UNIVERSITI PUTRA MALAYSIA

MULTIPLE WAVELENGTHS GENERATION UTILIZING NONLINEAR OPTICS OF FOUR WAVE MIXING

NORAN AZIZAN BIN CHOLAN

MULTIPLE WAVELENGTHS GENERATION UTILIZING NONLINEAR OPTICS OF FOUR WAVE MIXING

By

NORAN AZIZAN BIN CHOLAN

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

November 2014

To my beloved families and friends

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

MULTIPLE WAVELENGTHS GENERATION UTILIZING NONLINEAR OPTICS OF FOUR WAVE MIXING

By

NORAN AZIZAN BIN CHOLAN

November 2014

Chair: Mohd Adzir Mahdi, PhD

Faculty: Engineering

The response turns from linear to nonlinear when high intensity waves propagate in optical fibers, causing the emergence of nonlinear phenomena such as stimulated Brillouin scattering (SBS) and four wave mixing (FWM). While that phenomena cause optical communication systems to deteriorate, they are nevertheless useful for certain applications such as in multiple wavelengths generation. This dissertation presents experimental work that involves the manipulation of FWM in the developments of lasers and cascades. Four main research studies are successfully demonstrated in efforts to improve the performance of FWM-based lasers and cascades. The first study is related to multiwavelength BEFLs. Despite the advantage of wide tunability, they unfortunately suffer from the laser output flatness due to the nature of cascaded SBS processes. In this work, FWM in an optical fiber is applied to the laser lines of a multiwavelength BEFL through the incorporation of residual waves in order to make the output flat. Comparisons between the BEFL with and without the assistance of FWM suggest the effectiveness of the proposed technique. With the assistance of FWM, the uniformity or flatness records a 3.73 dB improvement as compared to the case without the assistance of FWM when the Brillouin pump is set to 1550 nm. The second research work is related to an experimental study on the residual waves of multiwavelength BEFLs. Experimental results suggest that the properties of residual waves are influenced by FWM. Multiple FWM processes in fibers are believed to cause the output power of the residual waves to grow gradually and the value of optical-signal-to-noise ratio to be lower due to the power sharing basis of FWM processes. The third research work, on the other hand, is aimed to improve continuous tunability of erbium-doped fiber lasers (EDFLs) in which the stability is obtained from multiple FWM processes in optical fibers. With the incorporation of tunable bandpass filters in the laser cavity, a proposed dual wavelength EDFL can achieve continuous wavelength spacing from 0.52 nm to 22.78 nm, limited only by the gain bandwidth of the erbium-doped fiber amplifier and the linewidth of filters. In the fourth research work, FWM cascades without external laser sources and modulators is proposed in a bid to reduce the complexity of the system. The need for laser sources is catered by a dual wavelength EDFL which acts as an intracavity pump, while the requirement for pump

modulators for SBS suppression is tackled by the broad linewidth of the EDFL. In summary, four research studies that are related to FWM in generating multiple wavelengths are experimentally demonstrated in this thesis. The first two studies focus on improvements in BEFLs, while the third and fourth study is for enhancements in EDFLs and FWM cascades respectively. All the four studies are found to be effective in elevating the performances and understanding of FWM-based lasers and cascades to further heights.

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

PENGHASILAN PANJANG GELOMBANG BERBILANG MENGGUNAKAN OPTIK TIDAK LINAR PERGAULAN EMPAT GELOMBANG

Oleh

NORAN AZIZAN BIN CHOLAN

November 2014

Pengerusi: Mohd Adzir Mahdi, PhD

Fakulti: Kejuruteraan

Tindak balas bertukar daripada linar kepada tidak linar apabila gelombang berkeamatan tinggi merambat dalam gentian optik, menyebabkan keluarnya fenomena tidak linar seperti penyerakan Brillouin rangsangan (SBS) dan pergaulan empat gelombang (FWM). Walaupun fenomena ini menyebabkan sistem komunikasi optik menjadi lebih merosot, ianya berguna untuk aplikasi tertentu seperti dalam penjanaan pelbagai gelombang. Tesis ini mempersembahkan kerja eksperimen yang melibatkan manipulasi FWM dalam pembangunan laser dan lata. Empat kajian penyelidikan utama telah berjaya ditunjukkan dalam usaha untuk memperbaiki pencapaian. Kajian pertama adalah berkaitan dengan laser gentian Brillouin-erbium (BEFLs) panjang gelombang berbilang. Walaupun dengan kelebihan penalaan yang luas, ianya mengalami masalah dari segi kerataan keluaran laser berikutan keadaan semulajadi proses SBS berlata. Dalam kajian ini, FWM dalam gentian optik diaplikasikan kepada laser Brillouin-erbium (BEFLs) panjang gelombang berbilang melalui penggunaan gelombang baki untuk menjadikan keluaran rata. Perbandingan diantara BEFL dengan dan tanpa bantuan FWM mengesahkan keberkesanan teknik ini. Dengan bantuan FWM, kerataan merekodkan penambahbaikan 3.73 dB berbanding dengan kes tanpa bantuan FWM apabila pam Brillouin disetkan kepada 1550 nm. Kajian penyelidikan kedua pula adalah berkaitan dengan sebuah kajian eksperimen tentang gelombang baki BEFLs panjang gelombang berbilang. Keputusan eksperimen mencadangkan bahawa ciri-ciri gelombang baki dipengaruhi oleh FWM. Proses berbilang FWM dalam gentian dipercayai menyebabkan keluaran kuasa gelombang baki bertumbuh secara perlahan dan nilai nisbah-isyarat optik-kepada-hingar menjadi lebih rendah akibat daripada asas perkongsian kuasa oleh proses FWM. Kajian penyelidikan ketiga pula bertujuan untuk memperbaiki penalaan berterusan laser gentian berdopkan erbium (EDFLs) yang mana kestabilan diperolehi daripada pelbagai proses FWM dalam gentian optik. Dengan penggunaan penapis lulus jalur, EDFL panjang gelombang berdua yang dicadangkan boleh mencapai jarak panjang gelombang berterusan daripada 0.52 nm hingga 22.78 nm, hanya dihadkan oleh lebar jalur gandaan penguat gentian berdop erbium dan lebar jalur penapis. Dalam kajian penyelidikan keempat, lata FWM tanpa sumber laser dan pemodulat luar dicadangkan dalam usaha untuk mengurangkan komplikasi sistem.

Keperluan untuk sumber laser dipenuhi oleh EDFL panjang gelombang berdua yang bertindak sebagai satu pam intrarongga, manakala keperluan untuk pemodulat pam bagi penghapusan SBS diatasi dengan EDFL yang berjalur lebar. Secara kesimpulannya, empat kajian penyelidikan yang berkaitan dengan FWM dalam menghasilkan panjang gelombang berbilang ditunjuk dalam tesis ini. Dua kajian pertama fokus kepada penambahbaikan dalam BEFLs, manakala kajian ketiga dan keempat adalah penambahbaikan untuk EDFLs dan lata FWM secara urutan. Semua empat kajian tersebut didapati berkesan dalam meningkatkan pencapaian dan kefahaman ke atas laser dan lata yang berdasarkan FWM ke tahap lebih tinggi.

