INVESTIGATION OF DUAL-PUMP FIBER OPTICAL PARAMETRIC AMPLIFIER USING HIGHLY NONLINEAR DISPERSION SHIFTED FIBER

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A project report submitted in
Partial fulfilment of the requirement for the award of the
Degree of Master of Electrical Engineering

Universiti Tun Hussein Onn Malaysia

JANUARY 2020

Sincerely dedicated to my beloved Parents and brothers….

ACKNOWLEDGEMENT

First and foremost, I would like to thank Almighty Allah for bestowing His blessings upon me and giving me the strength to carry out and complete this work.

I am extremely appreciated to my supervisor Assoc. Prof. Dr. TAY KIM GAIK, without her guidance and compassionate help, this research wouldn't have been possible. I also would like to thank Dr. NURULANATI BINTI OTHMAN and Dr. ARIFFUDDIN BIN JORET for their kindness help.

I also want to thank my parents who gave me the opportunity to fulfil my beautiful dream that is still yet become successful. They gave me what is good for me and they kept me away what is bad for me. I can't say only thank you because it's not enough for them, I have to say also God bless my Parents.

Last but not least, I would like to thank the University Tun Hussein Onn Malaysia and Faculty of Electrical and Electronic Engineering for giving me this opportunity.

ABSTRACT

Using multi-pump Raman amplifier provides high parametric gain over wide bandwidth with low noise figure (NF). Contrary to Raman amplifiers (RA), fiber optical parametric amplifiers (FOPA) can provide high and flat parametric gain over a bandwidth of tens or hundreds of nanometers with low-noise amplification using only 2 pumps. There are two types of FOPA: FOPA of single pump (1-P) and FOPA with dual pump (2-P). Both types of FOPA can provide adjustable gain and mid-frequency spectra, wavelength conversion, phase conjugation, pulse processing for signal processing and 0 dB noise counting. Furthermore, single pump FOPA had limited parametric gain over wide bandwidth, in addition to the difficulty to obtain an equalized power. To overcome such problem dual-pump FOPA was introduced. Performances of FOPA such as parametric gain, bandwidth, and saturation power, depend on the efficiency of the four-wave mixing (FWM) process. The higher-order dispersion coefficients affect the efficiency of FWM. Thus, this study involves determining the optimum value of the parameters in efforts to improve the spectrum of parametric amplification. The optimum values of the parameters were determined as a fiber length of 500 m, pump power P_1 and P_2 at input 0.75W and 1W respectively and a distance between central and zero dispersion wavelength is 1.63 nm. Meanwhile, the values of β_4 and β_6 are $6.231 \times 10^{-5}\text{ps}^4/\text{km}$ and $1.18 \times 10^{-8}\text{ps}^6/\text{km}$, respectively. When the parametric gain is reduced by 3 dB the saturation power is acquired. Saturation power for λ_s = 1550 nm is -39dBm using the optimized parameters. Saturation power over a span wavelength from 1480 nm to 1645 nm was simulated. It shows when parametric gain increases, the saturation power reduces and vice versa.

