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

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To my beloved family

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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

Gentian optik memainkan peranan yang penting bagi menampung peningkatan kapasiti penghantaran. Terdapat beberapa jenis kesan tidak linear dalam gentian optik. Salah satu kesan tidak linear tersebut ialah percampuran empat gelombang (FWM). Kajian yang mendalam terhadap FWM telah dijalankan dan didapati bahawa FWM mempunyai salah satu applikasi yang dikenali sebagai penguat parametrik gentian optik (FOPA). FOPA mempunyai keupayaan untuk mencapai nisbah dan lebar jalur yang tinggi. Salah satu pendekatan yang digunakan ialah lata FOPA. Lata FOPA adalah FOPA dengan dua atau lebih aktif media, biasanya gentian silika amat tidak linear (HNLF). Beberapa eksperimen lepas menunjukkan lata FOPA akan mempunyai nisbah dan lebar jalur yang lebih baik jika peranti pasif atau aktif dimasukkan di antara HNLF. Walau bagaimanapun, keputusan di setiap peringkat lata FOPA tidak dibincangkan. Hasil disetiap peringkat adalah penting untuk memastikan bahawa lata FOPA ditambah kuasa di setiap peringkat dan telah dikaji di dalam kajian ini. Dalam kajian ini, simulasi lata FOPA dijalankan dengan menggunakan perisian OptiSystem dengan empat peringkat HNLF yang mempunyai parameter berbeza. Dua kajian penyelidikan berkaitan dengan lata FOPA secara simulasi telah ditunjukkan dalam tesis ini. Kajian pertama memberi tumpuan kepada kesan penditeran pam terhadap lata FOPA, manakala kajian kedua membincangkan kesan komponen pasif kepada lata FOPA. Komponen pasif yang dipilih ialah pemencil dan tapis pita optik. Hasil kajian menunjukan bahawa lata FOPA dengan penditeran pam mampu menjana gandaan sehingga 27 dB, manakal tanpa pam penditeran hanya mampu mencapai gandaan sebanyak 9 dB. Bagi prestasi lata FOPA bersama komponen pasif, pemencil berjaya mendapat gandaan yang tinggi iaitu 30 dB manakala tapis pita optik berjaya melebarkan lebar jalur lata FOPA sebanyak 36 nm. Konklusinya, penditeran pam dan pemencil boleh digunakan bagi mendapatkan gandaan yang tinggi untuk FOPA dan tapis pita optik mampu mendapatkan lebar jalur yang lebar.

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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

χ_{1111} - Third-order nonlinear susceptibility

η - Channel spacing

n - Fiber refractive index

$\mathcal{D}$ - Degeneracy factor

L_{eff} - Effective length

A_{eff} - Effective area

α - 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}

ω_{p_1} - Angular frequency of pump one

ω_{p_2} - Angular frequency of pump two

ω_{i} - Angular frequency of idler

ω_s - Angular frequency of signal

ω_c - Center angular frequency

P_p - Pump power

P_s - Signal power

P_i - Idler power

γ - Nonlinear coefficient

$\Delta\beta$ - Low propagation mismatch

β_p - Propagation constant of pump

β_s - Propagation constant of signal

β_i - Propagation constant of idler

c - Speed of light

λ_o - Zero dispersion wavelength

λ_p - Pump wavelength

λ_s - Signal wavelength

λ_i - Idler wavelength

$\frac{dD}{d\lambda}$ - Slope of dispersion at zero dispersion wavelength

β_4 - Fourth-order dispersion coefficient

ϕ_p - Phase of the pump

ϕ_s - Phase of the signal

ϕ_i - Phase of the idler

θ - Relative phase difference

κ - Phase-matching condition

κ_M - Material dispersion

κ_W - Waveguide dispersion

κ_{NL} - Nonlinear dispersion
G - Gain
G_{exp} - Exponential gain
G_{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

LIST OF APPENDICES

LIST OF PUBLICATIONS

Journal:

(i) F. N. Salleh, N. S. M. Shah, N. N. Shamsuddin, S. N. S. Yaacob, N. Othman, “Cascaded Fiber Optical Parametric Amplifier with Isolators and Optical Bandpass Filter using Optisystem.” International Journal of Simulation Systems, Science and Technology.

Proceeding:

(i) F. N. Salleh, N. S. M. Shah, N. N. Shamsuddin, S. N. S. Yaacob, “The Investigation on Fiber Optical Parametric Amplifier (FOPA) Bandwidth using Optisystem.” Proceeding of The National Conference for Postgraduate Research 2016 (NCON-PGR), UMP, 24-25 September 2016.

