ARTICLE

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Analysis and Evaluation of Different Compensation Techniques for Fiber Losses

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تقييم وتحليل طرق تعويض تقنيات خسائر الالياف البصرية المختلفة

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ABSTRACT

The Linear and nonlinear effects in optical fibers are very important and influential factors that effect on the power of the signal transmitted within the optical fiber. In this paper, the mathematical model for these effects was presented. The most important methods used to compensate these losses were also reviewed. The compensation methods reviewed include various linear and nonlinear effects most of the methods reviewed focused on increasing the length of the optical fiber to transmit the signal with the least consumed power and high data transfer rate at low design cost.

Key words:

optical fibers , cross phase modulation , four wave mixing.

الخلاصة

تعتبر التأثيرات الخطية وغير الخطية في الألياف الضوئية من العوامل المهمة جدًا والمؤثرة التي تؤثر على قوة الإشارة المنقولة داخل الألياف الضوئية. في هذا البحث تم عرض النموذج الرياضي لهذه التأثيرات. كما تم استعراض أهم الطرق المستخدمة لتعويض هذه الخسائر. تتضمن طرق التعويض التي تمت مراجعتها تأثيرات خطية وغير خطية متنوعة ، حيث ركزت معظم الطرق التي تمت مراجعتها على زيادة طول الألياف الضوئية لنقل الإشارة بأقل طاقة مستهلكة ومعدل نقل بيانات مرتفع بتكلفة تصميم منخفضة.

الكلمات المفتاحية:

ألياف ضوئية ، تضمين الطور المتقاطع ، خلط اربع موجات .

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1-INTRODUCTION

1) Non- Linear impirments in optical fibers

There are descrption of the two different types of nonlinearities in optical fibers. The optical Kerr effect is caused by fluctuations in the refractive index with optical power, and the first is stimulated scattering (Raman and Brillouin) as shown in figure (1). The nonlinear refractive index of materila causes the power dependent of the phase shift for the optical signal, whereas stimulated scatterings cause the intensity dependent gain or loss. [1]

The threshold energy output at which the nonlinear effects exhibit themselves in stimulated scatterings are dissimilar from those in the Kerr effect, which does not. This is a critical distinction between scattering effects and the Kerr effect.

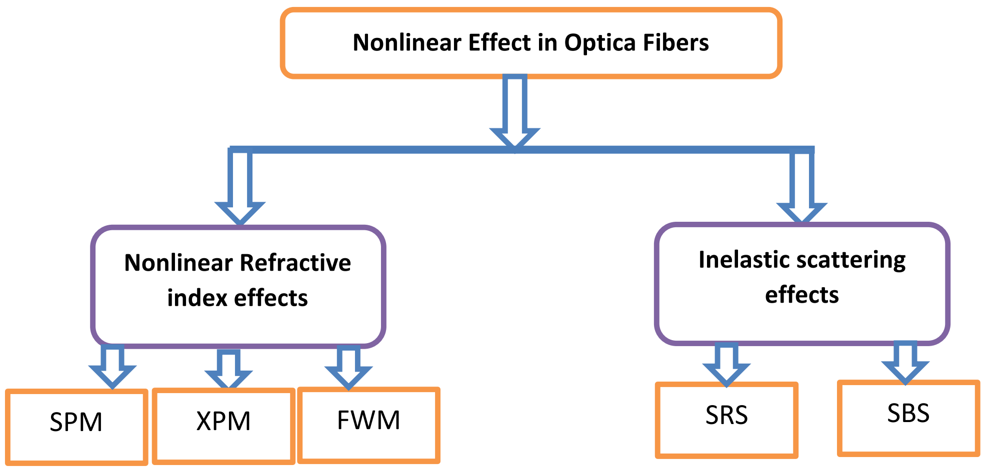

Figure 1 block digrame of fiber nonlinearties

a) Light Kerr Effect in optical fiber

Silica fiber's refractive index for optical systems has a weak relationship with optical intensity and is provided by [2]

$$n = n_0 + n_2 I(t) \qquad (1)$$

Where i(t) optical internsity, n_0 refractive index , n_2 nonlinear refractive index