ABSTRAK

Menggunakan penguat pelbagai pam Raman memberikan keuntungan parametric yang tinggi ke atas bandwidth yang lebar dengan rajah bunyi bising yang rendah (NF). Bertentangan dengan penguat Raman (RA), penguat parametrik gentian optik (FOPA) dapat memberikan keuntungan parametrik yang rata dan tinggi merentasi bandwidth puluhan atau ratusan nanometer dengan amplifikasi bunyi rendah menggunakan hanya 2 pam. Terdapat dua jenis FOPA: FOPA pam tunggal (1-P) dan FOPA dengan dua pam (2-P). Kedua-dua jenis FOPA boleh memberikan keuntungan laras dan spektrum pertengahan frekuensi, penukaran panjang gelombang, konjugasi fasa, pemprosesan denyutan untuk pemprosesan isyarat dan pengiraan bunyi 0 dB. Selain itu, FOPA pam tunggal mempunyai keuntungan parametrik terhad ke atas bandwidth yang lebar, di samping kesukaran untuk mendapatkan kuasa yang disamakan. Untuk mengatasi masalah tersebut, dua pam FOPA diperkenalkan. Prestasi FOPA seperti keuntungan parametrik, bandwidth, dan kuasa tepu, bergantung pada kecekapan proses pergaulan empat gelombang (FWM). Pekali penyebaran peringkat tinggi menjejaskan kecekapan FWM. Oleh itu, kajian ini melibatkan penentuan parameter optimum dalam usaha untuk meningkatkan spektrum penguatan parametrik. Nilai optimum parameter yang diperolehi ialah panjang gentian 500 m, kuasa pam P_1 dan P_2 pada input 0.75W dan 1W masing-masing dan jarak antara panjang gelombang penyebaran tengah dan sifar ialah 1.63 nm. Sementara itu, nilai β_4 dan β_6 adalah masing-masing $6.231 \times 10^{-5}\text{ps}^4$/km dan $1.18 \times 10^{-8}\text{ps}^6$/km. Apabila keuntungan parametrik dikurangkan sebanyak 3 dB, kuasa tepu diperolehi. Kuasa ketepuan untuk λ_s = 1550 nm ialah -39dBm menggunakan parameter yang dioptimumkan. Kuasa ketepuan sepanjang panjang gelombang dari 1480 nm hingga 1645 nm telah disimulasikan. Ia menunjukkan apabila keuntungan parametrik meningkat, kuasa tepu menurun dan sebaliknya.

TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

LIST OF SYMBOLS AND ABBREVIATIONS

α	Fiber loss
γ	Fiber nonlinearity
$\Delta\beta$	Linear phase-mismatch
λ_{P1}	Pump one wavelength
λ_{p2}	Pump two wavelength
λ_c	Central wavelength
λ_0	Zero dispersion wavelength
λ_s	Signal wavelength
ω	Frequency
ω_0	Zero-dispersion frequency
ω_c	Central frequency
ω_{p1}	Pump one frequency
ω_{p2}	Pump two frequency
ω_s	Signal frequency
β_{2m}	Higher order dispersion coefficients
1-P	One pump
2-P	Two pumps
AI	Artificial intelligent
A_i	Idler amplitude
A_j	amplitude for j$\in\{p_1, p_2, s, i\}$
$A_j{}^*$	Complex conjugate of A_j
A_{p1}	Pump one amplitude
A_{p2}	Pump two amplitude
A_s	Signal amplitude
ASE	Amplified spontaneous emission
CW	Continuous Wave

DSF	Dispersion shifted fiber
DWDM	Dense wavelength division multiplexing
EDC	Electronic dispersion compensation
EDFA	Erbium doped fiber amplifier
EDFL	Erbium doped fiber laser
FOPA	Fiber optical parametric amplifier
FWM	Four wave mixing
HNLF	Highly nonlinear fiber
HNL-DSF	Highly nonlinear dispersion shifted fiber
HODP	High order dispersion parameter
IM-DD	Intensity modulation and direct detection
MPI	Multipath interference
NF	Noise figure
OSNR	Optical signal-to-noise ratio
OTDM	Orthogonal time division multiplexing
PCF	Photonic crystal fiber
RA	Raman amplifier
SPM	Self-phase modulation
WDM	Wavelength division multiplexing
XPM	Cross phase modulation
ZDW	Zero dispersion wavelength

CHAPTER 1

INTRODUCTION

1.1 Background Study

In the 1820s the telegraph was used in communication cable until the telephone invention begun in 1876. The copper wire was used as an electrical conductor, so copper uses electrons to transmit data, while fiber uses photons to transmit data. And we know that light is faster than electrical pulses, so they invented fiber optic cables to transmit more bits of data per second and offer higher bandwidth[1].

To transmit data in fiber optic we need an amplifier to amplify the optical signal. Before optical amplifier, fiber optic uses an optical repeater to regenerate an optical signal. There are many types of optical amplifiers like Laser amplifier, Semiconductor optical amplifier, erbium-doped fiber amplifier (EDFA), Raman amplifier and fiber optical parametric amplifier (FOPA).

