UNIVERSITI PUTRA MALAYSIA

CONTINUOUS-WAVE FIBER OPTICAL PARAMETRIC AMPLIFIERS AND OSCILLATORS

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By

LIM LIEN TZE

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

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To my beloved parents

Abstract of thesis presented to the Senate of Universiti Putra Malaysia in fulfilment of the requirement for the degree of Doctor of Philosophy

CONTINOUS-WAVE FIBER OPTICAL PARAMETRIC AMPLIFIERS AND OSCILLATORS

By

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December 2015

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Faculty: Engineering

Fiber optical parametric amplifier (FOPA) is an optical amplifier that operates based on an optical nonlinear phenomenon known as four-wave mixing (FWM). Parametric amplification takes place when a forward-propagating pump light and a signal light are injected into a gain medium of highly nonlinear fiber (HNLF). This fiber medium of choice has its nonlinearity enhanced by about a factor of 10 than conventional silica fiber, which could easily lead to the onset of nonlinear effects such as FWM, stimulated Raman scattering (SRS) and stimulated Brillouin scattering (SBS) when a high continuous-wave (CW) pump power is supplied into a long interaction length of gain fiber. The formation of parametric gain spectrum is dependent on the chromatic dispersion characteristics of the fiber as well, whereby the phase-matching condition has to be met through the detuning between the pump and zero dispersion wavelength (ZDW) of the fiber in achieving uniformity and wide bandwidth over 100 nm at any arbitrary wavelength. Several advantages reported on FOPA have brought to its discovery in various important functions such as large gain amplification, optical oscillation, optical sampling, transparent wavelength conversion and pulse generation. Previous investigation has shown that it is possible to transform a fiber optical parametric oscillator (FOPO) into a tunable radiation source that is capable of accessing wavelength regimes beyond the reach of conventional lasers. The nonlinear process of SRS on parametric amplification was found to be a useful mechanism in creating a broadband laser source since SRS allows the generation of new frequency at 100 nm away from the pump. The presented work in relation to wavelength conversion under SRS effect has proven to be successful through the achievement of tunable S-band idlers from a lasing signal at long oscillation wavelengths (where SRS is dominant) in an anomalously pumped FBG-formed linear cavity FOPO. On the other hand, by using similar configuration with cascaded oscillators, the generation of broadband multi-wavelength (MW) lasers through the degeneration of FWM was also reported to span from 1436 nm to 1704 nm at initial power of 450 mW (26.5 dBm). There is

a need to control the gain competition between SRS and parametric process via the fiber Bragg grating (FBG) output reflectivity to achieve balance oscillation in this setup. Compared to previous Raman-assisted ring cavity FOPOs that operated under high pump power ranging from 3 W (35 dBm) to 5 W (37 dBm), the linear cavity FOPOs reported in this thesis have shown to perform well under low pump power of less than 1 W (30 dBm) to produce broadband laser at large pump-signal separation of over 100 nm. Moreover, further effort was made towards a single-frequency FOPO in a ring cavity configuration. In this demonstration, the single longitudinal mode (SLM) operation is realized using a 5 m fiber loop mirror (FLM) to increase the cavity mode spacing and a 35 cm long of un-pumped erbium-doped fiber (EDF) as the saturable absorber (SA) to select a single longitudinal mode in the cavity. As an outcome, an SLM laser with narrow linewidth of about 300 kHz (short term) has successfully measured at pump power of 1.188 W (30.75 dBm). Such achievement has indicated a significant improvement in the field since the first demonstration of SLM-FOPO did not specify nor reveal the performance of its SLM laser linewidth spectrally through measurement.