In modern optical fiber systems, the refractive index is no longer unimportant despite being a very minor function of signal power due to increased power from optical amplifiers and vast transmission distances. In fact, identity modulation (SPM), bridge modulation (CPM), and

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multiple mixing are some of the nonlinear effects caused by phase modulation caused by intensity dependent refractive index (FWM).

i) Self phase modulation

Self-phase modulation (SPM) is a nonlinear optical result of the interaction between light and matter. Due to the optical Kerr effect, an ultrashort pulse of light will cause the medium's refractive index to change while it travels across it. [1] The pulse's phase will shift as a result of this fluctuation in refractive index, changing the pulse's frequency spectrum. [3]

Silica's index of refraction depends only very weakly on intensity. so that it has the form and the index , where the result of self-phase modulation is depicted as a change in the optical pulse's phase as a result of the refractive index change brought on by the pulse's intensity. The optical Kerr effect is what causes the medium's fluctuating refractive index . The pulse's frequency spectrum changes as a result of the phase shift brought on by changing the refractive index. The description of this refractive index change is

$$n = n_0 + n_2 \frac{P}{A_e}. \quad (2)$$

For silica fibers, the coefficient n_2 is $2.6 * 10^{-20}$ m^2/W. This figure accounts for the polarization state of the light averaging out as it passes through the fiber. For light

$$\Phi_{NL} = \gamma P L_e, \quad (3)$$

travelling in a fiber of glass, the nonlinear contribution to the index of refraction causes a phase change. [4]

where we have defined the nonlinear coefficient

$$\gamma = \frac{2\pi n_2}{\lambda A_e}.$$

When an optical fiber carries an intensity-modulated signal, SPM happens. The peak of a pulse moves more slowly (or more rigorously, collects phase more fast) than the wings because of the nonlinear index of refraction. When accounting for fiber loss with effective length and neglecting dispersion, the nonlinear phase shift brought on by SPM on the propagating field is determined.

$$\emptyset_{NL}^{SPM}(L) = \frac{2\pi}{\lambda}\tilde{n}_2 |E|^2 L_{eff} = \gamma P L_{eff} \quad \mathbf{(4)}$$

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where P is the power of the propagating wave.

Dispersion must be considered, especially for data signals, and in this case, the NLSE needs to be numerically determined.

ii) Cross phase modulation

When the phase change of one beam is impacted by the intensity of another beam, this phenomenon is known as cross .phase modulation. It is essentially the shift in a light beam's optical phase brought on by contact with another beam in a nonlinear medium, more precisely a Kerr medium. Cross-phase modulation is another way in which intensity fluctuations impact the phase of a signal . In this instance, the WDM system's other channels' modulation is what causes the intensity fluctuations that are to blame.This can be explained by a change in the refractive index of [5]

$$\Delta n(\lambda_2) = 2n_2 I(\lambda_1)$$

In 1985, there was a first experimental confirmation of CPM. In WDM systems, XPM takes place and uses a similar principle to SPM. In this instance, changes in optical power in a WDM channel are transformed into changes in phase in other copropagating WDM channels. XPM giving as

$$\frac{\partial E_1}{\partial z} = j\gamma[P_1(z,t) + 2\sum_{i=2}^{M} P_i(z,t)]E_1 \quad (5)$$

The SPM contribution is shown by the first term in the equation, while the XPM effect is shown by the second term. For a given power, the factor 2 in the XPM expression demonstrates that XPM has a twice as large impact as SPM.

iii) Four wave mixing

A scattering mechanism known as four-wave mixing (FWM) is thought to involve the mixing of three photons to produce a fourth wave. This occurs when the four waves' momenta meet the requirement for maximum power transfer, often known as phase-matching. [6]

When interactions between two or three wavelengths produce the formation of one or two new wavelengths, this phenomenon is known as four-wave mixing (FWM) in nonlinear optics. It is comparable to the third-order intercept point of the electrical system. The intermodulation distortion in conventional electrical systems can be compared to four-wave mixing. [7]

When two or more light frequencies (or wavelengths) are sent via a fiber simultaneously, FWM develops. The power from the original frequencies is used to generate a new frequency of light, provided that the phase matching requirements are met.

