Therefore, \( \Delta\beta \) is given by:

\[ \Delta\beta = \frac{-\lambda_p^2}{2\pi c} \frac{dD}{d\lambda} \left( \lambda_p - \lambda_s \right) (\omega_s - \omega_p)^2 + \frac{\beta_s}{12} (\omega_s - \omega_p)^4 \]  
(2.13)
where:

- \( c \) is the speed of light in vacuum,
- \( \lambda_{o} \) is the ZDW of the fiber used,
- \( \frac{dD}{d\lambda} \) is the dispersion slope,
- \( \lambda_{p} \) is the pump wavelength,
- \( \beta_{i} \) is the fourth-order dispersion coefficient.

The relative phase difference between the waves is described as:

\[
\theta(z) = \Delta \beta z + \phi_{s}(z) + \phi_{i}(z) - 2\phi_{p}(z)\phi_{s}(z)\phi_{i}(z)
\]

(2.14)

where \( \phi_{p}(z) \), \( \phi_{s}(z) \) and \( \phi_{i}(z) \) are the phases of the pump, signal and idler wave.

By referring to the Equation 2.8 to 2.11, the FOPA can be distinguished from the phase-sensitive by controlling the phase relation, \( \theta \). By controlling the phase relation, the direction of the power from the pump to the signal to the idler and vice versa can be controlled. In addition, the signal can be attenuated or amplified by controlling the phase relation. If \( \theta = \pi/2 \), this means that the parametric amplification is occurring. The signal will be attenuated when \( \theta = -\pi/2 \). It proves that FOPA can be either a Phase-Insensitive Amplifier (PIA) or a Phase-Sensitive Amplifier (PSA).

### 2.4.2 Phase-Matching Condition

Phase-matching is defined as the balance between material dispersion, waveguide dispersion and nonlinear dispersion [21]. By following the work in [22], it states that the equation of phase-matching applies to the sum of the wavevectors of the different waves participating in the process and can be written as:

\[
\kappa \equiv \Delta \kappa_{M} + \Delta \kappa_{W} + \Delta \kappa_{NL}
\]

(2.15)
where $\Delta \kappa_M$, $\Delta \kappa_W$ and $\Delta \kappa_{NL}$ is material dispersion, waveguide dispersion and nonlinear dispersion, respectively.

This condition can only be satisfied if one of the three dispersions is having a negative value. $\Delta \kappa_M$ is in an anomalous dispersion regime. For single-mode fibers; $\Delta \kappa_M$ is far less than $\Delta \kappa_W$ except for the region near the ZDW as the waveguide dispersion and nonlinear dispersion can be adjusted to cancel the small dispersion.

In addition, FOPA must operate in a phase-matched condition. By following the equations in 2.8 to 2.11; when $\theta(z)$ is in phase-matched condition, the value is close to $\pi/2$. Thus, the third term in Equation 2.11 can be neglected and the approximation in Equation 2.16 can be made [23]:

$$\frac{d\theta}{dz} \approx \Delta \beta + \gamma \left(2P_p - P_s - P_i\right) + \gamma \left(2P_p - P_s - P_i\right) \approx \Delta \beta + 2\gamma P_p = \kappa$$ (2.16)

where $\kappa$ is the phase mismatch parameter.

The second approximation is only valid when the amplifier is operating in an undepleted mode. The linear phase mismatch is crucial to achieve the broad bandwidth of FOPA. The equation of the linear phase mismatch, $\Delta \beta$ shows that it is proportional to the fiber dispersion slope. The small value of dispersion slope will enhance the signal bandwidth further.

### 2.4.3 Gain Spectrum of FOPA

The gain of a parametric amplifier is dependent on the phase-matching condition. The parametric gain is approximately exponentially proportional to the applied pump power in the perfectly phase-matched condition.

In addition to the phase-matching, the gain value that can be attained is dependent on the nonlinear phase shift in the fiber. It can be identified that in the ideal case of perfect phase matching, where the relative phase is $\pi/2$, and does not change during propagation; the growth of the gain is exponentially dependent on $2\gamma P_p L$. In the absence of perfect phase matching, the change of the relative phase during
propagation need to be considered. Thus, by assuming no pump depletion and neglecting the signal and idler SPM and XPM due to its small values; the expression of the gain that relates to the phase mismatch parameter, \( \kappa \) can be derived as

\[
G = \left( 1 + \frac{\gamma P_p}{g} \sinh(g L_{\text{eff}}) \right),
\]

(2.17)

Where:

\[
g^2 = \left( \frac{\gamma P_p}{2} \right)^2 - \left( \frac{\kappa}{2} \right)^2.
\]

(2.18)

In the first case where \( \kappa = 0 \), which implies perfect phase matching; Equation 2.17 with the large nonlinear phase-shift can be further simplified by using the Taylor expansion and can be calculated as follows [19]:

\[
G_{\text{exp}} \approx \frac{1}{4} \exp \left[ 2\gamma P_p L_{\text{eff}} \right].
\]

(2.19)

