EFFECT OF DISPERSION AND FIBER LENGTH ON FOUR WAVE MIXING IN WDM OPTICAL FIBER SYSTEMS

Sakshi Garg\textsuperscript{1}, Shelly Garg\textsuperscript{2}, Harvinder Kumar\textsuperscript{3}

\textsuperscript{1}Scholar, Indus Institute of Engineering & Technology, Jind, Haryana
\textsuperscript{2}Professor, Indus Institute of Engineering & Technology, Jind, Haryana
\textsuperscript{3}Assistant Professor, Jind Institute of Engineering & Technology, Jind, Haryana

ABSTRACT:
This paper introduces the non linear optical effect known as four wave mixing (FWM). In wavelength division multiplexing (WDM) systems four wave mixing can strongly affect the transmission performance on an optical link. As a result it is important to investigate the impact of FWM on the design and performance of WDM optical communication systems. The main objective of this paper is to analyze the FWM power for different values of fiber length and dispersion by designing and simulating a model in Optisim. In this paper, we have simulated the FWM design for three waves. The results obtained show that when the optical fiber length and dispersion value is increased FWM effect reduces. This result confirms that the fiber nonlinearities play decisive role in the WDM.

KEYWORDS:
Four-wave mixing (FWM), Wavelength division multiplexing (WDM), and nonlinear effects.

1. INTRODUCTION:
Very high-capacity, long-haul optical communication systems are made possible by the extremely wide bandwidth of optical fibres, which is best exploited by wavelength division multiplexing (WDM). The performance of long distance optical communication systems is limited, however, by nonlinear effects of fiber, which interact and accumulate along the length of the optical link. One of the unique characteristics of optical fibres is their relatively low threshold for nonlinear effects. This can be a serious disadvantage in optical communications, especially in wavelength division multiplexing (WDM) systems, where many closely spaced channels propagate simultaneously, resulting in high optical intensities in the fiber. In fact, the development of the next generation of optical communication networks is likely to rely strongly on fiber nonlinearities in order to implement all-optical functionalities. In this paper, we have simulated the effect of FWM products in WDM environment by varying the parameters of dispersion and fiber length. It is observed that FWM components reduce to zero as dispersion and fiber length increases.

2. BACKGROUND
Optical fibres in telecommunication systems now carry more channels and higher optical powers than ever before. Systems are operating in which the fibre carries such a high optical power density that signals can modify the transmission properties of the fibre. By the term nonlinear, we mean that the optical signal leaving the fibre at a given wavelength no longer increases linearly with the input power at that wavelength. Nonlinearity in optical fibre essentially leads to the conversion of power from one wavelength to another. The system implications of this wavelength conversion depend on the type of channel or channels used to carry the data. One can distinguish two different types of nonlinearities [1, 2]: The nonlinearities that arise from scattering [stimulated Brillouin scattering (SBS) and stimulated Raman scattering (SRS)];

The nonlinearities that arise from optically induced changes in the refractive index, and result either in phase modulation [self-phase modulation (SPM) and crossphase modulation (XPM)] or in the mixing of several waves and the generation of new frequencies [modulation instability (MI) and parametric processes, such as fourwave mixing (FWM)].

For both types of nonlinearities, the optical response of the material (static or dynamic) is modified by a large optical field. This material response can be represented by an expansion of the polarization [9]:
$$P = \chi^{(1)}E + \chi^{(2)}EE + \chi^{(3)}EEE$$  \hspace{1cm} (1)

where $\chi^{(n)}$ is the $n$th-order susceptibility at optical frequencies. In glasses, because of the optical isotropy, the second-order susceptibility is zero, unless the glass has been poled. The various types of nonlinearities considered here can be expressed in terms of the real and imaginary parts of one of the nonlinear susceptibilities $\chi^{(n)}$ appearing in Equation (1).

The real part of the susceptibility is associated with the index of refraction and the imaginary part with a time or phase delay in the response of the material, giving rise to either loss or gain. For instance, the nuclear contribution to SRS or the electrostrictive stimulated Brillouin effect (both resulting in loss or gain) can be expressed in terms of the imaginary part of a $\chi^{(3)}$ susceptibility [3], while FWM (a purely electronic and almost instantaneous effect resulting in frequency conversion) contributes to the real part of the $\chi^{(3)}$ susceptibility [9].