Abstrak tesis yang dikemukakan kepada Senat Universiti Putra Malaysia sebagai memenuhi keperluan untuk ijazah Doktor Falsafah

GELOMBANG BERTERUSAN PENGUAT DAN PENGAYUN PARAMETRIK GENTIAN OPTIK

Oleh

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Penguat parametrik gentian optik (‘*Fiber optical parametric amplifier’*, FOPA) merupakan sejenis penguat optik yang beroperasi berdasarkan fenomena optik tidak linear yang biasanya diketahui sebagai pergaulan empat gelombang (‘*Four-wave Mixing*', FWM). Amplikasi parametrik optik ini berlaku apabila gelombang pam dan gelombang isyarat memasuki ke dalam gentian silika amat tidak linear (‘*Highly nonlinear fiber*', HNLF) yang selalunya digunakan sebagai medium gandaan. Sebab pilihan gentian medium ini ialah ia mempunyai tahap tidak linear yang sangat tinggi (dengan faktor kira-kira 10 jika dibanding dengan gentian silika konvensional) dan ia dengan mudahnya boleh mengakibatkan pelbagai fenenoma tidak linear, termasuk penyerakan Raman teransang (‘*Stimulated Raman scattering’*, SRS) dan penyerakan Brillouin teransang (‘*Stimulated Brillouin scattering’*, SBS) apabila kuasa pam yang tinggi disalurkan ke dalam gentian optik yang panjang. Pembentukan spektrum ganda parametrik bergantung kepada serak kromat dalam gentian optik, di mana syarat padan fasa perlu dipenuhi melalui pelarasan antara jarak gelombang pam dengan jarak sifar serak dalam gentian optik untuk mencapai lebar jalur ganda yang luas dan seragam. Kelebihan yang dilaporkan atas penguat parametrik gentian optik telah membawa kepada penemuan dalam pelbagai fungsi penting seperti penguat isyarat, system pertukaran jarak gelombang, persampelan optik, pengayunan optik, penjanaan nadi dan sebagainya. Siasatan menunjukkan bahawa adalah mungkin untuk mengubah pengayun parametrik gentian optic (‘*Fiber optical parametric oscillator’*, FOPO) ke sumber radiasi boleh tala yang mampu mencapai regim panjang gelombang di luar jangkauan laser konvensional. Kewujudan penyerakan Raman teransang dalam amplikasi parametrik boleh digunakan sebagai peranti yang berguna dalam menghasilkan sumber laser sedemikian. Ini kerana ia membenarkan generasi frekuensi baru pada jarak 100 nm dari jarak gelombang pam. Kerja kajian yang berkenaan penukaran panjang gelombang di bawah pengaruh penyerakan Raman teransang dalam tesis ini

menunjukkan idlers boleh tala dalam S-band boleh dihasilkan melalui ayunan panjang gelombang isyarat dalam rongga linear pengayun parametrik gentian optik. Tambahan pula, dengan konfigurasi pengayun parametrik gentian optik yang serupa tetapi terdiri daripada lata pengayun, jalur lebar untuk laser jarak gelombang berbilang dari 1436 nm ke 1704 nm berjaya diperolehi melalui proses merosot pencampuran empat gelombang pada permulaan kuasa pam lebih 450 mW (26.5 dBm). Persaingan ganda antara penyerakan Raman teransang dan proses parametrik melalui pantulan parutan Bragg gentian ('*Fiber Bragg grating*', FBG) perlu dikawal untuk mencapai keseimbangan ayunan dalam konfigurasi ini.

Eksperimen bagi rongga linear pengayun parametrik gentian optik dengan bantuan penyerakan Raman teransang menunjukkan bahawa pengayun yang beroperasi di bawah kuasa pam yang rendah iaitu kurang daripada 1 W (30 dBm) ini boleh menghasilkan laser jalur lebar pada jarak antara pam dan isyarat yang jauh. Tidak seperti rongga linear pengayun parametrik, rongga cincin pengayun parametrik gentian optik di bawah pengaruh penyerakan Raman teransang yang dilaporkan sebelum ini memerlukan kuasa pam yang agak tinggi iaitu dari 3 W (35 dBm) ke 5 W (37 dBm) untuk berfungsi pada jarak antara gelombang pam dan isyarat yang jauh. Selain itu, usaha untuk menghasilkan laser bersifat mod bujur tunggal melalui konfigurasi cincin rongga pengayun parametrik gentian optik juga dibuat. Dalam demonstrasi ini, operasi penghasilan laser bersifat mod bujur tunggal dilaksanakan dengan menggunakan cermin gelung dengan 5 m panjangnya untuk meluaskan jarak mod rongga dan 35 cm panjang erbium-didopkan gentian tanpa pam ('*Erbium-doped fiber*', EDF) yang berfungsi sebagai sempit lebar garis turas untuk mendapatkan mod tunggal dalam rongga. Dengan mekanisme tersebut, lebar garis bagi laser yang bersifat mod bujur tunggal berjaya dicapai dengan sempit lebar 300 kHz (jangka pendek) pada kuasa pam 1.188 W (30.75 dBm). Daripada hasil kerja ini, pencapaian dalam mengukur lebar garis untuk laser yang bersifat mod tunggul menandakan peningkatan yang penting dalam bidang penyelidikan tersebut kerana awal kerja kajian tidak mendedahkan penilaian tersebut dalam ekperimennya.