This case is known as the exponential gain because it depends exponentially on the nonlinear phase shift. The second case is when \( \kappa = -2\gamma P_p \) which means that there is no relative phase shift. It is because the signal and the pump wavelength is similar. Equation 2.17 can be used in case of large nonlinear phase-shift and it is simplified as Equation 2.20 [19]:

\[
G_{\text{quad}} \approx \left( 2\gamma P_p L_{\text{eff}} \right)^2.
\]

(2.20)

This case is known as quadratic gain because of the gain quadratically depending on the nonlinear phase-shift. Figure 2.7 shows the gain spectrum of FOPA with the specified exponential and quadratic gain regimes.
The previous work in [24] has shown enormous achievement involving gain spectrum of FOPA. For one-pump FOPA, the gain and bandwidth have been investigated. In that work, broad bandwidth has been introduced at first by combining the FOPA with a Raman gain and provided the 200 nm bandwidth with a low pump power of 13 dBm [25]. Next, the high pump power of 10 W and 16 W are used for one pump FOPA have managed to achieve bandwidths of 230 nm and 360 nm, respectively [26][27]. Practically, FOPA is assumed free from depletion, but there are cases where the reduction is included. In that case, the gain is 62 dB with a bandwidth of 420 nm and is performed by using the photonic crystal fiber (PCF) as a medium [28]. PCF has the advantage of broad bandwidth because of the high nonlinearity coefficient. For example, the PCF also has been used in other cases and achieved 520 nm bandwidth with small negative anomalous dispersion, $\beta_2 \leq 0$ and positive value of fourth-order dispersion parameter, $+\beta_4$ [29].

2.5 Cascaded FOPA

Cascaded FOPA is a technique that uses a concatenation of a few highly nonlinear fiber (HNLF). The fiber is cut into a few short lengths and spliced together. The shorter fiber can enhance the bandwidth of the gain spectrum. The first approach of cascaded FOPA is by rearranging the short pieces of fiber, considering the zero-dispersion of the fiber [30]. This method has relieved the phase mismatch and an extensive
conversion has been achieved. The cascaded FOPA is investigated from the Quasi-phase matching (QPM) theory. The QPM is one of the techniques to mitigate the phase-matching effect [31]. QPM technique has been applied to the slot waveguide to alter the phase-mismatch to achieve the broadband wavelength conversion [32]. In addition, the QPM has been implemented for transparent optical demultiplexer for 160 Gb/s – 10 Gb/s demultiplexer [33]. There is also an investigation conducted to observe the modulation instability of the multisection fiber with a numerical simulation of the nonlinear Schrödinger equation [34]. The design shows that the gain spectrum bandwidth is exceeded by 100nm with a ripple and 200nm when a pump power of 5 W is used.

Besides that, a dispersion compensation fiber (DCF) is placed in between the two HNLF to compensate the HNLF dispersion [35][36]. It is known as a periodic compensation. The widest bandwidth is achieved by using three stages of HNLF with a DCF. In the same way, the standard single-mode fiber (SSMF) is used to compensate the dispersion [37]. The difference of dispersion parameter can relieve the phase matching condition. The value of dispersion is set to get a high absolute value of $\beta_2$ that would lead to a high linear phase mismatch and eventually can compensate the HNLF dispersion and improve the gain. The performance is examined by observing each stage.

The cascaded FOPA can be analysed by using genetic algorithm [38][39]. The cascaded FOPA can also be done by rearranging the fiber and putting the isolators in between the HNLF [40]. The isolators have the ability to suppress the SBS effect [41]. Meanwhile, the highest gain achieved by the two-segment FOPA with an isolator is 60 dB [7]. The gain smoothened with a two-segment has been discussed before by using the idler removal filter to achieve the dispersion mismatch [42].

An optical bandpass filter (OBPF) has also been used in cascaded FOPA [43]. The gain of FOPA is enhanced as compared to the gain without an OBPF. The pump shifters have also been used in the cascaded FOPA where a gain of 21dB has been achieved with a gain flatness bandwidth of 25 nm [44]. Other than that, the cascaded FOPA with a phase shifter has widened the bandwidth from 9 nm to 30 nm [45]. Fiber-Bragg grating (FBG) can enhance the bandwidth when it is used in the cascaded configuration [46]. The cascaded FOPA with a FBG has achieved a 22-dB gain with a 50 nm bandwidth of gain flatness [47].
Cascaded FOPA without any elements is an advantage in wavelength conversion application. The previous work has achieved a 49 dB gain with 56 nm bandwidth [48]. Additionally, the cascaded FOPA can be used for polarization-insensitive configuration [49]. The advantages of cascaded FOPA over the polarization-insensitive configuration is the arbitrary input or output operation wavelength and the signal transparency. Moreover, the cascaded structure has an ability to obtain the PSA and PIA [50]. PSA has achieved the bandwidth of 170 nm while the PIA has reached 160 nm. It is considered significant as compared to the conventional PSA and PIA. Besides that, the SMF and DCF have been placed in between PIA and PSA segments to achieve power equalization and the gain bandwidth is broadened to 15 nm [51]. Table 2.2 shows the previous work of cascaded FOPA.