The conventional EDFA solutions are able to operate only in C wavelength band (1530 n–1562 nm). This brings to attention to the use of other amplification schemes. Even though S-band EDFA’s (1450 nm–1520 nm) and L-band EDFA’s (1570 nm–1605 nm) exist, the use of multiple EDFA’s is more complex and it can’t provide a combination of flat gain and low noise figure (NF).

It is possible to achieve high gain over a wide bandwidth with low NF by using multi-pump Raman amplifiers. Multi-pump configuration means 2 or more pumps, the number of required pumps increases together with the growth of the gain bandwidth.

Contrary to Raman amplifiers (RA), FOPAs can provide high flat gain over a bandwidth of tens or hundreds of nanometers with low-noise amplification using only 2 pumps. There are two types of FOPA: FOPA with single pump (1-P) and FOPA with dual pump (2-P). Both types of FOPA can provide adjustable gain and mid-frequency spectra, wavelength conversion, phase conjugation, pulse processing for signal processing and 0 dB noise counting. These FOPA advantages exceeded the limitations of conventional amplifiers, that is, RA and EDFA, therefore, were of interest to scientists to study the potential of FOPA beyond the current limit in optical communication systems [2].

In practice, FOPA is required to demonstrate good performance, that is high and flat parametric gain and wide bandwidth. The higher-order dispersion coefficients affect the efficiency of FWM. bandwidth. Parameters such as pump and fiber parameters affect FOPA performance.

1.2 Problem Statement

1-p FOPA has limitation to give uniform gain over the wide bandwidth which makes it difficult to equalize the power of the various channels in wavelength-division multiplexing (WDM) systems. 2-p FOPA which can provide uniform and flat gain over a wide bandwidth seems to surpass the 1-p FOPA. Similar to 1-p FOPA, the performance of the 2-p FOPA is influenced by fiber parameters (fiber length, fiber nonlinearity, fiber loss, dispersion coefficient) and pump parameters (pump power, pump separation, distance of central pump wavelength with zero dispersion wave length). Hence, in this study, the impact of fiber and pump parameters on the performance of the 2-p FOPA of HNL-DSF of OFS company will be investigated. Later, an optimized design of the 2-p FOPA will be proposed. Lastly, the saturation power of the optimized 2-p FOPA will be examined too.

1.3 Objectives

The objectives of this study are:

I. To simulate the parametric gain and amplification bandwidth of dual pump FOPA by varying fiber and pump parameters.
II. To obtain the optimum parametric gain and amplification bandwidth of dual pump FOPA by using optimum fiber and pump parameters.
III. To simulate the saturation power of the dual pump FOPA by using optimum fiber and pump parameters.

1.4 Scope of the Study

The scopes of this study are listed as follows:

- 2-p FOPA of HNL-DSF of OFS company with fiber loss of α=0.82 dB/km, the nonlinearity of γ=11.5 $W^{-1}Km^{-1}$ and ZDW at λ_0=1556.5 nm was used.
- The performance of the above 2-p FOPA will be simulated numerically.
- The numerical simulation will be simulated using a 4-wave model in small-signal and saturation regimes.
- Higher order dispersion up to sixth order will be used.

1.5 Outline of thesis

This thesis is totally organised as follows: In chapter 1. The background of FOPA is described then, the problem statements the objective and the scope of dual pumps FOPA. Literature review related to 2-P FOPA is discussed in Chapter 2. The methodology of this project work is explained in Chapter 3. The result discussion of the research is discussed in Chapter 4. Last the conclusion and recommendation of this research is also discussed in Chapter 5.

CHAPTER 2

LITERATURE REVIEW

2.1 FIBER OPTICAL PARAMETRIC AMPLIFIER

The amplifier is a device that can upturn the signal strength. An optical amplifier is an amplifier using an optical fiber as a means of amplification or gain medium. There are basically three types of optical amplifiers called EDFA, RA and FOPA.