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This thesis was submitted to the Senate of Universiti Putra Malaysia and has been accepted as fulfilment of the requirement for the degree of Doctor of Philosophy. The members of the Supervisory Committee were as follows:

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TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

LIST OF ABBREVIATIONS

ASE	Amplifier spontaneous emission
AOM	Acousto-optic modulator
BiF	Bismuth doped fiber
BS	Bragg scattering
CE	Conversion efficiency
CIR	Circulator
CW	Continuous wave
DRO	Doubly-resonant oscillator
DSF	Dispersion shifted fiber
EDFA	Erbium-doped fiber amplifier
EDFL	Erbium-doped fiber laser
ESA	Electrical spectrum analyser
FBG	Fiber Bragg grating
FLM	Fiber loop mirror
FOPA	Fiber optical parametric amplifier
FOPO	Fiber optical parametric oscillator
FSR	Free spectral range
FWHM	Full width half maximum
FWM	Four-wave mixing
HNLF	Highly nonlinear fiber
ITU	International Telecommunication Union
MI	Modulation instability
MLM	Multi-longitudinal mode
MW	Multiwavelength
MZI	Mach-Zehnder interferometer
OPA	Optical parametric amplifier
OPO	Optical parametric oscillator
OPM	Optical power meter
OSA	Optical spectrum analyser
OSNR	Optical signal noise ratio
PC	Polarization controller
PCF	Photonics crystal fiber
PCG	Phase-conjugation
PD	Photodetector
PM	Phase modulator
PO	Parametric oscillator
PPM	Pump phase modulation
PRBS	Pseudo random bit sequence
RA	Raman amplifier
RFSA	Radio frequency spectrum analyzer
RFL	Raman fiber laser
RO	Raman oscillator
SA	Saturable absorber
SBS	Stimulated Brillouin scattering
SHB	Spatial hole burning

SLM	Single longitudinal mode
SMF	Single mode fiber
SOP	State of polarization
SPM	Self-phase modulation
SRO	Single-resonant oscillator
SRS	Stimulated Raman scattering
TBF	Tunable bandpass filter
TLS	Tunable laser source
TWM	Two-waves mixing
VCO	Voltage controlled oscillators
VOA	Variable optical attenuator
WDM	Wavelength division multiplexing
XPM	Cross phase modulation
XGM	Cross gain modulation
ZDW	Zero dispersion wavelength

CHAPTER 1

INTRODUCTION

1.1 Overview

The variety of applications that are fully utilizing web services nowadays has created a high demand for advancements in optical telecommunications. Presently, much of the data transmission in computing and communication industry are conducted through fiber optic systems, as the optical fiber cables provide greater bandwidth that enables them to carry more information with greater fidelity than copper wire over massive distance. They are reliable to perform under noisy environment as well. Thus, these advantages have encouraged the widespread of fiber transmission line worldwide, connecting every possible corner to the global fiber network. The statement included below describes the rapid growth of activities for the expansion of current optical telecommunications networks in the recent years.