ACKNOWLEDGEMENTS

I would like to first express thanks to my supervisory committee; Prof. Dr. Mohd Adzir Mahdi, Assoc. Prof. Dr. Mohammed Hayder Al-Mansoori, Dr. Ahmad Shukri Muhammad Noor and Assoc. Prof. Dr. Alyani Ismail for providing me support and guidance throughout the whole course of the study. A special credit to Prof. Dr. Mohd Adzir Mahdi who has just believed in my work and capability, tirelessly trained me to get the best out of me and relentlessly taken me back on track whenever I went off it. Also, I would like to thank Prof. Michel E. Marhic of Swansea University, UK and Prof. Lu Chao of The Hong Kong Polytechnic University, Hong Kong for providing me exposure in the experiments and theories of optics during my research attachments in their laboratories. The same gratitude goes to my parents Cholan Taib, Norhayatti Abdul Aziz and Jamilah Hassan who always give their blessings and prayers for whatever I do in my life. For my beloved wife Nor Hafizah Ngajikin who becomes a pillar of my strengths, many thanks for your sacrifices in taking care of our families especially when I was away from home running experiments in the laboratories. For my little cuties Nurul Aisyah and Nur Raudhah, thank you for your constant cheers that have always made me smile and forget the frantic days in the lab. Equally important is all my lab colleagues and friends whose help and support being a main factor for this achievement. Not forgotten also my gratitude to journal editors and reviewers who are committed reviewing and improving the journal papers included in this thesis despite their busy schedules. Without their commitments, this research work would not come to this stage. Finally, all praises to Allah, the almighty for continuous guidance and forgiveness.

I certify that a Thesis Examination Committee has met on 20 November 2014 to conduct the final examination of Noran Azizan Bin Cholan on his thesis entitled "Multiple Wavelengths Generation Utilizing Nonlinear Optics of Four Wave Mixing" in accordance with the Universities and University Colleges Act 1971 and the Constitution of the Universiti Putra Malaysia [P.U.(A) 106] 15 March 1998. The Committee recommends that the student be awarded the Doctor of Philosophy.

Members of the Examination Committee were as follows:

Aduwati Sali, PhD
Associate Professor
Faculty of Engineering
Universiti Putra Malaysia
(Chairman)

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

Abu Sahmah Mohd Supaat, PhD
Professor Ir.
Universiti Teknologi Malaysia
Malaysia
(External Examiner)

Lawrence Chen, PhD
Professor
McGill University
Canada
(External Examiner)

ZULKARNAIN ZAINAL, PhD
Professor and Deputy Dean
School of Graduate Studies
Universiti Putra Malaysia

Date: 12 March 2015

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

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

Alyani Ismail, PhD
Associate Professor
Faculty of Engineering
Universiti Putra Malaysia
(Member)

Ahmad Shukri Muhammad Noor, PhD
Senior Lecturer
Faculty of Engineering
Universiti Putra Malaysia
(Member)

Mohammed Hayder Al-Mansoori, PhD
Associate Professor
Faculty of Engineering
Sohar University, Oman
(Member)

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

Date:

Declaration by graduate student

I hereby confirm that

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

Signature: ___________________________ Date: : ___________________

Name and Matric No: Noran Azizan Cholan GS26560

Declaration by Members of Supervisory Committee

This is to confirm that:

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

Signature:	____________________	Signature:	____________________
Name of Chairman of Supervisory Committee:	____________________	Name of Member of Supervisory Committee:	____________________
Signature:	____________________	Signature:	____________________
Name of Member of Supervisory Committee:	____________________	Name of Member of Supervisory Committee:	____________________

TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

LIST OF ABBREVIATIONS

ASE	Amplified spontaneous emission
BEFL	Brillouin-erbium fiber laser
BER	Bit error rate
BFL	Brillouin fiber laser
BP	Brillouin pump
CFBG	Chirped fiber Bragg grating
CFWM	Cascaded four wave mixing
CW	Continuous wave
DC	Direct current
DCF	Dispersion compensating fiber
DSF	Dispersion shifted fiber
DWDM	Dense wavelength division multiplexing system
EDF	Erbium-doped fiber
EDFA	Erbium-doped fiber amplifier
FBG	Fiber Bragg grating
FWMC	Four wave mixing cascades
FWHM	Full width half maximum
FWM	Four wave mixing
HNLF	Higly nonlinear fiber
I/Q	Inphase/quadrature
MLL	Mode-locked laser
NF	Noise figure
OFC	Optical frequency comb
OPM	Optical power meter
OSA	Optical spectrum analyzer
OSNR	Optical signal to noise ratio
PC	Polarization controller
PCF	Photonic crystal fiber
PMF	Polarization maintaining fiber
PRBS	Pseudo random bit sequence
RF	Radio frequency
RFS	Recirculating frequency shifter
SBS	Stimulated Brillouin scattering
SLM	Single longitudinal mode
SMF	Single mode fiber
SPM	Self phase modulation
SRS	Stimulated Raman scattering
TBF	Tunable bandpass filter
TLS	Tunable laser source
VOA	Variable optical attenuator
WDM	Wavelength division multiplexing
XPM	Cross phase modulation
ZDW	Zero dispersion wavelength

CHAPTER 1

INTRODUCTION

1.1 Background

In the modern age, the high speed internet is very important to the people. It is nowadays not an option but a necessity for many people as they are much reliant on the internet to cater for their needs in life. However, the high speed internet, which involves the processes of downloading and uploading signals at high data rates, requires an enormous bandwidth for operation. With the awesome bandwidth offered by optical fibers, dense wavelength division multiplexing (DWDM) technology is a competitive candidate that is more than capable to satisfy the demand for the rapid and reliable transmission of voice, video and data signals. A DWDM system whose channel spacing is very small in a fraction of nanometer is a system where a number of wavelengths are combined into an optical fiber for the transmission of signals. The combination is possible in this case due to the capability of optical fibers to transport many different wavelengths concurrently without mutual interference.

As illustrated in Fig. 1.1, several optical devices are integrated in order to generate, distribute, isolate and amplify optical power for transmission in DWDM systems. Several channels corresponding to different wavelengths are transmitted into the same optical fiber. They are multiplexed before entering the optical fiber link. Along the transmission link, optical fiber amplifiers in different positions keep the channels at certain required levels and dispersion compensators are used to nullify the impact of dispersion in optical fibers. In addition, there are nodes along the link where specific DWDM channels can be added into the optical stream or dropped from it. At the end of the link, the channels are demultiplexed before they reach optical receivers and the information carried by the DWDM channels can be recovered at the receivers.

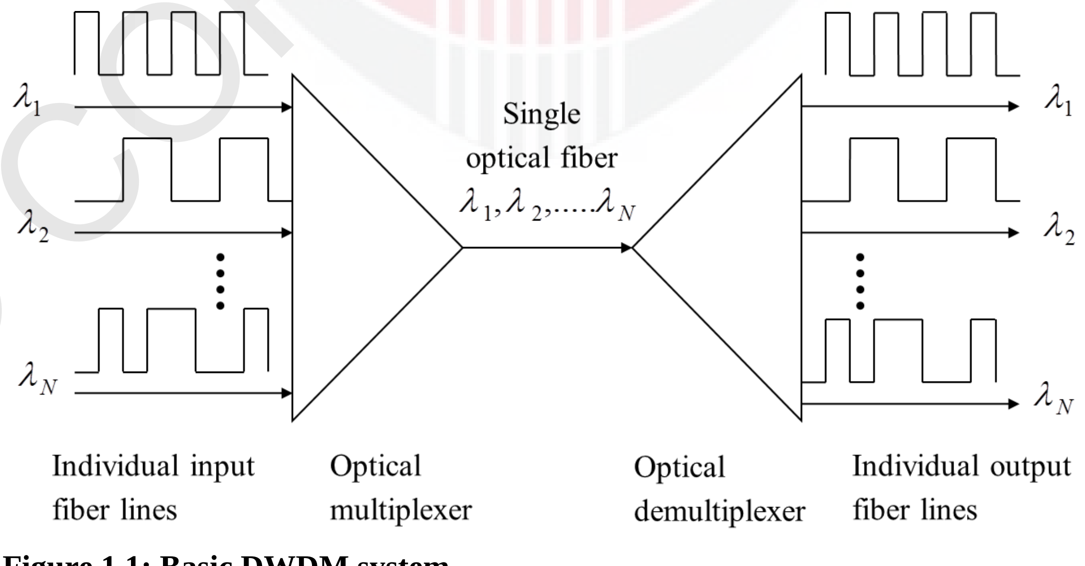

Figure 1.1: Basic DWDM system.