(ii) S. N. S. Yaacob, N. S. M. Shah, F. N. Salleh, “High Non-Linear Fiber Length Verification in Optical Regeneration using Non-Return Zero and Return Zero Signal.” Proceeding of The National Conference for Postgraduate Research 2016 (NCON-PGR), UMP, 24-25 September 2016.

(iii) F. N. Salleh, N. S. M. Shah, N. Othman, “The Effect of Pump Dithering on Cascaded FOPA at Each Stage by Using Optisystem.” Proceeding of International Conference on Electrical and Electronic Engineering 2017 (IC3E), Johor Bahru, 14-15 August 2017.

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

Nonlinearity category	**Single Channel**	**Multiple Channel**
Index related	Self-phase modulation	Cross-phase modulation Four-wave mixing
Scattering related	Stimulated Brillouin Scattering	Stimulated Raman Scattering

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.

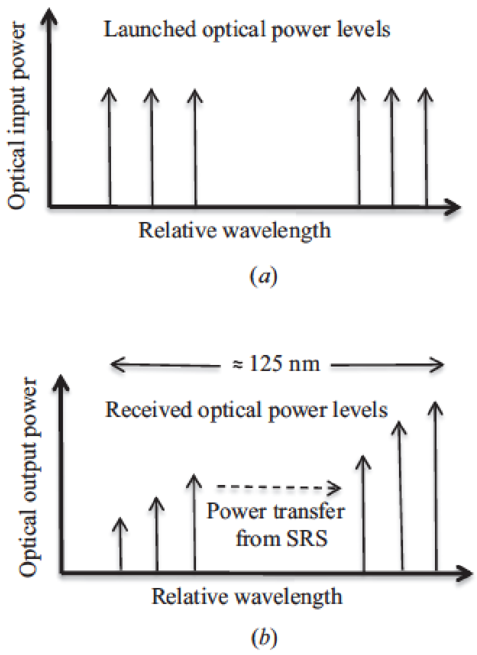

Figure 2.1: The optical power transfer (a) before and (b) after the SRS effects [8].

2.2.2 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.

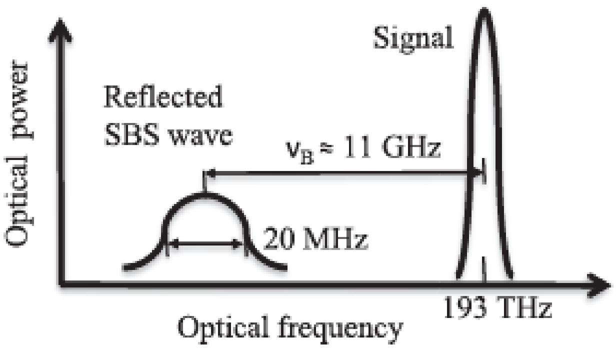

Figure 2.2: The SBS power depletion from the original signals [8].

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.

$$P_{th} \sim \frac{21kA_{eff}}{g_o L_{eff}} \left(\frac{\Delta v_B \Delta v_P}{\Delta v_B} \right) \tag{2.1}$$

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,

Δv_B is the Brillouin gain bandwidth,

Δv_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, Δv_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

REFERENCES

[1] T. Li, “Advances in Optical Fiber Communications: An Historical Perspective,” *IEEE J. Sel. Areas Commun.*, vol. 1, no. 3, pp. 356–371, 1983.

[2] K. Inoue, “Four-Wave Mixing in an Optical Fiber in the Zero-Dispersion Wavelength Region,” *J. Light. Technol.*, vol. 10, no. 11, pp. 1553–1561, 1992.

[3] M. Jinno, T. Sakamoto, J. I. Kani, S. Aisawa, K. Oda, M. Fukui, H. Ono, M. Yamada, and K. Oguchi, “1580-nm band, equally spaced 8x10 Gb/s WDM channel transmission over 360 km (3x 120 km) of dispersion-shifted fiber avoiding FWM impairment,” *IEEE Photonics Technol. Lett.*, vol. 10, no. 3, pp. 454–456, 1998.

[4] M. R. Phillips, K. Y. Wu, and F. X. Villarruel, “Crosstalk and distortion caused by four-wave mixing in a subcarrier-multiplexed WDM lightwave link,” *OFC/NFOEC 2008 - 2008 Conf. Opt. Fiber Commun. Fiber Opt. Eng. Conf.*, pp. 2–4, 2008.