“Tokyo, June 27, 2013: *The SJC Parties, today announced that the Southeast Asia-Japan Cable (SJC) system is now operational. The SJC is an 8,900-kilometer cable system, which could further extend to 9,700 kilometers. At a project cost of around US$400 million, the SJC cable system consists of 6 fiber pairs with the initial design capacity of 28 Terabits per second to meet bandwidth-intensive applications such as internet TV, online games and enterprise data exchange.*

NEC News, June 27, 2013 [1]

“MANILA, Philippines, Aug. 28, 2014: The Southeast Asia - United States Cable (SEA-US) will provide much needed Asia-US connectivity and will be the fastest cable connecting Indonesia and the Philippines to the United States. NEC has awarded contract to build first 100 Gb/s submarine cable with a span over 10,000 km. This capacity will cater to the exponential growth of bandwidth demand between both continents.”

NEC News, Aug 28, 2014 [2]

In the early 1980s, the existing transmission technology using coaxial cables has been recognized as inadequate to accommodate high data capacity transmission. As an alternative to meet the required capacity, the telecommunication industry has expanded their transmission capabilities by slowly replacing copper wires with fiber optic cables, which permits large amount of data to be transmitted over vast distance in high speed [3]. The optical fiber was originally impractical in long distance communications due to high loss experienced by the propagating signals during transmission. With relentless effort from the researchers to resolve the problem, the first optical fiber with attenuation less than 20 dB/km was successfully demonstrated in 1970 [4] and that brought remarkable progress in the production of low loss transmission medium for long haul transmission system. To encounter inevitable power attenuation across the long distance, electrical repeater system acting as optoelectronic regenerator device was initially installed to amplify and retransmit the signal. This scheme appears effective, though it has a drawback in that the bandwidth of the device is much less than the bandwidth of the optical fibers thus the repeaters become bottlenecks that severely limit the speeds of signals transmission. The incompetency of optoelectronic repeaters has motivated the development of optical amplifiers, which are capable of wideband amplification without undergoing the E/O conversion process.

The first successful optical amplifier that has been developed and revolutionized the optical communication industry is the erbium-doped fiber amplifiers (EDFAs) [5]. With subsequent modern fibers that exhibit losses of less than 0.2 dB/km at 1550 nm, new type of optical amplifier called fiber optical parametric amplifier (FOPA) was created [6]. Like the EDFA, FOPA can support the technology of wavelength division multiplexing (WDM) where the capacity can be increased by enabling multiple channel wavelengths to be carried in a single fiber, reducing the number of cables deployed [7]. Current WDM technologies have the ability to transport data in excess of 10 Gb/s. With the development of optical amplifiers, laser can be produced simply by operating the optical amplifier with a positive feedback. By feeding back the output of an optical amplifier to its input for laser oscillation, a fiber laser could be obtained when a continuous-wave (CW) or pulsed pump is added into the cavity. The output laser can consist of either a single or multi wavelength with certain tunability. Most research work presented in this thesis focus on the fiber laser generated from fiber optical parametric oscillator (FOPO) as its architectural concept is based on the addition of fiber-Bragg gratings (FBGs) to provide light feedback. FOPO can be utilized in applications with WDM technology that will be demonstrated by generating broadband multiwavelength (MW) based on the nonlinear effect of four-wave mixing (FWM) and Stimulated Raman Scattering (SRS). The parametric gain obtained from FOPA under combined influence of FWM and SRS is investigated first before continuing on to the experimental studies of FOPO. Besides that, a single frequency FOPO will be developed and analyzed. This type of fiber laser has found to be useful in coherent communication.