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If we suppose the two co-polarized co-propagating fields, E_1 and E_2 with frequencies f_1 and f_2 and propagation constants β_1 and β_2 in the optical fiber produces an intensity beating at frequencies $f_2 - f_1$ which leads to variation in the refractive index due to the Kerr effect.

The phase matching condition is the requirement that k1 + k4 = k2 + k3, which can be simplified to the requirement that zero GVD frequency needs to be at the center of the four waves by expanding the wave vectors kj near the center of the four frequencies. [8]

The dispersion at the center frequency should be a little out of the ordinary when the nonlinear phase shift is taken into consideration. Non-degenerate FWM processes feature optical fields oscillating at distinct frequencies, whereas degenerate processes involve two fields oscillating at the same frequency.

If we take the three waves as shown in figure 2.7, new fields are generated at frequencies,

$$f_{jkl} = f_j + f_k - f_l \quad (6)$$

The non-degenerate FWM processes, $j, k, l \in \{1,2,3\}, j \neq k, j \neq l, k \neq l$ and the degenerate FWM processes $j, k, l \in \{1,2,3\}, j = k \neq l$ create three unique new frequency fields each

2) Compensation Techniques for Optic Fiber losses

Non-linear effects such as self-phase modulation(SPM), cross-phase modulation(XPM) and four wave mixing (FWM) are considered to be destructive in fiber optic communication. These effects are present in optical fiber however, they can be compensated to reduce their effect during transmission. The techniques used are either DSP techniques in the electrical domain or optical domain. In this report, selected compensation techniques are explained for the three Non Linear Effects. [9]

- **Compensation of Self-Phase Modulation (SPM)**

Recent developments and enhancements of optical fibers have completely disrupted the landscape of the area of communication, in which, the optical fibers are essential components. The physical process of complete internal reflection is responsible for the transmission of light via optical fibers in a controlled manner. Even if there are losses that are certain throughout the transmission, they losses are greatly decreased using silica fibers, as well as developments in fabrication technology [1]. The perspective from self-phase modulation in optical fibers that have anomalous chromatic dispersion may be compensated for by the dispersion, and this may result in the creation of solitons. Despite the SPM effect, the spectral width of pulses does not change during propagation when basic solitons are present in a lossless fiber. This is the case even though the SPM effect. One significant aspect in which the Optical Phase Conjugation technique diverges from all previous dispersion-compensation strategies is the fact that, given the right set of circumstances, it is able to concurrently compensate for both the group velocity dispersion (GVD) and the SPM. In

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addition, it is not difficult to demonstrate that when there are no fibre losses, the SPM and GVD are properly compensated. This is the case even when there are no fibre losses. [10]

There are some ways to compensate the SPM:

A. Utilization of Anomalous Dispersion in Nonlinear Optical Communications Systems: A negative frequency chirp is created by an anomalous dispersion of group velocity in fibers. The frequency with positive chirp brought about by SPM has been balanced out by the frequency with negative chirp brought about by GVD. Optical systems can minimize self-phase modulation with the correct group velocity dispersion. Together, self-phase modulation and anomalous group velocity dispersion enhance the performance of the system [2].
B. By using a negative nonlinear index of refraction with the help of a LiNbO3 electro-optic phase modulator, this method is a straightforward, all-fiber approach to lowering nonlinear phase that is brought on by self-phase modulation in fiber-based chirped-pulse amplification (CPA) systems. This is accomplished by reducing the amount of fiber that is used in the method [3].
C. Utilizing an electro-optic for phase modulator for the reason of altering the phase of the pulses. Such technology mimics the usage of negative refraction nonlinear index material, has proven effective within the fiber-optic in addition to the free-space based optical communications utilizing phase-shift keying system with nanosecond pulses that owns a large peak power. As input pulses, this approach utilizes Gaussian or hyperbolic secant pulses with conventional intensity profiles. Using a basic sinusoidal drive signal with the correct amplitude and frequency for the phase modulator is sufficient to reduce the nonlinear effect. This method have been demonstrated in Fig. 2 [4].