[5] J. D. Marconi, J. M. C. Boggio, and H. L. Fragnito, “Nearly 100 nm bandwidth of flat gain with a double-pumped fiber optic parametric amplifier,” *Opt. Fiber Commun. Natl. Fiber Opt. Eng. Conf.*, pp. 1–3, 2007.

[6] J. M. C. Boggio, C. Lundström, J. Yang, H. Sunnerud, and P. a. Andrekson, “Double-pumped FOPA with 40 dB flat gain over 81 nm bandwidth,” *Eur. Conf. Opt. Commun. ECOC*, vol. 2, no. September, pp. 87–88, 2008.

[7] K. K. Y. Wong, K. Shimizu, K. Uesaka, G. Kalogerakis, M. E. Marhic, and L. G. Kazovsky, “Continuous-Wave Fiber Optical Parametric Amplifier with 60-dB Gain Using a Novel Two-Segment Design,” *IEEE Photonics Technol. Lett.*, vol. 15, no. 12, pp. 1707–1709, 2003.

[8] G. Keiser, *Optical Fiber Communication*, 5th Editio. McGraw-Hill, 2015.

[9] R. Boyd, *Nonlinear Optics*, 3rd Editio. New York: Academic Press, 2008.

[10] Michel E. Marhic, *Fiber optical parametric amplifiers, oscillators, and related devices*. Cambridge University Press, 2007.

[11] J. B. Coles, B. P.-P. Kuo, N. Alic, S. Moro, C.-S. Bres, J. M. Chavez Boggio, P. a Andrekson, M. Karlsson, and S. Radic, “Bandwidth-efficient phase modulation techniques for stimulated Brillouin scattering suppression in fiber optic parametric amplifiers.,” *Opt. Express*, vol. 18, no. 17, pp. 18138–18150, 2010.

[12] M. Onishi, T. Okuno, T. Kashiwada, S. Ishikawa, N. Akasaka, and M. Nishimura, “Highly Nonlinear Dispersion-Shifted Fibers and Their Application to Broadband Wavelength Converter,” *Opt. Fiber Technol.*, vol. 4, no. 2, pp. 204–214, 1998.

[13] R. H. Stolen and W. N. Leibolt, “Optical fiber modes using stimulated four photon mixing.,” *Appl. Opt.*, vol. 15, no. 1, pp. 239–243, 1976.

[14] M. J. Holmes, D. L. Williams, and R. J. Manning, “Highly nonlinear optical fiber for all optical processing\napplications,” *IEEE Photonics Technol. Lett.*, vol. 7, no. 9, pp. 1045–1047, 1995.

[15] C. Floridia, M. L. Sundheimer, L. D. S. Menezes, and A. S. L. Gomes, “Optimization of spectrally flat and broadband single-pump fiber optic parametric amplifiers,” *Opt. Commun.*, vol. 223, no. 4–6, pp. 381–388, 2003.

[16] C. W. Thiel, “Four-Wave Mixing and its Applications,” *Citeseer*, vol. 156, no. 3, pp. 1–19, 2008.

[17] H. Pakarzadeh, “Optimization of two-pump fiber optical parametric amplifiers for broadband flat gain and low pump-to-signal noise transfer,” in *Symposium on Photonics and Optoelectronics, SOPO*, 2012, no. 4, pp. 3–6.

[18] O. Aso, M. Tadakuma, and S. Namiki, “Four-wave mixing in optical fibers and its applications,” *Furukawa Rev.*, vol. 19, no. 19, pp. 63–68, 1999.

[19] J. Hansryd, P. A. Andrekson, M. Westlund, J. Li, and P. O. Hedekvist, “Fiber-based optical parametric amplifiers and their applications,” *IEEE J. Sel. Top. Quantum Electron.*, vol. 8, no. 3, pp. 506–520, 2002.

[20] M. E. Marhic, *Fiber Optical Parametric Amplifier, Oscillators and Related Devices*. Cambridge University Press; 1 edition (December 3, 2007), 2008.

[21] J. Toulouse, “Optical nonlinearities in fibers: Review, recent examples, and systems applications,” *Journal of Lightwave Technology*, vol. 23, no. 11. pp. 3625–3641, 2005.

[22] G. P. Agrawal, *Nonlinear fiber optics*, 3rd Editio. 2001.

[23] R. Stolen and J. Bjorkholm, “Parametric amplification and frequency conversion in optical fibers,” *IEEE J. Quantum Electron.*, vol. 18, no. 7, pp. 1062–1072, 1982.