1.2 Problem Statement

Typical FOPOs operate under relatively high pump power oscillation between 1 W (30 dBm) to 5 W (37 dBm). Unfortunately, if the pump power is not properly managed, the induced nonlinear processes will bring a detrimental effect to the desired output. This effect involves the growth of backward Stimulated Brillouin scattering (SBS) when there is increasing pump power within the gain fiber and that would consequently reduce the amount of transmitted power from the oscillator. Such a drawback cannot be eliminated, but proper approach has been suggested to minimize them. In the study of fiber lasers, most single wavelength and MW fiber lasers operated and confined within C- or L-band region due to the limited gain bandwidth. One possible way to achieve single wavelength as well as MW lasers across wide wavelength region for > 100 nm in FOPO is to utilize the influence of nonlinear Raman scattering to perform laser oscillation. So far, the investigation on Raman-assisted parametric oscillator has only been found using ring cavity configuration. And, no previous work on the laser oscillation under nonlinear Raman effect in U-band is reported using a linear cavity FOPO. A few issues have been encountered when pursuing the development of a single-longitudinal mode (SLM) operation in FOPO. This includes the use of a long gain medium (> 50 m) for achieving high gain (~ 30 dB) with wide bandwidth (~ 80 nm), which forms a long cavity on FOPO. This characteristic favors the generation of densely spaced longitudinal modes within the cavity. Hence, a noisy laser could likely be produced from this type of fiber laser. It is impossible to achieve SLM-FOPO without any external mode suppression mechanism. The introduction of an external mode suppression mechanism into the cavity of FOPO for achieving SLM oscillation however comes with some disadvantages such as the structure of the cavity would get complex and it demands an even higher pump power to overcome the cavity losses for lasing. Furthermore, the stability of FOPO system could also be severely affected as the devices used for generating a single mode laser are sensitive to the environment perturbation. In the past, there is only one research work done on SLM-FOPO which a subring cavity and an un-pumped EDF are deployed as the mode suppression devices in the setup to produce SLM laser. However, no result was reported on the performance of its SLM linewidth and stability from this demonstration.

1.3 Research Objectives

The research objectives of this thesis are stated below:

a. To investigate the SBS suppression through pump phase modulation (PPM) technique using different waveform of pseudo random binary sequence (PRBS) and sinusoidal frequency in FOPA.

b. To investigate the system performance of a linear cavity FOPO under Raman effect in ultralong (U-band) wavelength region.

c. To design a new structure of linear cavity FOPO utilizing Raman effect to generate a broadband multiwavelength lasers.

d. To design and investigate a SLM-FOPO based on the proposed mechanism of subring cavity and unpumped EDF in the ring cavity.

1.4 Scope of Research Work

This research study emphasizes mainly on the implementation of single-pump FOPOs, which utilize a standard highly nonlinear fiber (HNLF) as its gain medium to generate laser. Prior to the experimental work of FOPO, a setup of FOPA is characterized experimentally first and the pump phase modulation technique is adopted in the FOPA to suppress the backward SBS from the high pump power injection into the fiber. Next, a FOPO using a normal FBG pair to form its linear cavity is introduced to operate under the influence of SRS with parametric amplification. The proposed work that is based on combined processes of FWM and SRS will then be applied for different applications in two different architectures as listed below:

1) **Architecture 1**: A linear cavity FOPO formed using a pair of FBGs with its center wavelength lasing within the Raman-dominant gain region. This proposed design intends to investigate the wavelength conversion at large pump-signal separation of about 100 nm under SRS effect.