The guidelines to determine the wavelength and the wavelength spacing of DWDM channels are provided by ITU-T G.694.1, a recommendation issued by the International Telecommunication Union (ITU) [1]. The recommendation provide a frequency grid for DWDM applications for channel spacings of 12.5 GHz, 50 GHz, 100 GHz and wider with a reference frequency fixed at 193.10 THz (1552.52 nm). Table 1.1 illustrates one example of the frequency grid. It is important to note that despite with enhanced transmission capacity when implementing DWDM systems, wavelengths or frequencies need to be stable for reliable operation due to the close spacing of wavelengths. Precision temperature control of laser transmitters is a necessity in DWDM systems to prevent the wavelengths from drifting.

Table 1.1: Nominal central frequencies of DWDM grid

Nominal central frequencies (THz) for spacings of:				Wavelengths (nm)
12.5 GHz	**25 GHz**	**50 GHz**	**100GHz and above**	
193.1000	193.100	193.10	193.1	1552.5244
193.0875	-	-	-	1552.6249
193.0750	193.075	-	-	1552.7254
193.0625	-	-	-	1552.8259
193.0500	193.050	193.05	-	1552.9265
193.0375	-	-	-	1553.0270
193.0250	193.025	-	-	1553.1276
193.0125	-	-	-	1553.2282
193.0000	193.000	193.00	193.0	1553.3288
192.9875	-	-	-	1553.4294
192.9750	192.975	-	-	1553.5300
192.9625	-	-	-	1553.6307

Multiple wavelengths are required for operation in DWDM systems. The technique normally used to provide the wavelengths is by utilizing individual semiconductor lasers as carriers for optical modulators. The use of semiconductor lasers however increases complexity and this is especially true when the number of channels is large as each semiconductor laser requires temperature and current controllers in their operation. One way to reduce the complexity is by incorporating multiwavelength sources to provide the multiple wavelengths as illustrated in Fig. 1.2. While the multiwavelength sources still need an optical demultiplexer to separate the multiple wavelengths into individual wavelength, the drawback is offset by the removal of individual semiconductor lasers as carriers for optical modulators. This makes multiwavelength sources as a competent candidate to be a multiple wavelength provider in DWDM systems.

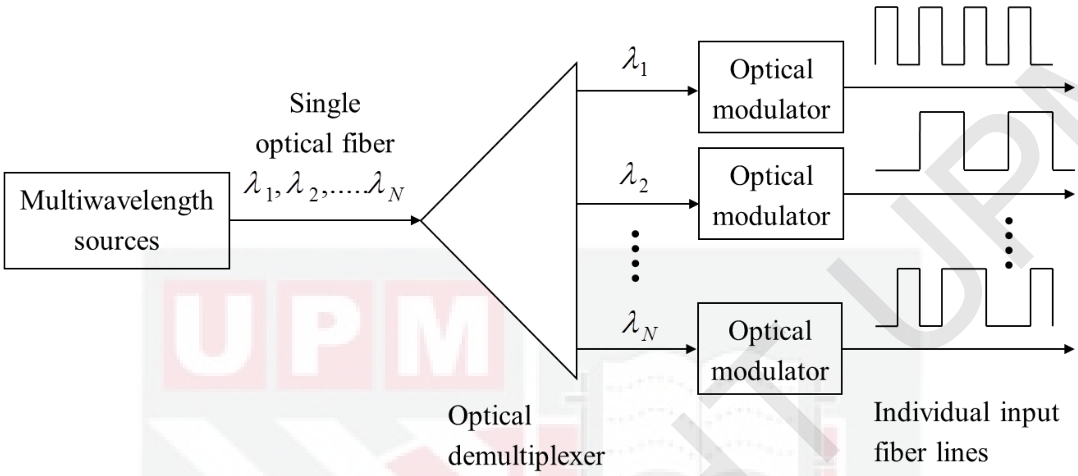

Figure 1.2: Application of multiwavelength sources as transmitters in DWDM system.

Multiwavelength sources can be realized using many methods. One of the methods is by utilizing nonlinearities in optical fibers. The nonlinear optics are actually originated from the behavior of optical fibers that turns from linear to nonlinear when the intensity of input light is relatively high. While the nonlinear optics are harmful to optical communication systems, they bring benefits to the generation of multiple wavelengths. Nonlinear optics such as such as four wave mixing (FWM), stimulated Brillouin scattering (SBS) and stimulated Raman scattering (SRS) can be manipulated to be a source of multiple wavelength generation. For example, despite the requirement for high pump power, cascaded FWM can be used to generate spectral lines covering over a wide band provided that the phase matching is preserved during the propagation. Besides being multiwavelength sources, nonlinear optics can also help improve the performance of multiple wavelength generators. For example, FWM can be manipulated to improve the flatness of multiwavelength fiber lasers.

1.2 Problem Statement

In view of improving the performances of multiwavelength sources, four main problems are identified in this research work. Out of four, two problems are related to multiwavelength Brillouin erbium fiber lasers (BEFLs) and one problem each for erbium-doped fiber lasers (EDFLs) and four wave mixing cascades (FWMC) respectively. The problems stated here are obtained from the literature review that is carried out during the study and they provide a basis for the objectives of this thesis.

The first problem on BEFLs is related to the flatness of multiwavelength laser output. While the multiwavelength BEFLs have wide tunability as a result of the suppression of self-lasing cavity modes, it suffers from the laser output uniformity. In a proposed BEFL in [2], the tunability obtained spans over the entire C-band but the peak power difference between the first and the last channel is 7.68 dB. The same is also true for another configuration proposed in [3]. The first and the last channel recorded peak powers of 8.19 and -8.3 dBm respectively, bringing the peak power difference to 16.49 dB. The significant discrepancy in power for the multiwavelength output can bring harm especially to a long haul optical communication system where a number of amplifiers are necessary to overcome losses during the transmission. After going through the amplifiers, the power discrepancy can possibly become larger that it can cause a channel to be lost during the transmission due to the gain mode competition in the amplifiers. Therefore, a flat multiwavelength output is vital for a reliable and robust long haul optical communication system.

The second problem on BEFLs is associated with a lack of explanation on the cause behind the generation of Stokes and anti-Stokes lines in BEFLs. In [2]-[6], FWM in optical fibers is exploited in increasing the number of Stokes and anti-Stokes lines. However, the formation and roles of residual waves that become seeds for the generation of laser lines in BEFLs are not clearly explained and clarified in that research work. Moreover, the properties of residual waves (forward transmitted) such as the output power and optical-signal-to-noise-ratio (OSNR) characteristics in comparison to the waves of BEFL (backward reflected) have not been experimentally explored. The knowledge in such properties and roles of residual waves can help researchers to get a better insight on the impact of FWM and residual waves on the performance of BEFLs.