3. FOUR WAVE MIXING

Four wave mixing (FWM) is the major source of nonlinear crosstalk in wavelength division multiplexing (WDM). The physical origin of FWM-induced crosstalk, and the resulting system degradation, can be understood by noting that FWM can generate a new wave at the frequency $\omega_f = \omega_a + \omega_b - \omega_c$.

Whenever three waves of frequencies $\omega_a$, $\omega_b$, and $\omega_c$ copropagate inside the fiber [2]. Shibata et al. [6] stated that estimation of the FWM efficiency is very important for both the design and evaluation of wavelength division multiplexed (WDM) system. Song et al. [8] reported that the generation of a new frequency of radiation due to FWM has applications in the development of tunable sources and wavelength conversion in all-optical routing systems.

FWM is a nonlinear process in optical fibers in which generally three signal frequencies combine and produce several mixing products. Fig 1 is a schematic diagram that shows four-wave mixing in the frequency domain [7].

Fig. 1: Schematic diagram that shows four-wave mixing in the frequency domain

Where $f_{p1}$ and $f_{p2}$ are the pumping light frequencies and $f_{\text{probe}}$ is the frequency of the probe light. This condition is called the frequency phase-matching condition.

The number of the side bands use to the FWM increases geometrically, and is given by,

$$P = \left( \frac{Q^3 - Q^2}{2} \right)$$  \hspace{1cm} (3)

Where, $Q$ is the number of channels and $P$ is the number of newly generated side bands. For example, eight (8) channels produce 224 side bands.

The time-averaged FWM power $P_{\text{abc}}$ generated at the end of fiber due to interactions of channels at frequencies $f_a$, $f_b$, and $f_c$ is given by [4, 5],

$$P_{\text{FWM}} = \frac{\eta \left( \frac{1024 \pi^6}{n^3 \lambda^2 c^2} \right) \left[ D \chi_3 \right]^2 \left( \frac{L_{\text{eff}}}{A_{\text{eff}}} \right)^2}{P_a P_b P_c \exp(-\alpha L)}$$  \hspace{1cm} (4)

Where $L$ is the fiber length;

$\eta$ is the FWM efficiency;

$n$ is the refractive index of the core;

$\lambda$ is the wavelength;

$c$ is the light velocity in free space;

$D$ is the degeneracy factor, whose values equal 1, 3, and 6 respectively for the cases of $f_a = f_b = f_c$, $f_a = f_b \neq f_c$, $f_a \neq f_b \neq f_c$;

$\chi$ is the third-order nonlinear susceptibility;
\( \alpha \) is the fiber attenuation coefficient; \( A_{\text{eff}} \) is the effective area of the fiber core; 

\( P_a, P_b, \) and \( P_c \) are the input pump powers launched into the fiber; \( \Delta \beta \) is the propagation constant difference.

Here \( \beta \) indicates the propagation constant. 

\( L_{\text{eff}} \) is the effective fiber length given as

\[
L_{\text{eff}} = \frac{1}{\alpha} \exp(-\alpha L)
\]

\( D_{\text{ch}} \) is the fiber-chromatic dispersion value given by

\[
D_{\text{ch}} = \left( \frac{\alpha^2}{2\pi c} \right) \left[ \frac{d^2 \beta(\omega)}{d\omega^2} \right]
\] (5)

The propagation constant difference is given by

\[
\Delta \beta = \left( \frac{2\pi \chi^2}{c} \right) \Delta f_{pq} \Delta f_{nm} \left[ D_{\text{ch}} + \left( \frac{\chi^2}{2c} \right) (\Delta f_{nm} + \Delta f_{pq}) \left( \frac{dD_{\text{ch}}}{d\lambda} \right) \right]
\] (6)

Where \( \Delta f_{pq} = |f_p - f_q| \) \((m,n = a, b, c)\) Generally, \( D_{\text{ch}} \) dominates, and the contribution of \( dD_{\text{ch}}/d\lambda \) can be neglected at the wavelength far from zero chromatic dispersion wavelengths around 1.3 and 1.55 \( \mu \)m. At the zero chromatic dispersion wavelength \( D_{\text{ch}} = 0 \) and the dispersion slope \( dD_{\text{ch}}/d\lambda \) must be included. The generated wave efficiency \( \eta \) with respect to phase mismatch \( \Delta \beta L \) can be expressed as

\[
\eta = \left[ \frac{\alpha^2}{\alpha^2 + (\Delta \beta)^2} \right] \left[ 1 + 4 \exp(-\alpha L) \sin^2 \left( \frac{\Delta \beta L}{2} \right) \right] \left[ 1 - \exp(-\alpha L) \right]^2
\] (7)

4. THE SIMULATION SET UP

Using Optsim software, a simulation set-up has been developed to study FWM effects as shown in the Fig 2.