[24] C. Lundstrom, “Phase-Sensitive Fiber Optic Parametric Amplifiers and Their Applications in Optical Communication,” Chalmers University of Technology, 2012.

[25] M. C. Ho, K. Uesaka, M. Marhic, Y. Akasaka, and L. G. Kazovsky, “200-nm-bandwidth fiber optical amplifier combining parametric and Raman gain,” *J. Light. Technol.*, vol. 19, no. 7, pp. 977–981, 2001.

[26] A. Vedadi, M. Jamshidifar, and M. E. Marhic, “Continuous-wave one-pump fiber optical parametric amplifier with 230 nm gain bandwidth,” *2nd IEEE LEOS Winter Top. WTM 2009*, pp. 231–232, 2009.

[27] K. K. Y. Wong, M. E. Marhic, G. Kalogerakis, and L. G. Kazovsky, “Fiber optical parametric amplifier and wavelength converter with record 360 nm gain bandwidth and 50 dB signal gain,” *Conf. Lasers Electro-Optics, 2003. CLEO ’03.*, pp. 5–6, 2003.

[28] H. Zhu, L. Wang, B. Luo, X. Gao, and Z. Wang, “Bandwidth optical parametric amplifier by using photonic crystal fiber with pump depletion,” in *6th International Symposium on Advanced Optical Manufacturing and Testing Technologies: Optoelectronic Materials and Devices for Sensing, Imaging, and Solar Energy*, 2012, vol. 8419, pp. 32-1-32–5.

[29] P. S. Maji and P. R. Chaudhuri, “Gain and bandwidth investigation in a near-zero ultra-flat dispersion PCF for optical parametric amplification around the communication wavelength.,” *Appl. Opt.*, vol. 54, no. 11, pp. 3263–72, 2015.

[30] K. Inoue, “Arrangement of fiber pieces for a wide wavelength conversion range by fiber four-wave mixing.,” *Opt. Lett.*, vol. 19, no. 16, pp. 1189–91, 1994.

[31] J. Kim, O. Boyraz, J. H. Lim, and M. N. Islam, “Gain enhancement in cascaded fiber parametric amplifier with quasi-phase matching: Theory and experiment,” *J. Light. Technol.*, vol. 19, no. 2, pp. 247–251, 2001.

[32] F. Zhou, M. Zhang, Y. Wang, J. Dai, L. Deng, and D. Liu, “High-efficiency and broadband wavelength conversion in a slot waveguide with the periodic structure altering the phase-mismatch,” *2015 Opto-Electronics Commun. Conf. OECC 2015*, vol. 54, no. 25, 2015.

[33] S. Ono, “Broadened gain characteristics of single-pumped parametric amplifier using highly-nonlinear fibers for transparent optical demultiplexer,” *Proc. 2008 10th Anniv. Int. Conf. Transparent Opt. Networks, Ict.*, vol. 1, pp. 274–277, 2008.

[34] L. Provino, A. Mussot, E. Lantz, T. Sylvestre, and H. Maillotte, “Broadband and flat parametric amplifiers with a multisection dispersion-tailored nonlinear fiber arrangement,” *J. Opt. Soc. Am. B*, vol. 20, no. 7, p. 1532, 2003.

[35] M. E. Marhic, F. S. Yang, M. Ho, and L. G. Kazovsky, “High-Nonlinearity Fiber Optical Parametric Amplifier with Periodic Dispersion Compensation,” *J. Light. Technol.*, vol. 17, no. 2, pp. 210–215, 1999.

[36] J. Gao, Y. Cao, F. Chen, B. Sun, and Z. Hu, “Theoretical and simulation analysis of the fiber optical parametric amplifier (FOPA) with cascaded structure,” in *Photonics and Optoelectronics Meetings (POEM) 2011: Optoelectronic Devices and Integration*, 2011, vol. 8333, p. 83330K–1–83330K–8.

[37] H. Zhu, B. Luo, W. Pan, L.-S. Yan, J.-P. Zhao, Z.-Y. Wang, and X.-R. Gao, “Gain Improvement of Fiber Parametric Amplifier via the Introduction of Standard Single-Mode Fiber for Phase Matching,” *Chinese Phys. Lett.*, vol. 30, no. 7, pp. 1–3, 2013.