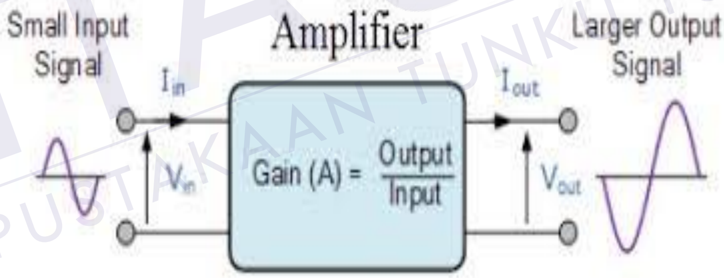

Figure 2.1: Amplifier

Since its invention in the late 1980s, erbium doped fiber have proven to be a versatile system of materials with a wide range of applications, including broadband optical sources, broadband optical amplifiers and tunable lasers. Broadband optical sources have been used in a variety of areas, such as optical characterization, gyroscopes and optical coherence tomography. Spontaneous Enhanced Emission (ASE) in shingle embedded fibers has been used to produce light sources with the advantages of high output power and high bandwidth. EDFA was the first successful optical amplifier and revolutionized the optical communications industry in the early 1990s. Today, it is widely used in all types of fiber communication systems, especially in wavelength multiplexing (WDM) systems. Erbium Doped Fiber Laser (EDFL), one of the most popular fiber lasers, has made tremendous progress in recent years. They have the advantages of good beam quality, widely adjustable wavelength, small size and lower cost etc.[3]. The ability to reduce energy fluctuations along the transmission line is advantageous through the use of distributed amplifiers compared to grouped amplifiers. Therefore, the distributed EDFA design approach differs from achieving efficient active fiber with a gain factor for array gain amplifiers, given that the fiber dispersion varies with the numerical aperture of the fiber.[4].

Sir Chandrasekhar Raman discovered in 1928 the Raman scattering. He describes a process in which optical photons of matter molecules are scattered to a higher wavelength (less energy). The photon excites the matter molecules in a state of high energy (virtual) and then relaxes in the ground state by emitting another photon in addition to the vibrational energy (i.e. acoustically). Due to the vibrational energy, the emitted photon has less energy than the incident photon and therefore a longer wavelength. The Raman catalyst dispersion describes a similar process in which a high wavelength photon stimulates the diffusion process, i.e. The absorption of the primary photons, resulting in the emission of a second photon with higher wavelength and amplification [5]. Raman speakers have some basic advantages. First, there is a Raman gain in all fibers that provides a cost-effective way of upgrading from both ends of the station. Second, the reinforcement is inelastic, meaning that it is available over the entire fiber transparency range of between about 0.3 and 2 meters. The third advantage of Raman amplifiers is that the gain spectrum can be designed by adjusting the wavelengths of the pump. For example, multiple pump lines may be used to increase the optical bandwidth, and the pump distribution determines the flattening of the gain. Another advantage of Raman amplification is that it is a relatively broadband amplifier with a bandwidth of 5 THz and that the gain is reasonably flat over a long wavelength [6] [7] [8]. In an optical transmission system using WDM, the Raman amplifier distributed by WDM for optical amplification effectively reduces noise and extends the gain range. The researcher has developed a numerical simulator to predict the properties of the Raman amplifier in a model, the signal input and output characteristics, noise character and multipath interference (MPI) contains Rayleigh dispersion and non-linear phase shift. When designing a Raman subwoofer, it is crucial to determine the wavelength of the pump and the performance of the pump to obtain the various required properties [9].

FOPAs are multifunctional devices used in a variety of applications, especially in pulse sources, demultiplexers, amplifiers, wavelength converters and telecommunications, where they are used as a complete optical scan. FOPAs have been of great interest in telecommunications applications for the last 20 years. In phase-free or phase-sensitive configurations, it provides instant high gain, high bandwidth and low noise levels near the fundamental limits [10] [11]. FOPA offers very high gain and bandwidth despite being in the same operating style. FOPA offers some unique features compared to other amplifiers. The FOPA amplifier (and the Brillouin amplifier) only increases in one direction [12] [13]. The search for OPA-fiber optics was greatly facilitated by the development of DSFs with a scattering wavelength (ZDW) of approximately. 1550 nm in band C. This allowed the use of various fiber components developed for communication systems. In 1995, a non-linear DSF was developed, which increased approximately. 10 times reducing the core diameter and increasing the concentration of germanium. Since the ratings are high (linearity ratio a to attenuation ratio a), these are highly non-linear DSFs (HNL-DSF or HNLF only).