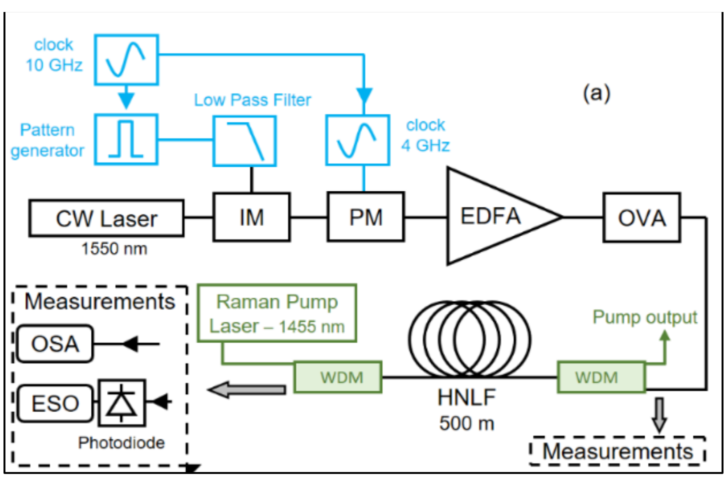

Figure 2: Experimental setup for electro-optic for phase modulator for SPM Compensator [11].

D. The SPM is decreased with the aid of the Mach Zehnder Modulator so that the signal can be transmitted without error. This method works up to 50 kilometers. The SPM then decreases, although the eye height is greater than at 50 kilometers. Because Narrow Eye Height necessitates greater Crosstalk, and vice versa. As input power increases, eye height decreases. Then, SPM is decreased with the aid of MZM, the optimal value of input power, and various fiber lengths, such as 50 km, 60 km, 70 km, and 80 km, which result in varying BER, Q-factor, and Eye Height values. This method is shown in Fig. 3.

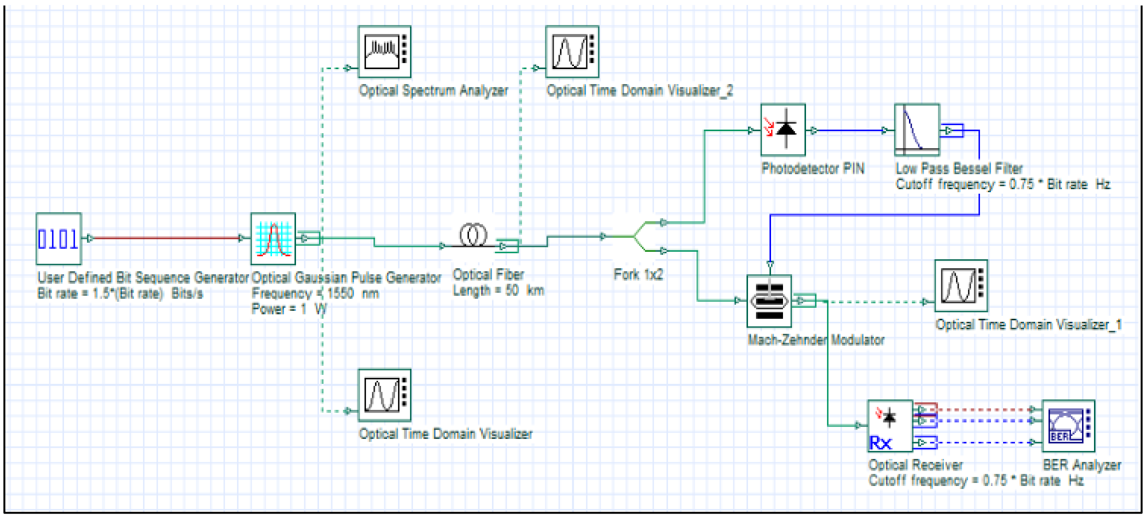

Fig. 3: Installing a Mach-Zehnder modulator to decrease the SPM effect [4].