The third problem is related to the wavelength spacing tunability of EDFLs. In efforts to stabilize EDFLs against the gain mode competition, a self-stability mechanism of FWM is proven to be a successful way in diminishing the fierce competition for erbium gain in erbium-doped fibers (EDFs) [7]. Despite the achievement, the wavelength spacing is fixed due to the use of fiber Bragg gratings (FBGs) in the operation. A scheme is then proposed in order to achieve the tunability [8]. While the wavelength spacing is tunable in the scheme, the tunability is not continuous but discrete. For the FWM-based EDFL to achieve continuous tunability, a scheme is then recommended where a special mechanical apparatus is utilized to modify a chirp ratio of an FBG so that it can ultimately tune the wavelength spacing of the EDFL continuously [9]. However, the tunability is limited from 0.32 to 0.81 nm and the use of mechanical apparatus for operation makes the system more complex. Therefore, a scheme with wide and continuous wavelength spacing tunability, operated in a simple way, is necessary to further improve the performances of FWM-based EDFLs.

The fourth problem is associated with the complexity of FWMC. It is known that for an FWMC to operate, it requires tunable laser sources to be the seeds and phase/intensity modulators to get the linewidth of laser sources to be wide enough for SBS suppression [10]-[13]. The requirements though would increase the complexity. For example, the modulators need to be driven with a certain combination of few periodic radio frequencies or pseudorandom bit sequence for SBS suppression and this could make the design more complicated. In addition, the utilization of phase/intensity modulators could affect the performance of the system. It is theoretically and experimentally reported that the phase modulation could cause the signal and idler powers to fluctuate more and this could lead to the degradation of optical communication systems [14]-[15]. Hence, a scheme needs to be designed in such a way that it is free from external laser sources and phase/intensity modulators so that the complexity to design an FWMC can be reduced.

1.3 Research Objectives

The main objective of this research is to improve the performances of multiple wavelengths generation that utilizes nonlinear optics of FWM in the operation. Specific objectives are as follow:

i. To design and develop a flat multiwavelength BEFL in which a mechanism of FWM is manipulated in flattening the output.
ii. To investigate the formation, properties and role of residual waves in generating Stokes and anti-Stokes lines in multiwavelength BEFLs.
iii. To enhance the wavelength spacing tunability of a dual wavelength EDFL in which the stability of lasers is obtained from a self-stability mechanism of FWM in an optical fiber.
iv. To design and develop an FWMC that is free from any external tunable laser sources and phase modulators in an effort to reduce the complexity of the design.

1.4 Thesis Outline

This thesis consists of eight chapters. The first chapter (Chapter 1) is devoted to the introduction of thesis. In this chapter, the application of multiwavelength sources to DWDM systems, problems and objectives of the research work are presented. The literature review is then elaborated in Chapter 2. The phenomena of nonlinear optics such as self-phase modulation (SPM), cross-phase modulation (XPM), FWM, SBS and SRS are discussed here, as well as the explanations of mechanisms and progress of BEFLs, EDFLs and FWMC. Chapter 3 afterwards presents the research methodology. In the beginning, the research design that illustrates links between the four studies conducted is clarified. This is then followed by the clarifications on the experimental procedures as well as the input and output parameters utilized in the experiments.

As this is a publication-based thesis, chapter 4 to 8 comprise of journal papers which are published over the period of this study. Chapter 4 is an article published in Applied Physics B, ISSN 1432-0649 (Appl. Phys. B, Vol. 112, No. 2, pp. 215-221, 2013). This article is related to a study on multiwavelength BEFLs which is aimed to flattening the laser output via FWM. Chapter 5 meanwhile presents the second article that is published in Optics Communications, ISSN 0030-4018 (Opt. Commun., Vol. 329, pp. 163-167, 2014). The article is about an investigation on the formation, properties and role of residual waves in multiwavelength BEFLs. In chapter 6, the third article which is published in Applied Physics B, ISSN 1432-0649 (Appl. Phys. B, Vol. 115, No. 2, pp. 251-256, 2014) is presented. This article is related to a single and dual-wavelength EDFL which has wide wavelength-spacing tunability due to the incorporation of tunable filters. Chapter 7 meanwhile is formed by the fourth article that is published in Optics Express, ISSN 1094-4087 (Opt. Express, Vol. 21, No. 5, pp. 6131-6138, 2013). An FWMC scheme which can operate without external laser sources and modulators is reported here.

In the last chapter (Chapter 8), we take readers to conclusions that are drawn based on the main experimental results discussed in the previous chapters. This is then followed by the discussions on the achievements and problems faced by the proposed schemes as well as the recommendations for improvement that can be practically implemented in the future work.

REFERENCES

[1] ITU-T G.694.1, “Spectral grids for WDM applications: DWDM frequency grid,” www.itu.int/rec/T-REC-G.694.1/en.

[2] M. Ajiya, M. A. Mahdi, M. H. Al-Mansoori, S. Hitam, and M. Mokhtar, “Seamless tuning range based-on available gain bandwidth in multiwavelength brillouin fiber laser,” *Opt. Express*, vol. 17, no. 8, pp. 5944–5952, 2009.

[3] M. Ajiya, M. A. Mahdi, M. H. Al-Mansoori, S. Hitam, and M. Mokhtar, “Broadly tunable multiple wavelength Brillouin fiber laser exploiting erbium amplification,” *J. Opt. Soc. Am. B*, vol. 26, no. 9, pp. 1789-1794 , 2009.

[4] H. A. Al-Asadi, M. H. Al-Mansoori, M. Ajiya, S. Hitam, M. I. Saripan, and M. A. Mahdi, "Effects of pump recycling technique on stimulated Brillouin scattering threshold: a theoretical model," *Opt. Express*, vol. 18, no. 21, pp. 22339-22347, 2010.

[5] D. S. Lim, H. K. Lee, K. H. Kim, S. B. Kang, J. T. Ahn, M. Y. Jeon, and M.-Y. Jeon, "Generation of multiorder Stokes and anti-Stokes lines in a Brillouin erbium-fiber laser with a Sagnac loop mirror," *Opt. Lett.*, vol. 23, no. 21, pp. 1671–1673, 1998.

[6] J. Tang, J. Sun, L. Zhao, T. Chen, T. Huang, and Y. Zhou, "Tunable multiwavelength generation based on Brillouin-erbium comb fiber laser assisted by multiple four-wave mixing processes," *Opt. Express*, vol. 19, no. 15, pp. 14682–14689, 2011.

[7] X. Liu, X. Yang, F. Lu, J. Ng, X. Zhou and C. Lu, “Stable and uniform dual-wavelength erbium-doped fiber laser based on fiber Bragg gratings and photonic crystal fiber”, *Opt. Express*, vol. 13, no. 1, pp. 142–147, 2005.

[8] Y. –G. Han and S. B. Lee, “Flexibly tunable multiwavelength erbium-doped fiber laser based on four-wave mixing effect in dispersion-shifted fibers”, *Opt. Express*, vol. 13, no. 25, pp. 10134-10139, 2005.

[9] Y. –G. Han, J. H. Lee, S. B. Lee, L. Poti and A. Bogoni, “Novel Multiwavelength Erbium-Doped Fiber and Raman Fiber Ring Lasers With Continuous Wavelength Spacing Tunability at Room Temperature”, *IEEE J. Lightw. Technol.*, vol. 25, no. 8, pp. 2219–2225, 2007.