Since then, fiberglass has remained the preferred medium for experimental studies focusing on communication with OPAs [14].

2.1.1 Single-pump FOPA

FOPA is classified into two forms: single-pump FOPA (1-P) and dual-pumps (2-P). The FOPA 1-P, where the pump wave is applied to the fiber, is a simple model and is mainly used to amplify optical signals. The FOPA gain spectrum is strongly dependent on the fiber scattering properties, particularly the ZDW position for the pump wavelength. In addition, changes in operating parameters such as temperature cause average and large variations in ZDW. For example, it was reported that HNLFs used primarily for the FOPA project can have ZDW variations of up to 1 nm / 100 m.

and therefore, the importance of phase adaptation [15]. One-pump FOPA has the advantage of cost and complexity. It is therefore interesting to improve the profits of one FOPA. Further efforts are needed to improve its profitability and thus improve the functioning of FOPA [16].

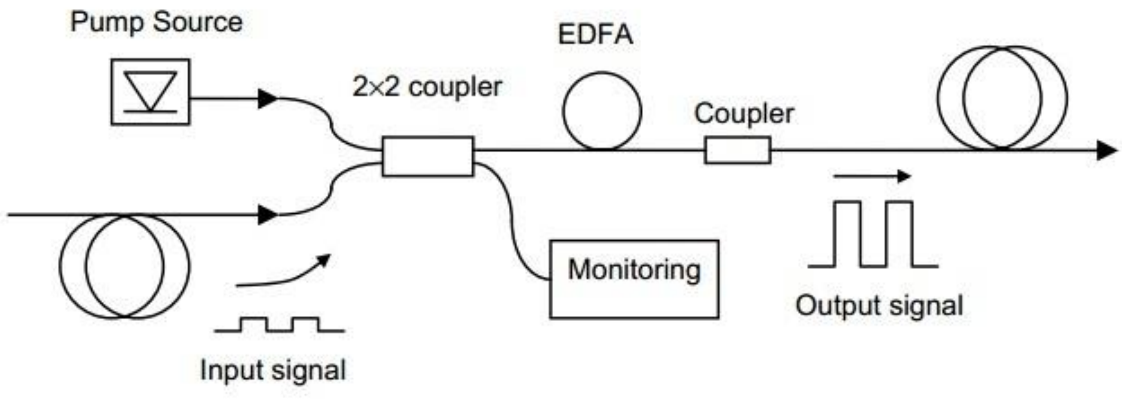

Figure 2.2: Single pump[17].

2.1.2 Dual-Pump

The parametric amplification with two pumps in quartz fibers is based on uninterrupted FWM, when two powerful pumps with angular frequencies ω_{p1} and ω_{p2} are supplied to HNLF together with the signal at assumed values of ωs to be on the inner band of two pumps [18]. Most FOPA molecules with two pumps use two continuous pumps located at a wavelength of 40-50 nm, but located almost symmetrically around the wavelength of zero fiber radiation. The main advantage of FOPA with two pumps is that they can offer a similar mechanical gain with a much wider bandwidth than is possible with FOPA with one pump. In this case, an almost identical gain in the spectrum between the pumps is obtained. The pump power required for such FOPA is high (100 mW). However, the amount of energy pumped through the fiber is limited by the stimulated Brillouin scattering (SBS). Because SBS has a narrow gain spectrum (100 MHz bandwidth), it is possible to raise the SBS threshold above the required pump power level by extending the pump spectrum to more than 1 GHz [19]. As shown in Figure 2.3, the FOPA 2-P assembly, wherein pump 1 and pump 2 are connected to each other by a fiber coupler (FC).