E. Midspan Optical Phase Conjugation can be utilized to simultaneously manage SPM. Despite the fact that the SPM produces soliton pulses, the individual effects have been utilized in significant ways regarding the pulse compressing, passive mode-locking, pulse amplifying and high speed optical switching. The midspan technique is depicted in Fig.4.

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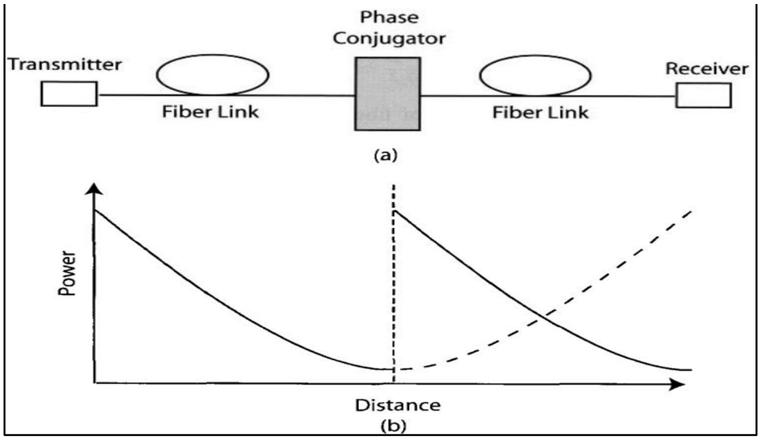

Fig. 4: (a) A diagram illustrating how midspan phase conjugation can be utilized to address dispersion. (b) Variations in fiber link power resulting from an amplifier that improves signal intensity at the phase conjugator. The dashed line is how the power profile should appear for SPM adjustment [8].

- **Compensation of Cross Phase Modulation (XPM)**

The ability to reduce optical channel linear and nonlinear effects limits optical communications system capacity. Digitally rectifying linear impairments is easy, while fiber nonlinearity is harder to control. Cross-phase modulation (XPM), an inter-channel degradation produced by a joint wavelength division multiplexed (WDM) links, it is the boundary constant once the next-generation systems are considered [5].

Optics and electronics can correct the nonlinearity distortions of the fiber. Digital back propagation (DBP) is an effective compensation approach for nonlinearity, symbolized as NLC for non-linear compensation in the direct link communications. Due to the signal-ASE interaction, DBP cannot fully adjust for nonlinearity. Endspan approaches like DBP cannot accurately adjust XPM networks due to NLC methods requires knowledge regarding the wave at each point within the channel, which is impossible when the channels are combined then dropped. Distributed NLC with several compensators along the link overcomes these restrictions. In an optical routed based networks with minimum one NLC amongst the switching nodes, periodic compensator would work.

Compensating XPM inline may occur by periodical delay dispersion modules. This method causes considerable walk-off between adjacent channels, reducing XPM accumulation in the channel. In recent years, inline NLC can happen using optical phase conjugators is suggested [5]. However, the compensation methods have been listed as follows:

A. XPM influence is mitigated via launching variant channels that own orthogonal state of polarization (SOPs). When one channel has been transmitted via the fiber, the state of polarization (SOP) is controlled using a straightforward method that is frequently used in actual practice. To be more exact, individual channels are broadcast in such a way that any two channels that are adjacent to one another are polarized in the opposite direction. In actual reality, channels with even numbers and channels with odd numbers are added together, so their own SOPs have been constructed as orthogonal before wise being transmitted across the fiber network. The polarization channel interleaving technique is another name for this method occasionally used to refer to this scheme. The XPM interaction that occurs between two polarizations that are orthogonal to one another does not disappear, but its strength is greatly diminished. When adjacent links of WDM have been polarized orthogonally, a reduction in the XPM intensity is what brings about an improvement in the system's performance since it brings the XPM-induced phase shift down to a more manageable level.