[10] A. Cerqueira Sodre, J. M. Chavez Boggio, A. A. Rieznik, H. E. Hernandez-Figueroa, H. L. Fragnito, and J. C. Knight, "Highly efficient generation of broadband cascaded four-wave mixing products," *Opt. Express*, vol. 16, no. 4, pp. 2816–2828, 2008.

[11] C. Arismar, J. D. Marconi, H. E. Hernandez-Figueroa, and H. L. Fragnito, “Broadband cascaded four-wave mixing by using a three-pump technique in optical fibers,” *Opt. Commun.*, vol. 282, no. 22, pp. 4436–4439, 2009.

[12] J. Li, X. Xiao, L. Kong, and C. Yang, "Enhancement of cascaded four-wave mixing via optical feedback," *Opt. Express*, vol. 20, no. 20, pp 21940–21945, 2012.

[13] E. Myslivets, B. P. P. Kuo, N. Alic, and S. Radic, “Generation of wideband frequency combs by continuous wave seeding of multistage mixers with synthesized dispersion,” *Opt. Express*, vol. 20, no. 3, pp. 3331–3344, 2012.

[14] F. Yaman, Q. Lin, S. Radic, and G. P. Agrawal, “Impact of pump-phase modulation on dual-pump fiber-optic parametric amplifiers and wavelength converters,” *IEEE Photon. Technol. Lett.*, vol. 17, no. 10, pp. 2053–2055, 2005.

[15] A. Durecu-Legrand, A. Mussot, C. Simonneau, D. Bayart, T. Sylvestre, E. Lantz, and H. Maillotte, “Impact of pump phase modulation on system performance of fiber-optical parametric amplifiers,” *Electron. Lett*., vol. 41, no. 6, pp. 350–352, 2005.
[16] G. P. Agrawal, Nonlinear Fiber Optics, 3rd ed. San Diego, CA: Academic, 2001.
[17] Gerd Keiser, Optical fiber communications, McGraw-Hill, 2000.
[18] K. Inoue, “Four-wave mixing in an optical fiber in the zero-dispersion wavelength region,” *IEEE J. Lightwave Technol*., vol. 10, no. 11, pp. 1553–1561, 1992.
[19] J. Hansryd , P. A. Andrekson , M. Westlund , L. Jie and P. O. Hedekvist "Fiber-based optical parametric amplifiersand their applications", *IEEE J. Sel. Top. Quantum Electron*., vol. 8, no. 3, pp. 506 -520, 2002.
[20] Ming-jun Li "Managing nonlinearity in optical fiber for high-power lasers," *SPIE Newsroom*, Jul. 2006.
[21] M. E. Marhic, Fiber Optical Parametric Amplifiers, Oscillators and Related Devices. Cambridge, U.K.: Cambridge Univ. Press, 2008.
[22] N. El Dahdah, D. S. Govan, M. Jamshidifar, N. J. Doran, and M. E. Marhic, “Fiber optical parametric amplifier performance in a 1-Tb/s DWDM communication system,” *IEEE J. Sel. Top. Quantum Electron*., vol. 18, no. 2, pp. 950–957, 2012.
[23] Z. Tong, A. Bogris, M. Karlsson, and P. A. Andrekson, “Full characterization of the signal and idler noise figure spectra in single-pumped fiber optical parametric amplifiers,” *Opt. Express*, vol. 18, no. 3, pp. 2884–2893, 2010.
[24] Z. Tong, C. Lundström, P. A. Andrekson, C. J. McKinstrie, M. Karlsson, D. J. Blessing, E. Tipsuwannakul, B. J. Puttnam, H. Toda, and L. Grüner-Nielsen, “Towards ultrasensitive optical links enabled by low-noise phase sensitive amplifiers,” *Nat. Photonics*, vol. 5, no. 7, pp. 430–436, 2011.
[25] J. M. C. Boggio, E. A. M. Fagotto, M. E. Marhic, F. A. Callegari, and H. L. Fragnito “Amplification of 12 × 10 Gb/s WDM signals with negligible FWM crosstalk in a double-pumped fiber optical parametric amplifier,” *Opt. Commun*., vol. 280, no. 2, pp. 468–471, 2007.
[26] N. Yoshizawa and T. Imai "Stimulated Brillouin scattering suppression by means of applying strain distribution to fiber with cabling", *IEEE J. Lightw. Technol*., vol. 11, no. 10, pp.1518 -1522, 1993.
[27] J.D. Marconi, J. M. C. Boggio and H. L. Fragnito " Narrow linewidth wavelength converter with 70 nm of signal tuning band using strain distribution to suppress SBS", Proc. Conf. on Optical Amplifiers and Their Applications, Whistler, Canada, Jul. 2006.
[28] K. K. Y. Wong, M. E. Marhic and L. G. Kazovsky, “Temperature control of the gain spectrum of fiber optical parametric amplifiers,” *Opt. Express*, vol. 13, no. 12, pp. 4666 -4473, 2005.
[29] Y. Takushima and T. Okoshi "Suppression of stimulated Brillouin scattering using optical isolators", *Electron. Lett*., vol. 28, no. 12, pp.1155 -1156, 1992.
[30] T. Nakanishi, M. Tanaka, T. Hasegawa, M. Hirano, T. Okuno, and M. Onishi, "Al2O3-SiO2 core highly nonlinear dispersion-shifted fiber with Brillouin gain suppression improved by 6.1 dB," in ECOC’2006, post-deadline paper Th. 4.2.2, 2006.
[31] J. Hansryd , F. Dross , M. Westlund , P. A. Andrekson and S. N. Knudsen "Increase in the SBS threshold in a short highly nonlinear fiber by applying a