The frequency of the phase modulator drive signal was kept at 2.4 GHz. The phase modulator has been used to sweep the optical frequency, it was necessary to first integrate the drive signal. Each component in the simulation set-up, shown in Figure 4.2 has its own role, to play in the process.

The first step in the design of an optical communication system is to decide how the electrical signal would be converted into an optical bit stream. Normally, the output of an optical source such as a semiconductor laser is modulated by applying the electrical signal either directly to the optical source or to an external modulator.

There are two choices for the modulation format of the resulting optical bit stream known as the return-to-zero (RZ) and nonreturn-to-zero (NRZ) formats.

The Pseudo Random Bit Sequence Generator is a device or algorithm, which outputs a sequence of statistically independent and unbiased binary digits.

The continue wave (CW) Generator is a generator of continuous-wave millimeter-wave optical signals. The spectral linewidth of the generated millimeter wave signals is 2 kHz. The power of the measured cw millimeter-wave signals is almost in proportion to the power multiplication of the two input optical signals.

The Mach-Zehnder Modulator, is a modulator, which has two inputs, one for the laser diode and the other for the data from the channels.

The WDM Multiplexer is a method of transmitting data from different sources over the same fiber optic link at the same time whereby each data channel is carried on its own unique wavelength.

The Optical Fiber is a component, used in the simulation is a single mode fiber (SMF-28), where the dispersive and nonlinear effects are taken into account. Besides the above components Optical Power Meter, Optical Spectrum Analysis and WDM Analyzer are also used.

In the FWM simulation model layout, two types of tools have been used. The optical spectrum analyzer and the power meter were fixed after MUX and at the end of the fiber optic. The results obtained after the multiplexer are same as the input power level shown before the nonlinear effect. The nonlinear effect occurs only during the propagation of signals through the fiber. The optical spectrum analyzer has been used to show the waveform.
5. RESULTS AND DISCUSSION

A. Effect of fiber length
To see the effect of fiber length on WDM network, the length of fiber is varied from 0 km to 450 km. Below are the tables for parameters setting.

**Table 1: Simulation parameters**

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>CW Laser 1 frequency</td>
<td>193.025 THz</td>
</tr>
<tr>
<td>CW Laser 2 frequency</td>
<td>193.075 THz</td>
</tr>
<tr>
<td>CW Power</td>
<td>-10 dBm</td>
</tr>
<tr>
<td>Optical Fiber Length</td>
<td>0-450 km</td>
</tr>
<tr>
<td>Initial Laser Phase Noise</td>
<td>0</td>
</tr>
<tr>
<td>Mach-Zehnder Modulator Bias Voltage (Vpi)</td>
<td>5 V</td>
</tr>
</tbody>
</table>

Figure 3(a)-3(e) shows the optical spectrum for the optical signal received at the receiver through PIN photodiode by varying fiber length values at 100 km, 200 km, 300 km, 400 km and 450 km and different power level obtain are 18 dBm, -8 dBm, -28 dBm, -48 dBm and -58 dBm respectively. These result shows that the FWM products were reduced when the fiber length parameter is increased. It is important to mention that the fiber length parameter can not be set at too high value because it does bring limitation in bandwidth in the WDM model.

The Simulation result at fiber length of 100 km is shown in Fig. 3(a), where the sideband power is observed as 18 dB.
Fig. 3(a): Optical spectrum including FWM component for length = 100 km

When the fiber length is set to 200 km, the power level of new interfering wavelength generated decreases to -8 dB as shown in Fig. 3(b).

Fig. 3(b): Optical spectrum including FWM component for length = 200 km

Fig. 3(c): Optical spectrum including FWM component for length = 300 km

Fig. 3(c) shows that optical spectrum at fiber length of 300 km, the power level of new wavelength decreases to -28 dB.

Fig. 3(c): Optical spectrum including FWM component for length = 300 km

Fig. 3(d): Optical spectrum including FWM component for length = 400 km

Fig. 3(d) shows that optical spectrum at fiber length of 400 km, the power level of new wavelength decreases to -48 dB.

Fig. 3(d): Optical spectrum including FWM component for length = 400 km
Fig. 3(e) shows that optical spectrum at fiber length of 450 km, the power level of new wavelength decreases to -58 dB. Therefore, when the fiber length parameter is increased, then with the decrease in power level, the FWM effect reduces.