B. Correcting noise of inter-channel phase that is by occupied via the XPM requires the use of optical injection locking, which is abbreviated as OIL. In this technique, a residual carrier is turned into a local oscillator for a homodyne receiver by using an injection lock. The locking happens quickly enough to account for the phase distortion, however, in slowly pace to disregard the bands that have been only slightly distinct of the pilot signal. At the destination, the receiver is able to cancel out some of the XPM because it is the same for both signals and the pilot [6].

C. In WDM, one simple solution to decrease the effect of XPM is to combine the receiver-side phase recovery technique with split NLC technique. Within such context, split NLC method has a potential to stop the nonlinear phase noise (NLPN) from developing into a nonlinear interference noise (NLIN) with Gaussian style. This reduces signal's sensitivity to the XPM, and when added together with phase recovery method, it may correct the NLPN, and further reduces signal's sensitivity. [7].

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D. In dispersion controlled optical fiber networks, the perturbation theory based digital compensation strategy is developed to address XPM aberrations. It is receiver-side system which utilizes the perturbation approach in order to make data estimations to compute XPM. Split-step Fourier approach based intra-channel DBP is utilized to get rid of any nonlinear channel distortions that may exist before to the hard-decision unit. It has been found that the perturbation method is successful at reducing the amount of XPM distortions. However, when incorrect estimates are utilized to make a tough decision, it can be quite dangerous [8].

- **Compensation of Four-Wave Mixing.**

A. Highly nonlinear fiber (HNLF) with Laser. FWM compensator that has been proposed is installed directly towards the receiver. Such compensator shifts signals wavelengths as well as FWM component wavelengths, which are created within the fiber towards another wavelength region in comparison to the laser wavelength. In addition to that, a great number of newly created FWM components can be found inside of this FWM compensator [9].

However, because of the π/2 phase generated extra delay that occurs in each FWM step, the new produced FWM components have been put of phase when compared to the components formed within the fiber. As a consequence of this, the FWM components that are formed in the transmission fiber might be able to be compensated for by FWM units that are produced in the compensator. It was demonstrated that the use of this method could successfully increase the bit-error rate of the WDM waves as well as correct for FWM crosstalk that was produced within the fiber. The FWM process results in a phase delay that is π /2 longer than normal. In order to compensate for the FWM, it was made use of such extra phase delay [9]. After the transmission, the FWM components (S3 and S4) shown in Fig. 1(a) are generated on two sides of the WDM waves (S2,S1) shown in the Fig. 4. Such signals as well as the FWM units (S1 to S4) have been transmitted towards FWM compensator, which is comprised of pump laser and HNLF. The former works in precise manner at the frequency of HNLF known as zero-dispersion wavelength. The compensator flips wavelengths S1to S4 so that they rely on the other side of spectrum from the pumping wavelength. In addition, a great deal of the FWM's components, such as P1, P2, have been generated as new, as shown in Fig. 5(b). Therefore, the spectral units C1 to C4 are made up of units S1 to S4 that have had their wavelengths converted, as well as the new produced FWM units at the respective wavelengths.

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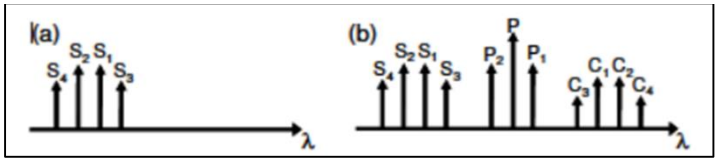

Fig. 5: Optical spectrum (a) input (b) output regarding some methods to compensate the FWM. [6]

B. The use of optical code division multiple access (OCDMA). FWM signals are known to appear when signal strength causes a change in the optical fiber's refractive index. The phases of the signals shift when index is changed, resulting in intermodulation for the frequencies fi, fm, and fn. If center frequency FWM unit falls for the current channels bandwidth of the receiver, interference will happen with the desired waves. However, prior to this solution, other researcher attempted to mitigate impact of FWM penalty. Ramprasad et al. proposed alternate method to circumvent the crosstalk of FWM using this technology (OCDMA) by relocating any frequency to spacings that are unequal and equal, dictated by optically distributed code. According to the outcomes, the FWM crosstalk power gradually improves as the input power of the channel increases [10].