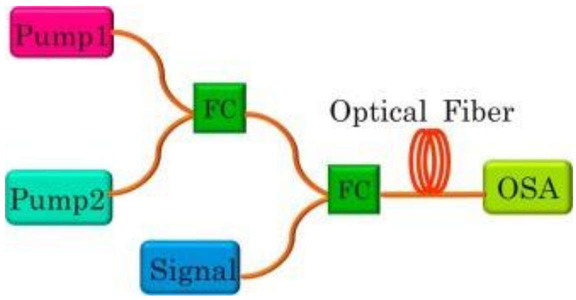

Figure 2.3: Dual pumps

2.1.3 The analytical gain for both single-pump and dual-pump FOPA

With a single pump, the parametric gain G is obtainable by considering the signal and the inactive waves. This is given by:

$$G = 1 + [\frac{\gamma P_p}{g} \sinh{(gL)}]^2 \tag{2.1}$$

Where γ is the nonlinear coefficient, P_p is the pump power, g is the gain coefficient and L is the fiber length, the gain coefficient g is expressed by:

$$g = \sqrt{(\gamma P_p)^2 - (\frac{k}{2})^2} \tag{2.2}$$

And the whole disagreement of the phase [20]. k is given by:

$$k = \Delta\beta + 2\gamma P_p \tag{2.3}$$

For dual pumps, the parameter gain G can be obtained also by considering the signal and the inactive waves. This is given by:

$$G(\omega_3) = [1 + \left(\frac{1 + K^2}{4g^2}\right) sinh^2(gL)] \times e^{-\alpha L} \tag{2.4}$$

If g is defined as:

$$g^2 = 4\gamma^2 P_1 P_2 - \left(\frac{K}{2}\right)^2 \tag{2.5}$$

Here, K is the standard phase adaptation, and the parameter gain is determined by the phase adaptation condition of the given phase.

$$\mathrm{K} = \Delta\beta + \gamma(P_1 + P_2) \tag{2.6}$$

2.1.4 Amplification Bandwidth

The ability of EDFA is the ability to amplify signals over a single band length makes it possible to use signals to operate outside of existing bands in Group C and group L. The wavelength from which the signal is extended and the parametric gain decreases by 3 dB from the maximum gain is called 3 dB bandwidth and is shown in figure 2.4. the Broadband optimization also increases its level. There are several ways to increase the amplification bandwidth of the flatness of FOPA [21]. For example, instead of using one pump (1-P FOPA), FOPA can operate two pumps (2-P FOPA).

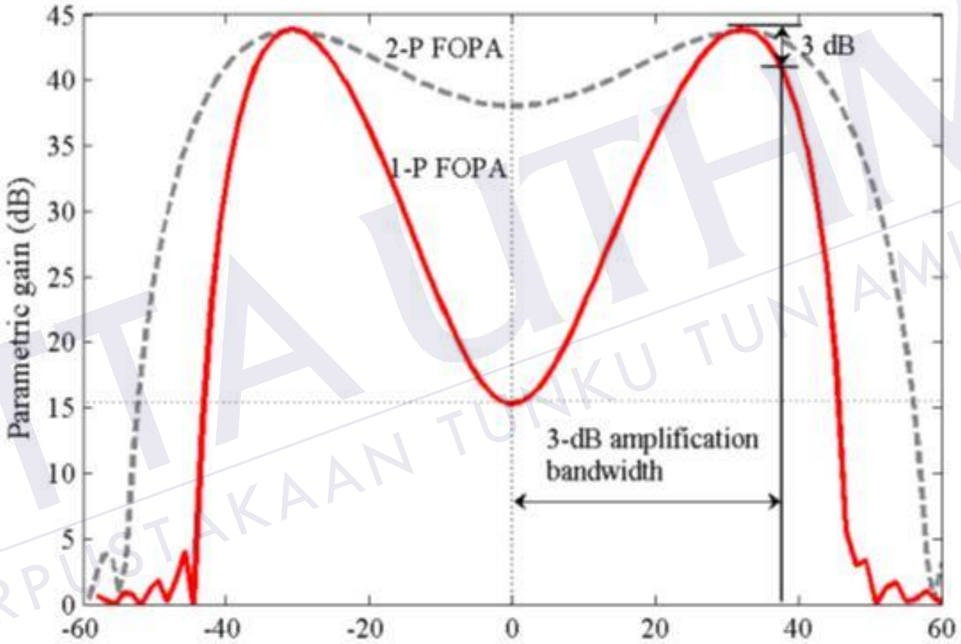

Figure 2.4: Single and Dual pumps FOPA[21]..