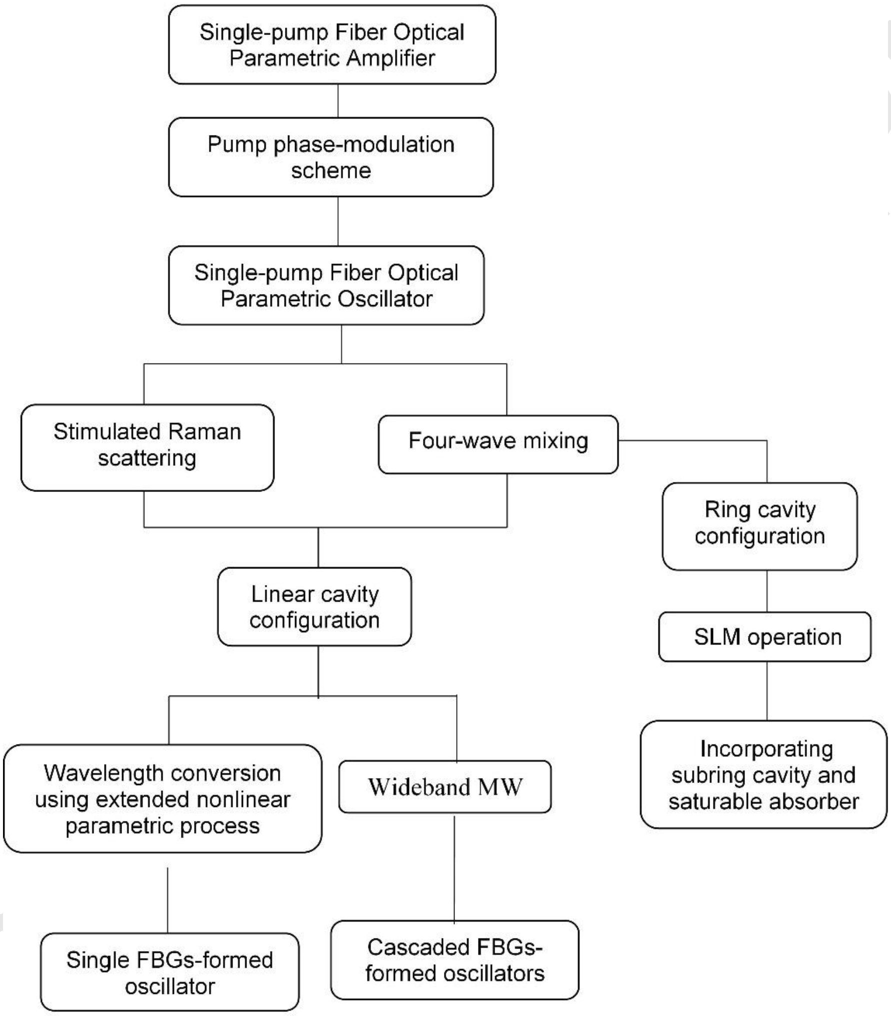
2) **Architecture 2:** Cascaded oscillators formed using two pairs of FBGs, with one center wavelength oscillating within the parametric-dominant gain region and another in the Raman-dominant region, in a linear cavity configuration. The motivation of this study is to obtain MW lasers in extended FWM bandwidth by deliberately manipulating each of their oscillation strength through FBG reflectivity to balance gain competition between parametric oscillator (PO) and Raman oscillator (RO) in series.

This dissertation also includes the investigation of SLM operation in a ring cavity FOPO using proposed setup mentioned below.

3) **Architecture 3:** A ring-cavity SLM-FOPO is designed using a passive subring cavity and an unpumped EDF as the saturable absorber to obtain an SLM laser. The outcome of this experimental setup will be evaluated between two cases under multiple longitudinal mode (MLM) and SLM condition of the cavity.

The research scope of this dissertation is summarized using a flow chart in Figure 1.1.

Figure 1.1: Scope of work chart



1.5 Thesis Organization

The content of this thesis is organized into six chapters. The present chapter 1 introduces the latest trends in modern optical fiber communication networks and the research objectives of this thesis.

In Chapter 2, a comprehensive review on the literature of nonlinear optics is included and the nonlinear phenomena based on third-order susceptibility of the optical fiber are discussed in detail. The chapter also includes the association of the configuration of a laser resonator to the cavity modes. The basic theory of SLM operation is studied and discussed with a graphical description.

Chapter 3 introduces the theoretical studies and experiments to characterize the fiber optical parametric amplifiers (FOPAs) by including their experimental set-up and results. Several techniques such as multi-tone radio frequency (RF) modulation and PRBS modulation for SBS suppression are investigated. The impact of SBS suppression on FOPA is presented.

Chapter 4 presents extensive theoretical studies of the combined influence of nonlinear parametric process and SRS in a FOPA. Using these nonlinear effects, a linear-cavity FOPO with oscillation occurs at long wavelength will then be described. The performance of linear cavity FOPO will be determined and discussed through these parameters: threshold power, output power, wavelength tunability, conversion efficiency (CE) and stability.

Chapter 5 proposes the mechanism involved to produce SLM in a FOPO. The performance requirement for obtaining SLM in an optical oscillator will be identified through experimental results. The proposed system design utilizing feedback mirror configuration for narrow laser in ring cavity will be discussed and evaluated based on mode observation, laser linewidth measurement and stability.

Chapter 6 summarizes the overall research work done and at the end, some recommendations for future works are included.

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