temperature distribution", *J. Lightw. Technol.*, vol. 19, no. 11, pp.1691 -1697 2001.
[32] G. J. Cowle and D. Y. Stepanov "Hybrid Brillouin/erbium fiber laser", *Opt. Lett.*, vol. 21, no. 16, pp.1250 -1252, 1996.
[33] G. J. Cowle and D. Y. Stepanov, "Multiple wavelength generation with Brillouin/erbium fibre lasers", *IEEE Photon. Technol. Lett.*, vol. 8, no. 11, pp.1465 -1467 1996.
[34] N. S. Kim "Multiwavelength operation of EDFA-enhanced Brillouin/erbium fiber lasers", *Electron. Lett.*, vol. 34, no. 7, pp. 673 -675, 1998.
[35] M. H. Al-Mansoori, B. Bouzid, B. M. Ali, M. K. Abdullah and M. A. Mahdi, "Multi-wavelength Brillouin erbium fiber laser in a linear cavity," *Opt. Commun.*, vol. 242, no. 1-3, pp. 209 -214, 2004.
[36] M. H. Al-Mansoori and M. A. Mahdi, "Reduction of gain depletion and saturation on a Brillouin–erbium fiber laser utilizing a Brillouin pump pre-amplification technique," *Appl. Opt.* vol. 48, no. 18, pp. 3424 -3428, 2009.
[37] M. A. Mahdi, M. H. Al-Mansoori, and M. Premaratne, "Enhancement of multiwavelength generation in the L-band by using a novel Brillouin–erbium fiber laser with a passive EDF booster section," *Opt. Express*, vol. 15, no. 18, pp. 11570–11575, 2007.
[38] M. H. Al-Mansoori and M. A. Mahdi, "Multi-wavelength L-band Brillouin-Erbium comb fiber laser utilizing nonlinear amplifying loop mirror," *IEEE J. Lightw. Technol.*, vol. 27, no. 22, pp. 5038–5044, 2009.
[39] M. H. Al-Mansoori and M. Mahdi, "Broadly tunable L-band multiwavelength BEFL utilizing nonlinear amplified loop mirror filter," *Opt. Exp.*, vol. 19, no. 24, pp. 23981–23988, 2011.
[40] Y. J. Song, L. Zhan, S. Hu, Q. H. Ye and Y. X. Xia, "Tunable multiwavelength Brillouin- Erbium fiber laser with a polarization-maintaining fiber sagnac loop filter," *IEEE Photon. Technol. Lett.*, vol.16, no. 9, pp. 2015-2017, 2004.
[41] L. Zhan, J. H. Ji, J. Xia, S. Y. Luo, and Y. X. Xia, "160-linemultiwavelength generation of linear-cavity self-seeded Brillouin–erbium fiber laser," *Opt. Express*, vol. 14, no. 22, pp. 10233–10238, 2006.
[42] Z. Zhang, L. Zhan, and Y. Xia, "Tunable self-seeded multiwavelength Brillouin–erbium fiber laser with enhanced power efficiency," *Opt. Express*, vol. 15, no. 15, pp. 9731–9736, 2007.
[43] Y. Huang, L. Zhan, J. H. Ji, S. Y. Luo, and Y. X. Xia, "Multiwavelength self-seeded Brillouin-erbium fiber laser with 45-nm tunable range," *Opt. Commun.*, vol. 281, no. 3, pp. 452-456, 2008.
[44] M. H. Al-Mansoori and M. A. Mahdi, "Tunable range enhancement of Brillouin–erbium fiber laser utilizing Brillouin pump pre-amplification technique," *Opt. Express*, vol. 16, no. 11, pp. 7649–7654, 2008.
[45] M. H. Al-Mansoori, M. A. Mahdi, and M. Premaratne, "Novel multiwavelength L-Band Brillouin-Erbium fiber laser utilizing double-pass Brillouin pump preamplified technique," *IEEE J. Sel. Top. Quantum Electron.*, vol. 15, no. 2, pp. 415-421, 2009.
[46] B. Dong, D. P. Zhou and L. Wei, "Tunable multiwavelength Brillouin –erbium fiber laser by controlling self-lasing cavity modes," *Opt. Fiber Technol.*, vol. 16, no. 1, pp. 17–19, 2010.
[47] C. Huang, X. Dong, N. Zhang, S. Zhang and P. Shum, "Multiwavelength Brillouin-erbium random fiber laser incorporating a chirped fiber Bragg

grating," *IEEE J. Sel. Top. Quantum. Electron.*, vol. 20, no. 5, pp. 0902405, 2014.
[48] C. Huang, X. Dong, N. Zhang, S. Zhang and P. Shum,, "Cascaded Random Fiber Laser Based on Hybrid Brillouin-Erbium Fiber Gains," *IEEE Photon. Technol. Lett*., vol. 26, no. 13, pp. 1287–1290, 2014.
[49] Y. Yuan, Y. Yao, M. Yi, B. Guo and J. Tian, "Multiwavelength fiber laser employing a nonlinear Brillouin optical loop mirror: experimental and numerical studies," *Opt. Express*, vol. 22, no. 13, pp. 15352–15363, 2014.
[50] S. Yamashita and K. Hotate, "Multiwavelength erbium-doped fiber laser using intracavity etalon and cooled by liquid nitrogen," *Electron. Lett*.,vol. 32, no. 14, pp. 1298-1299, Jul. 1996.
[51] X. Feng, H. Tam and P. K. A. Wai, "Stable and uniform multiwavelength erbium-doped fiber laser using nonlinear polarization rotation," *Opt. Express*, vol. 14, no. 18, pp. 8205-8210, 2006.
[52] A. P. Luo, Z. C. Luo, and W. C. Xu, "Multiwavelength switchable erbium-doped fiber ring laser with a PBS-based Mach-Zehnder comb filter," *IEEE Photon. J.*, vol. 3, no. 2, pp. 197-202, 2011.
[53] A. M. Ramzia Salem, M.H. Al-Mansoori, H. Hizam, S.B. Mohd Noor, M.H. Abu Bakar, M.A. Mahdi, "Multiwavelength L-band fiber laser with bismuth-oxide EDF and photonic crystal fiber, " *Appl. Phys. B*, vol. 103, no. 2, pp. 363-368, 2011.
[54] S. W. Harun , S. Shahi and H. Ahmad "Compact Brillouin-erbium fiber laser", *Opt. Lett*., vol. 34, no. 1, pp.46 -48, 2009.
[55] M. I. Johari "Ring cavity multiwavelength Brillouin-erbium fiber laser with apartially reflective fiber Bragg grating", *J. Opt. Soc. Am. B*, vol. 26, no. 9, pp.1675 -1678, 2009.
[56] S. Harun , R. Parvizi , S. Shahi and H. Ahmad "Compact BI-EDF-based Brillouin erbium fiber laser operating at the 1560-nm region", *IEEE Photon.J*., vol. 1, no. 5, pp.254 -258, 2009.
[57] A. Bellemare, M. Karasek, M. Rochette, S. LaRochelle, and M. Tetu, "Room temperature multifrequency erbium-doped fiber lasers anchored on the ITU frequency grid," *J. Lightwave Technol*., vol. 18, no. 6, pp 825- 831, 2000.
[58] Y. Liu, X. Feng, S. Yuan, G. Kai, and X. Dong, "Simultaneous four-wavelength lasing oscillations in an erbium-doped fiber laser with two high birefringence fiber Bragg gratings," *Opt. Express*, vol. 12, no. 10, pp. 2056-2061, 2004.
[59] D. Liu , N. Q. Ngo , X. Y. Dong , S. C. Tjin and P. Shum "A stable dual-wavelength fiber laser with tunable wavelength spacing using a polarization-maintaining linear cavity", *App. Phys. B.*, vol. 81, no. 6, pp.807 -811, 2005.
[60] Y.-G. Han, G. Kim, J. H. Lee, S. H. Kim, and S. B. Lee, "Lasing wavelength and spacing switchable multiwavelength fiber laser from 1510 to 1620 nm," *IEEE Photon. Technol. Lett*., vol. 17, no. 5, pp. 989-991, 2005.
[61] Z. Luo, M. Zhou, Z. Cai, C. Ye, J. Weng, G. Huang and H. Xu, "Graphene-assisted multiwavelength erbium-doped fiber ring laser," *IEEE Photon. Technol. Lett*., vol. 23, no. 8, pp. 501-503, 2011.
[62] M. Zhou, Z. Luo, Z. Cai, C. Ye, H. Xu and J. Wang, "Switchable and tunable multiple-channel erbium-doped fiber laser using graphene-polymer nanocomposite and asymmetric two-stage fiber Sagnac loop filter", *Appl. Opt*. vol. 50, no. 18, pp. 2940-2948, 2011.