2.1.5 Gain Medium

Laser medium is a powerful (also known as a laser generator or gain medium or amplifier), a laser source for optimum efficiency. By expanding or breaking the benefits of the power grid leading to the low energy area, the maximum energy efficiency is increased. Recommend a powerful laser system for distributing the camera to make the energy transfer known as non-human. This condition is called the strength of external sources and laser treatment. Therefore, the current pump is electric (for example, Semiconductor or gas from a high voltage source) or light from a semiconductor lamp. Broadband amplifiers, with high frequency response, are characterized by high power radio frequency.

In addition, for the research and development of fiber optic FOPA, especially DSF 100-band ZDW, which is approximately 1550 nm from 1995, the fundamental basis of DSF and stress. many in general. In the minerals of the upper and lower quartile, most of the germanium is yet to be produced. of silica-DSF development of HNL-DSF, as well as pipelines developed for high degree of compatibility operating in the FOPA environment. For many layers of microstructure in two, two silicate leaves, photonic crystal fiber (PCF), fiber Although many of these filament fibers, contribute to the presence of DSF HNL-DSF. FOPA usage information is suitable for low weight, dietary methods and is easy to appreciate in its structure. More importantly, in terms of the use of chromatic genes, dispersion can easily become HNLDSF for a period of time [9].

2.1.5.1 Efficiency of the gain medium

The efficiency of gain medium can be explained.

$$E = \frac{I_s G}{I_p A} \tag{2.7}$$

In the same model you can show the efficiency as follows:

$$E = \frac{\omega_s}{\omega_p} \frac{1 - V/p}{1 + U/s} \tag{2.8}$$

For optimum power, the pump and signal should be higher than the saturation force.

$$\frac{p}{V} \gg 1, \text{ and } \frac{s}{U} \gg 1 \tag{2.9}$$

The formula above is useful for paint, which is often filled with bombs and reflects light. Spontaneous combustion can be minimized because some areas are well pumped but the pumps do not oxidize via signals during current sample flow disturbances.

2.2 Nonlinearities in Optical Fiber

The nonlinearity of the strands was first proposed in 1996, when materials had a negative nonlinear coefficient, which was less practical, so the Electronic Dispersion Compensation (EDC) allowed us to use this idea. Most studies have influenced the receiver's EDC to increase the fiber throughput to reduce nonlinearity and increase system efficiency. Fiber volume can be increased by increasing the OSNR, reducing channel spacing, or by setting more modulation modes. Nonlinearity arises as a result of the introduction of WDM systems, and since then continuous efforts have been made to reduce or eliminate these penalties [22].

WDM works by combining and sending multiple signals at different frequencies in a single high-quality WDM fiber optic system, which is required to achieve the desired result. Some external factors affect the performance of a nonlinear WDM system. Therefore, the two main factors that impair the performance of optical communication systems are fiber propagation and non-linearity, which limits system throughput. The major nonlinearity in the refractive index is a four-wave mixture, which is an intermodulation phenomenon. The principle of FWM is to create multiple wavelengths through two mutual lengths [23].