Fig 3(e): Optical spectrum including FWM component for length = 450 km

Fig 4 shows the variation of optical power received at the receiver end for FWM component w.r.t fiber length. It can be seen from the graph that the power level reduces from -14 dBm to about -90 dBm. It is also to be noticed that at high fiber length, FWM component almost reduces to zero.

Fig 4: Output optical power vs length for FWM component

Below are the tables for parameters setting. Table 2 shows the set of the global parameters set for the CW laser sources.

### B. Effect of dispersion
Wavelength dispersion is a signal dispersion which occurs mostly in single-mode fiber. Here, some amount of light given at input of the fiber gets seeped into the cladding which is wavelength dependent and hence affects the transmission speed. To see the effect on WDM network, the dispersion of fiber is varied from 0 ps/nm/km to 4 ps/nm/km.

**Table 2: Simulation parameters**

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>CW Laser 1 frequency</td>
<td>193.025 THz</td>
</tr>
<tr>
<td>CW Laser 2 frequency</td>
<td>193.075 THz</td>
</tr>
<tr>
<td>CW Power</td>
<td>-10 dBm</td>
</tr>
<tr>
<td>Dispersion</td>
<td>0-4 ps/nm/km</td>
</tr>
<tr>
<td>Initial Laser Phase Noise</td>
<td>0</td>
</tr>
<tr>
<td>Mach-Zehnder Modulator Bias Voltage (Vpi)</td>
<td>5 V</td>
</tr>
</tbody>
</table>

The results obtained at the end of the fiber when the power level is set at 0 dBm and the dispersion is varied from 0 to 4 ps/nm-km as shown in Figures from 5 (a) to (e).

The Simulation result at dispersion of 0 ps/nm/km is shown in Fig. 5(a), where the sideband power is observed as 18 dB.

**Fig. 5(a):** Optical spectrum including FWM component for D = 0 ps/nm-km
When the fiber dispersion is set to 1 ps/nm/km, the power level of new wavelength generated decreases to 9 dB as shown in Fig. 5(b).

Fig. 5(b): Optical spectrum including FWM component for D = 1 ps/nm/km

Fig. 5(c) shows the optical spectrum at dispersion of 2 ps/nm-km, the power level of new wavelength decreases to 3 dB value.

Fig. 5(c): Optical spectrum including FWM component for D = 2 ps/nm-km

Fig. 5(d) shows the optical spectrum dispersion of 3 ps/nm-km, the power level of new wavelength decreases to 0 dB value.

Fig. 5(d): Optical spectrum including FWM component for D = 3 ps/nm/km

Fig. 5(e) shows the optical spectrum dispersion of 4 ps/nm-km, the power level of new wavelength decreases to -1 dB value.

Fig. 5(e): Optical spectrum including FWM component for D = 4 ps/nm-km

Fig. 6: Output optical power vs dispersion of FWM component
Fig. 6 shows the variation of optical power received at the receiver end for FWM component w.r.t dispersion. It can be seen from the graph that the power level reduces from -14 dBm to about -32.6 dBm. It is also to be noticed that at a value of high dispersion, FWM component almost reduces to zero.

6. CONCLUSION
In this paper we investigate Four Wave Mixing (FWM) effect by varying parameter of optical transmission length (100-450 km) and dispersion (0-4 ps/nm/km). The performance analysis of four wave mixing in optical communication system for different values of fiber length and dispersion has been done. The comparison of four wave mixing effect at various values of length revealed that power level reduces from -14 dBm to about -90 dBm and for dispersion -14 dBm to about -32.6 dBm. It can be seen from the graphs that as value of fiber length and dispersion increases, FWM effect decreases. The results obtained have shown the spectral characteristics of the FWM in WDM where the effects of FWM are found to decrease with increase in fiber length.

7. REFERENCES

AUTHOR'S BIBLIOGRAPHY
Sakshi Garg received her B.Tech degree in Electronics and communication engineering from Jind institute of engineering and technology in 2013 and pursuing M.Tech in Electronics and communication engineering from Indus institute of engineering and technology presently.

Harvinder Kumar received his B.Tech degree in Electronics and communication engineering from Jind institute of engineering and technology in 2006 and M.Tech degree in Electronics and communication engineering from N.C. College of engineering, Israna in 2006. Presently he is working as Asst Prof. and Head of Department in ECE department in JIET, Jind.