From the table below, the previous work has been focusing on the gain and bandwidth because they are the most important parameters to measure the performance of cascaded FOPA. However, because of the structure of the cascaded FOPA it which has a few stages of HNLF, the spectrum at each stage needs to be observed to monitor the changes at the respective stage. In this work, the characteristics at each stage are observed. It is crucial as it is a lot easier to detect the problems from the stage by stage basis.
Table 2.2 Comparison of previous work for cascaded FOPA

<table>
<thead>
<tr>
<th>Ref.</th>
<th>Element in between Cascaded FOPA</th>
<th>Number of Stages</th>
<th>Methodology</th>
<th>Performance</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Bandwidth</td>
</tr>
<tr>
<td>[31]</td>
<td>No element (DSF cascaded with SMF-28)</td>
<td>3</td>
<td>Simulation and Experimental</td>
<td>16.1 nm</td>
</tr>
<tr>
<td>[33]</td>
<td>No element</td>
<td>2</td>
<td>Experimental</td>
<td>50 nm</td>
</tr>
<tr>
<td>[34]</td>
<td>No element</td>
<td>4</td>
<td>Simulation</td>
<td>100 nm</td>
</tr>
<tr>
<td>[35]</td>
<td>DCF</td>
<td>4</td>
<td>Numerical</td>
<td>40 nm</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Experimental</td>
<td>40 nm</td>
</tr>
<tr>
<td>[36]</td>
<td></td>
<td>4</td>
<td>Numerical</td>
<td>220 nm</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Simulation</td>
<td>80 nm</td>
</tr>
<tr>
<td>[37]</td>
<td>SSMF</td>
<td>2</td>
<td>Experimental</td>
<td>Not mention</td>
</tr>
<tr>
<td>[38]</td>
<td>No element (Genetic algorithm)</td>
<td>2</td>
<td>Simulation</td>
<td>110 nm</td>
</tr>
<tr>
<td>[39]</td>
<td></td>
<td>3</td>
<td></td>
<td>405 nm</td>
</tr>
<tr>
<td>[40]</td>
<td>Isolator</td>
<td>4</td>
<td>Experimental</td>
<td>27 nm</td>
</tr>
<tr>
<td>[7]</td>
<td></td>
<td>2</td>
<td></td>
<td>50 nm</td>
</tr>
<tr>
<td>[43]</td>
<td>OBPF</td>
<td>2</td>
<td>Simulation</td>
<td>12 nm</td>
</tr>
<tr>
<td>[44]</td>
<td>FBG</td>
<td>3</td>
<td>Experimental</td>
<td>25 nm</td>
</tr>
<tr>
<td>[45]</td>
<td></td>
<td>4</td>
<td>Experimental</td>
<td>30 nm</td>
</tr>
<tr>
<td>[46]</td>
<td></td>
<td>2</td>
<td>Experimental</td>
<td>Not mention</td>
</tr>
<tr>
<td>[47]</td>
<td></td>
<td>2</td>
<td>Experimental</td>
<td>50 nm</td>
</tr>
</tbody>
</table>
CHAPTER 3

METHODOLOGY

3.1 Introduction

This chapter highlights the techniques and methods employed to study the performance of a cascaded FOPA. The effects of pump dithering towards the cascaded FOPA is investigated. Then, the effects of passive components towards the gain and bandwidth are observed. The details of simulation work are also explained in this chapter.

3.2 Simulations in Optisystem software

OptiSystem is a comprehensive software design suite that enables users to plan, test, and simulate the optical links in the transmission layer of modern optical networks. The simulations feature the result of each parameter that needs to be observed in this work.

In this work, each layout can have certain component parameters assigned to be in a sweep mode. The number of sweep iterations to be performed on the selected parameters is defined beforehand. It is observed that at the value of the parameters changes at each sweep of iterations which produces a series of different calculation results.
3.3 The Simulation Components

The simulation is performed to observe the phenomenon of FWM inside the optical fibers and the gain and bandwidth of the four stages of cascaded FOPA. Besides that, the output at each stage of cascaded FOPA is observed to monitor the signal power.

The cascaded FOPA setup includes the optical sources, optical amplifier, optical filter, modulation and visual analyzer. Each of the components is discussed in the following section.

3.3.1 Continuous-Wave Laser

A continuous-wave (CW) laser is an optical source that will continuously emit the light. The CW laser is chosen as the input source to the optical fiber due to the ability of the laser to reach a gain saturation by using a small signal input power [52]. The block diagram of the CW laser is shown in Figure 3.1. In this simulation setup, the CW laser is used as a pump and signal input source. Table 3.1 tabulates the parameters of the pump and signal light.

![Figure 3.1: The CW laser block diagram](image)

Table 3.1: Parameters of the CW laser

<table>
<thead>
<tr>
<th>Input sources</th>
<th>Wavelength (nm)</th>
<th>Power (dBm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pump light</td>
<td>1554.1</td>
<td>30</td>
</tr>
<tr>
<td>Signal light</td>
<td>1540 – 1570</td>
<td>-20</td>
</tr>
</tbody>
</table>
REFERENCES