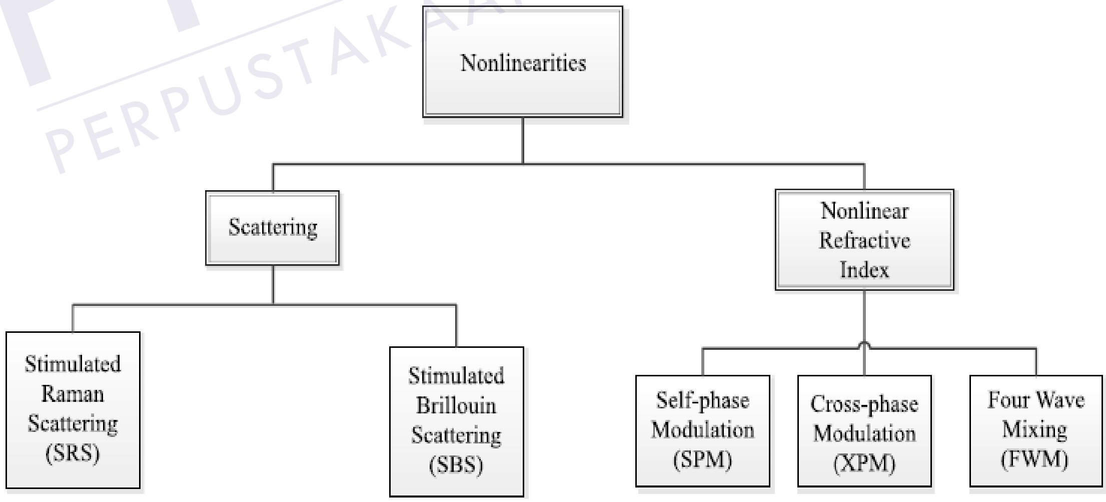

Figure 2.5: Nonlinearity[23].

2.2.1 SPM

Self-phase modulation (SPM) is a non-linear optical effect on the impact of light materials. When light pulses are very short, because they move average, the change in refractive index of the environment stimulates the light effect of the deaf. This change in the refractive index leads to a change in the pulse phase, causing a change in the pulse frequency spectrum. Changing the degree of self-calibration has a significant impact on optical systems that use short and weak pulses, such as optical and laser communication systems. Nonlinear acoustic wave propagation in thin biological layers has also been reported when the modulation of fading is due to the different elastic properties of the fat layers [24].

2.2.2 SPM Frequency Shift

For an ultrashort Gaussian pulse and constant phase, the time intensity is I (t)

$$\mathrm{I}(t) = \mathrm{I}_0 \exp\left(-\frac{t^2}{\tau^2}\right) \tag{2.10}$$

where I0 is the maximum intensity, and τ is healthy with respect to the momentum. When pulsating in the middle, the Kerr optical effect causes a sharp change in the refractive index.

$$\mathrm{n}(\mathrm{I}) = \mathrm{n}_0 + \mathrm{n}_2.\mathrm{I} \tag{2.11}$$

where n0 is the linear refractive index, and n2 is the second-order nonlinear refraction. You can apply impulses to respond, intensity to create or stretch in time, and then shake off when prompted by a passage. This will produce a refractive index of the variable care over time.

$$\frac{\mathrm{dn(I)}}{\mathrm{dt}} = \mathrm{n}_2\frac{\mathrm{dI}}{\mathrm{dt}} = \mathrm{n}_2.\mathrm{I}_0.\frac{-2\mathrm{t}}{\tau^2}.\exp\left(\frac{-\mathrm{t}^2}{\tau^2}\right) \tag{2.12}$$

The refractive index can be changed by changing the instantaneous phase of the pulse.

$$\emptyset(\mathrm{t}) = \omega_0\mathrm{t} - \mathrm{kz} = \omega_0\mathrm{t} - \frac{2\pi}{\lambda_0}.\mathrm{n(I)L} \tag{2.13}$$

where a pulmonary wave (vacuum) is spread and distributed, the pulse and care distance spread the pulse.

A change in phase causes a change in heart rate. Then the instantaneous frequency ω (t) is equal to

$$\omega(t) = \frac{d\phi(t)}{dt} = \omega_0 - \frac{2\pi}{\lambda_0} . \frac{dn(t)}{dt} \tag{2.14}$$

and the above equation for dn / dt

$$\omega(t) = \omega_0 + \frac{4\pi L n_2 I_0}{\lambda_0 \tau^2} . t . \exp\left(\frac{-t^2}{\tau^2}\right) \tag{2.15}$$

Graph ω (t) of the change in the frequency of change before the parts of the pulse. The lower limit deactivates the lower frequencies ("red" waves of the lungs), the trailing edge controls higher frequencies ("whiter"), and the tip of the pulse does not change. For the middle part of the pulse (between t = ± τ / 2), you can change the relatively linear frequency (tweet) after

$$\omega(t) = \omega_0 + \alpha . t \tag{2.16}$$

where α

$$\alpha = \frac{d\omega}{dt}|_0 = \frac{4\pi L n_2 I_0}{\lambda_0 \tau} \tag{2.17}$$

Obviously, additional frequencies generate SPM, expanding the frequency spectrum of the symmetrical pulse. In the time domain, changing in time, but in no real medium that simultaneously does not affect dispersion effects, can be seen in Figure 2.6 [25].

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