[38] X. Zhang and C. Jiang, “Gain characteristics and optimization of dual-pump fiber optical parametric amplifier using two-section highly nonlinear fibers,” *Opt. Laser Technol.*, vol. 39, no. 3, pp. 638–643, 2007.

[39] M. Gao, “Dual-pump broadband fiber optical parametric amplifier with a three-section photonic crystal fiber scheme,” *Proc. SPIE*, vol. 5623, pp. 300–307, 2005.

[40] C. Lundström, R. Malik, L. Grüner-Nielsen, B. Corcoran, S. L. I. Olsson, M. Karlsson, and P. A. Andrekson, “Fiber optic parametric amplifier with 10-dB net gain without pump dithering,” *IEEE Photonics Technol. Lett.*, vol. 25, no. 3, pp. 234–237, 2013.

[41] S. Takushima and O. T, “Supression of the simulated brillouin scattering using optical isolator,” *Electron. Lett.*, vol. 8, no. 12, pp. 1155–1157, 1992.

[42] K. S. Yeo, F. R. Mahamd Adikan, M. Mokhtar, S. Hitam, and M. A. Mahdi, “Gain smoothening filter in two-segment fiber-optical parametric amplifier,” *Opt. Commun.*, vol. 286, no. 1, pp. 353–356, 2013.

[43] H. Zhu, "Gain optimization of one-pump fiber- optical parametric amplifier with optical band-pass filter reducing the idler wave," *Opt. Eng.*, vol. 51, no. 6, p. 64301, 2012.

[44] S. Takasaka, Y. Mimura, H. Matsuura, M. Morimoto, M. Takahashi, and R. Sugizaki, "FOPA with Flat 21-dB Gain and NF less than 4-dB using Alternately Concatenated Pump-Phase Shifters and HNLFs," *Opt. Fiber Commun. Conf. Fiber Opt. Eng. Conf. 2013*, pp. 1–3, 2013.

[45] S. Takasaka, Y. Mimura, M. Takahashi, R. Sugizaki, and H. Ogoshi, "Flat and Broad Amplification by Quasi-Phase-Matched Fiber Optical Parametric Amplifier," *Opt. Fiber Commun. Conf.*, pp. 1–3, 2012.

[46] H. Zhu, B. Luo, W. Pan, L. Yan, S. Xiang, and K. Wen, "Gain enhancement of fiber optical parametric amplifier via introducing phase-shifted fiber Bragg grating for phase matching," *J. Opt. Soc. Am. B*, vol. 29, no. 6, p. 1497, 2012.

[47] S. Takasaka, Y. Taniguchi, M. Takahashi, J. Hiroshi, and M. Tadakuma, "Quasi Phase-Matched FOPA with 50 nm Gain Bandwidth Using Dispersion Stable Highly Nonlinear Fiber," in *Optical Fiber Communications Conference and Exhibition (OFC), 2014*, 2014, pp. 3–5.

[48] J. Hansryd and P. A. Andrekson, "Broad-band continuous-wave-pumped fiber optical parametric amplifier with 49-dB gain and wavelength-conversion efficiency," *IEEE Photonics Technol. Lett.*, vol. 13, no. 3, pp. 194–196, 2001.

[49] H. Nguyen Tan, T. Inoue, K. Tanizawa, S. Petit, Y. Oikawa, S. Takasaka, T. Yagi, and S. Namiki, "Counter-dithering pump scheme for cascaded degenerate FWM based wavelength converter," *Conf. Opt. Fiber Commun. Tech. Dig. Ser.*, pp. 31–33, 2014.

[50] X. Ruihong, C. Yu, X. Sang, and D. Hsu, "Research on QPM and Its Cascaded Structure Applied in FOPA," *Cybern. Inf. Technol.*, vol. 16, no. 5, pp. 50–58, 2016.

[51] M. Xia, Y. Wu, S. Xia, G. Liu, H. Yang, Z. Ping, and T. Wang, "Power Equalization for Non-degenerate Cascaded Phase-sensitive Fiber-optic Parametric Amplifier," *4th Int. Conf. Comput. Sci. Netw. Technol.*, pp. 1236–1239, 2015.

[52] K. Inoue and T. Mukai, "Experimental Study on Noise Characteristics of a gain-saturated fiber optical parametric amplifier," *J. Light. Technol.*, vol. 20, no. 6, pp. 969–974, 2002.

[53] A. Kobyakov, M. Sauer, and D. Chowdhury, “Stimulated Brillouin scattering in optical fibers,” *Adv. Opt. Photon.*, vol. 2, no. 1, pp. 1–59, 2010.