C. Fig. 2.10: shows how to use two channels. (Except where it's shaded.) The FWM compensator method is shown in the inset of Fig. 5, and it is made by combining a pump laser with a one-kilometer-long HNLF. Also, three different modulated WDM signals are used to test how well the proposed FWM compensator works (i.e., shaded area included in Fig. 2.10).

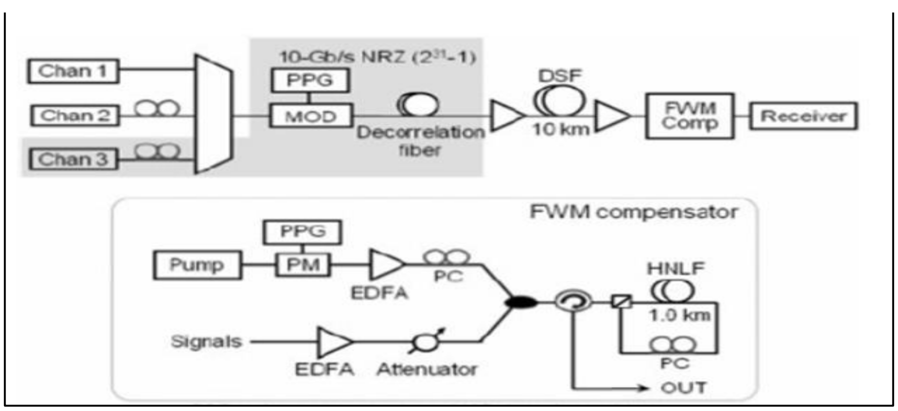

Fig. 6: Experiment design: PC: Polarization, PM: phase modulator, MOD: intensity modulator, PPG: pulse pattern generator. [7]

D. Utilizing a relatively compact fiber-optic parametric amplifier In recent years, fiber-optical parametric amplifiers, also known as OPAS, have been increasingly popular for use in optical communication systems in order to eliminate FWM crosstalk, which could lead to a WDM system with a broad gain spectrum. It was hypothesized that utilizing fiber, where the length of the fiber is decreased from 340m to 50m and power is raised to maintain 20dB gain, could mitigate the FWM crosstalk effect. Utilization of the suggested optical parametric amplifier comes with the advantage of being able to prevent FWM crosstalk [10].
E. WDM and TDM are combined into a single approach here. The fact all channels have been separated in the domain of frequency by same distance is the primary advantage that the suggested hybrid TDM/WDM system possesses. The twelve channel that make up the system are all separated by the same amount of physical space.

Utilizing a combination dispersion correction fiber and fiber brag grating module that saves money is an excellent method to achieve this. In conjunction with its suppression mechanism, this method exhibits FWM nonlinearity. At high FWM powers, there is the maximum nonlinearity, but at low FWM powers there is little nonlinearity. Several FWM degradation strategies have been proposed thus far, however they are not very effective and are quite costly, such as the phase conjugator. This method prevents FWM by employing an economical FBG with uniform chirping and tanhapodization. Additionally, a single tanhapodized FBG, a conventional FBG, and a module with both a DCF and an FBG were compared [11].

5. Conclusions

The most influence linear and non-linear losses compensation methods have been reviewed in this paper. the concluded results obtained from review the most compensation methods, that the optical phase conjugation is the preferred in terms of low power consumption and low design costs, in addition to the simple manufacturing process, as well as ease of implementation, so it can be used in optical fiber applications in the field of communications and the medical field.

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