[63] H. Ahmad, A. A. Latif, I. M. Abdul Khudus Muhammad, A. Z. Zulkifli, M. Z. Zulkifli, K. Thambiratnam and S. W. Harun, "Highly stable graphene-assisted tunable dual-wavelength erbium-doped fiber laser, " *Appl. Opt*., vol. 52, no. 4, pp. 818-823, 2013.
[64] H. Ahmad, S. Shahi and S. W. Harun, "Multi-wavelength laser generation with Bismuth-based Erbium-doped fiber," *Opt. Express*, vol. 17, no. 1, pp. 203-207, 2008.
[65] H. L. Liu , H. Y. Tam , W. H. Chung , P. K. A. Wai and N. Sugimoto "La-codoped bismuth-based erbium-doped fiber ring laser with 106-nm tuning range", *IEEE Photon. Technol. Lett*., vol. 17, no. 2, pp.297 -299, 2005.
[66] X. Liu, X. Zhou, and C. Lu, "Multiple four wave mixing self-stability in optical fibers," *Phys. Rev. A*, vol. 72, no. 1, p. 013811, 2005.
[67] X. M. Liu, "Four-wave mixing self-stability based on photonic crystal fiber and its applications on erbium-doped fiber lasers," *Opt. Commun*., vol. 260, no. 2, pp. 554–559, 2006.
[68] X. M. Liu, "Theory and experiments for multiple four-wave-mixing processes with multi-frequency pumps in optical fibers," *Phys. Rev. A*, vol. 77, no. 4, p. 043818, 2008.
[69] X. Liu, X. Zhou, X. Tang, J. Ng, J. Hao, T. Y. Chai, E. Leong, and C. Lu, "Switchable and tunable multiwavelength erbium-doped fiber laser with fiber Bragg gratings and photonic crystal fiber," *IEEE Photon. Technol. Lett*., vol. 17, no. 8, pp. 1626–1628, 2005.
[70] X. Liu and C. Lu, "Self-stabilizing effect of four-wave mixing and its applications on multiwavelength erbium-doped fiber lasers," *IEEE Photon. Technol. Lett*., vol. 17, no. 12, pp. 2541–2543, 2005.
[71] X. M. Liu, X. Q. Zhou, and C. Lu, "Four-wave mixing assisted stability enhancement: Theory, experiment and application," *Opt. Lett*., vol. 30, no. 17, pp. 2257-2259, 2005.
[72] P. Wang, D. Weng, K. Li, Y. Liu, X. Yu and X. Zhou, "Multi-wavelength Erbium-doped fiber laser based on four-wave-mixing effect in single mode fiber and high nonlinear fiber," *Opt. Lett*., vol. 21 , no. 10, pp. 12570–12578, 2013.
[73] T. Udem, R. Holzwarth, and T. W. Hänsch, "Optical frequency metrology," *Nature*, vol. 416, no. 6877, pp. 233–237, 2002.
[74] A. E. H. Oehler, S. C. Zeller, K. J. Weingarten, and U. Keller, "Broad multiwavelength source with 50 GHz channel spacing for wavelength division multiplexing applications in the telecom C band," *Opt. Lett*., vol. 33, no. 18, pp. 2158–2160, 2008.
[75] T. Ohara, H. Takara, T. Yamamoto, H. Masuda, T. Morioka, M. Abe, and H. Takahashi, "Over-1000-channel ultradense WDM transmission with supercontinuum multicarrier source," *IEEE J. Lightwave Technol*., vol. 24, no. 6, pp. 2311–2317, 2006.
[76] R. Holzwarth, T. Udem, T. W. Hänsch, J. C. Knight, W. J. Wadsworth, and P. S. J. Russell, "Optical frequency synthesizer for precision spectroscopy," *Phys. Rev. Lett.*, vol. 85, no. 11, pp. 2264–2267, 2000.
[77] A. Schliesser, M. Brehm, F. Keilmann, and D. van der Weide, "Frequency-comb infrared spectrometer for rapid remote chemical sensing," *Opt. Express*, vol. 13, no. 22, pp. 9029 –9038, 2005.

[78] J. Zhang, Z. H. Lu, and L. J. Wang, “Precision measurement of the refractive index of carbon dioxide with a frequency comb,” *Opt. Lett*. vol. 32, no. 21, pp. 3212–3214, 2007.
[79] Z. Jiang, C.-B. Huang, D. E. Leaird, and A. M. Weiner, “Optical arbitrary waveform processing of more than 100 spectral comb lines,” *Nat. Photonics*, vol. 1, no. 8, pp. 463–467, 2007.
[80] Z. Jiang, D. E. Leaird, C. Huang, H. Miao, M. Kourogi, K. Imai, and A. M. Weiner, “Spectral line-by-line pulse shaping on an optical frequency comb generator,” *IEEE J. Quantum Electron*., vol. 43, no. 12, pp. 1163–1174, 2007.
[81] J. Yao, “Microwave photonics: Arbitrary waveform generation,” Nat. Photonics, vol. 4, no. 2, pp. 79–80, 2010.
[82] P. Balling, P. Křen, P. Mašika, and S. A. van den Berg, “Femtosecond frequency comb based distance measurement in air,” *Opt. Express*, vol. 17, no. 11, pp. 9300–9313, 2009.
[83] H. Inaba, Y. Daimon, F.-L. Hong, A. Onae, K. Minoshima, T. R. Schibli, H. Matsumoto, M. Hirano, T. Okuno, M. Onishi, and M. Nakazawa, “Long-term measurement of optical frequencies using a simple, robust and low noise fiber based frequency comb,” *Opt. Express*, vol. 14, no. 12, pp. 5223–5231, 2006.
[84] Y. Takita, F. Futami, M. Doi, and S. Watanabe, “Highly stable ultra-short pulse generation by filtering out flat optical frequency components,” *CLEO*, CTuN1, 2004.
[85] S. Ozharar, F. Quinlan, I. Ozdur, S. Gee, and P. J. Delfyett, “Ultraflat optical comb generation by phase-only modulation of continuous-wave light,” *IEEE Photon. Technol. Lett*., vol. 20, no. 1, pp. 36–38, 2008.
[86] T. Yamamoto, T. Komukai, K. Suzuki, and A. Takada, “Spectrally flattened phase-locked multi-carrier light generator with phase modulators and chirped fibre Bragg grating,” *Electron. Lett*., vol. 43, no. 19, pp. 1040–1042, 2007.
[87] R. Wu, V. R. Supradeepa, C. M. Long, D. E. Leaird, and A. M. Weiner, “Generation of very flat optical frequency combs from continuous-wave lasers using cascaded intensity and phase modulators driven by tailored radio frequency waveforms,” *Opt. Lett*., vol. 35, no. 19, pp. 3234–3236, 2010.
[88] Y. Dou, H. Zhang, and M. Yao, “Improvement of flatness of optical frequency comb based on nonlinear effect of intensity modulator,” *Opt. Lett*., vol. 36, no. 14, pp. 2749–2751, 2011.
[89] J. Zhang, N. Chi, J. Yu, Y. Shao, J. Zhu, B. Huang, and L. Tao, “Generation of coherent and frequency-lock multi-carriers using cascaded phase modulators and recirculating frequency shifter for Tb/s optical communication,” *Opt. Express*, vol. 19, no. 14, pp. 12891–12902, 2011.
[90] J. Zhang, J. Yu, Z. Dong, Y. Shao, and N. Chi, “Generation of full C-band coherent and frequency-lock multicarriers by using recirculating frequency shifter loops based on phase modulator with external injection,” *Opt. Express*, vol. 19, no. 27, pp. 26370–26381, 2011.
[91] L. Xi, J. Li, X. Zhang, F. Tian, and W. Zhang, “Factors affecting the performance of a multi-tone carrier source based re-circulating frequency shifter,” *Chin. Phys. B*, vol. 20, no. 8, pp. 084202, 2011.
[92] F. Tian, X. Zhang, J. Li, and L. Xi, “Generation of 50 stable frequency-locked optical carriers for Tb/s multicarrier optical transmission using a recirculating frequency shifter,” *IEEE J. Lightwave Technol*., vol. 29, no. 8, pp. 1085–1091, 2011.

[93] J.-W. Shi , C.-C. Chen , Y.-S. Wu , S.-H. Guol and Y.-J. Yang "High-power and high-speed Zn-diffusion single fundamental-mode vertical-cavity surface-emitting lasers at 850 nm wavelength", *IEEE Photon. Technol. Lett*., vol. 20, no. 13, pp.1121 -1123, 2008.

[94] D. Zhou and L. J. Mawst "High-power single-mode antiresonant reflecting optical waveguide-type vertical-cavity surface-emitting lasers", *IEEE J. Quantum Electron.*, vol. 38, no. 12, pp.1599 -1606, 2002.

[95] A. Furukawa , S. Sasaki , M. Hoshi , A. Matsuzono , K. Moritoh and T. Baba "High-power single-mode vertical-cavity surface-emitting lasers with triangular holey structure", *Appl. Phys. Lett*., vol. 85, no. 22, pp.5161 -5163, 2004.

[96] S. Noda "Photonic crystal lasers-ultimate nanolasers and broad-area coherent lasers [Invited]", *J. Opt. Soc. Amer. B*, vol. 27, no. 11, pp.B1 -B8, 2010.

[97] S. K. Turitsyn "Random distributed feedback fiber laser", *Nature Photon.*, vol. 4, no. 4, pp.231 -235, 2010.

[98] A. M. R. Pinto and M. Lopez-Amo, "Double Random Mirror Hi–Bi Photonic Crystal Fiber Sagnac Based Multiwavelength Fiber Laser," *Appl. Phys. B*, vol. 103, no. 4, pp. 771–775, 2011.

[99] Y. Li, J. Hou, Z. Jiang, and J. Leng, "Efficient generation of broad Raman sidebands in an index-guided photonic crystal fiber," *Appl. Opt.* vol. 52, no. 10, pp. 2049-2054, 2013.

[100] F. Couny, F. Benabid, P. J. Roberts, P. S. Light, and M. G. Raymer, "Generation and photonic guidance of multi-octave optical frequency combs," *Science*, vol. 318, no. 5853, pp. 1118–1121, 2007.

[101] Y. Y. Wang, C. Wu, F. Couny, M. G. Raymer, and F. Benabid, "Quantum-fluctuation-initiated coherence in multi-octave Raman optical frequency combs," *Phys. Rev. Lett*., vol. 105, no. 12, p. 123603, 2010.

[102] P. Ghenuche, S. Rammler, N. Y. Joly, M. Scharrer, M. Frosz, J. Wenger, P. S. J. Russell, and H. Rigneault, "Kagome hollow-core photonic crystal fiber probe for Raman spectroscopy," *Opt. Lett*., vol. 37, no. 21, pp. 4371–4373, 2012.

[103] Alexis Labruyère, Badr M. Shalaby, Katarzyna Krupa, Vincent Couderc, Alessandro Tonello, and Fabio Baronio, "Simultaneous broadband Raman cascading and parametric conversion in potassium titanyl phosphate," *Opt. Lett*., vol. 38, no. 19, pp. 3758-3761, 2013.

[104] Z. A. Rahman , S. Hitam , M. Al-Mansoori , A. Abas and M. Mahdi "Multiwavelength Brillouin fiber laser with enhanced reverse-S-shaped feedback coupling assisted by out-of-cavity optical amplifier", *Opt. Exp.*, vol. 19, no. 22, pp.21238 -21245, 2011.

[105] R. Parvizi , H. Arof , N. M. Ali , H. Ahmad and S. W. Harun "0.16 nm spaced multi-wavelength Brillouin fiber laser in a figure-of-eight configuration", *Opt. Laser Technol.*, vol. 43, no. 4, pp.866 -869, 2011.

[106] M. Shirazi , M. Biglary , S. Harun , K. Thambiratnam and H. Ahmad "Bidirectional multiwavelength Brillouin fiber laser generation in a ring cavity", *J. Opt. A: Pure Appl. Opt.*, vol. 10, no. 5, pp.055101, 2008.

[107] B. A. Ahmad , A. W. Al-Alimi , A. F. Abas , M. Mokhtar , S. W. Harun and M. A. Mahdi "Compact Brillouin fiber laser based on highly nonlinear fiber with 51 double spacing channels", *IEEE Photon. J.*, vol. 4, no. 4, pp.1087-1094, 2012.

[108] G. Mamdoohi, A. R. Sarmani, A. F. Abas, M. H. Yaacob, M. Mokhtar, and M. A. Mahdi, "20 GHz spacing multi-wavelength generation of Brillouin-Raman

fiber laser in a hybrid linear cavity," *Opt. Express*, vol. 21, no. 16, pp. 18724–18732, 2013.

[109] B. Min, P. Kim, and N. Park, "Flat amplitude equal spacing 798-channel Rayleigh-assisted Brillouin-Raman multi-wavelength comb generation in dispersion compensating fiber," *IEEE Photon. Technol. Lett.*, vol. 13, no. 12, pp. 1352–1354, 2001.

[110] K.-D. Park, B. Min, P. Kim, N. Park, J.-H. Lee, and J.-S. Chang, "Dynamics of cascaded Brillouin-Rayleigh scattering in a distributed fiber Raman amplifier," *Opt. Lett*., vol. 27, no. 3, pp. 155–157, 2002.

[111] A. R. Sarmani, M. H. Abu Bakar, A. A. A. Bakar, F. R. Mahamd Adikan, and M. A. Mahdi, "Spectral variations of the output spectrum in a random distributed feedback Raman fibe r laser," *Opt. Exp*., vol. 19, no. 15, pp. 14 152–14 159, 2011.

[112] V. Karalekas, J. D. Ania Castanon, P. Harper, S. A. Babin, E. V. Podivilov, and S. K. Turitsyn, "Impact of nonlinear spectral broadening in ultra-long Raman fibre lasers," *Opt. Exp*., vol. 15, no. 25, pp. 16 690–16 695, 2007.

[113] K. S. Yeo, F. R. M. Adikan, M. Mokhtar, S. Hitam, and M. A. Mahdi, "Continuous wave tunable fiber optical parametric oscillator with double-pass pump configuration," *Appl. Phys. B,* vol. 110, no. 3, pp. 353–357, 2013.

[114] Z. Luo, W. D. Zhong, Z. Cai, C. Ye, H. Xu, X. Dong, and L. Xia, "Multiwavelength fiber optical parametric oscillator," *IEEE Photon. Technol. Lett*., vol. 21, no. 21, pp. 1609–1611, 2009.

[115] C. J. S. de Matos, J. R. Taylor, and K. P. Hansen, "Continuous-wave, totally fiber integrated optical parametric oscillator using holey fiber," *Opt. Lett*., vol. 29, no. 9, pp. 983–985, 2004.

[116] H. Takara, T. Ohara and K. Sato, "Over 1000 km DWDM transmission with supercontinuum multi-carrier source," *Electron Lett.*, vol. 39, no. 14, pp. 1078-1079, 2003.

[117] H. Takara, T. Ohara, T. Yamamoto, H. Masuda, M. Abe, H. Takahashi and T. Morioka, "Field demonstration of over 1000-channel DWDM transmission with supercontinuum multi-carrier source," *Electron Lett.*, vol. 41, no. 5, pp. 270-271, 2005.