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Effect of Fiber Length on Four Wave Mixing in WDM Optical Fiber Systems

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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 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 transmision length is 100 km, 200 km, 300 km, 400 km and 450 km the FWM power is respectively, becomes about 18 dBm, -8 dBm, -28 dBm, -48 dBm and -58 dBm. This result confirms that the fiber nonlinearities play decisive role in the WDM. It is also to be noticed that as the value of optical length increases, FWM component almost reduces to zero.

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 fibers, which is best exploited by wavelength divison 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 fibers 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 fiber length parameter. It is observed that FWM components reduce to zero as fiber length increses.

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. An optical channel can then affect how it and other channels propagate through the fibre leading to nonlinear effects. 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]:

1. The nonlinearities that arise from scattering [stimulated Brillouin scattering (SBS) and stimulated Raman scattering (SRS)];
2. 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]:

$$P = \chi^{(1)}E + \chi^{(2)}EE + \chi^{(3)}EEE \tag{1}$$

where $\chi^{(n)}$ is the nth-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 one of the major limiting factors in wavelength division multiplexing (WDM) optical fiber communication systems that use low dispersion fibers or narrow channel spacing. 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].

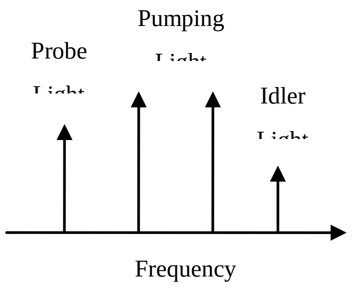

Fig 1: Schematic diagram that shows four-wave mixing in the frequency domain

As can be seen, the light that was there from before launching, sandwiching the two pumping waves in the frequency domain, is called the probe light (or signal light). The idler frequency f_{idler} may then be determined by

$$f_{idler} = f_{p1} + f_{p2} - f_{probe} \tag{2}$$

Where f_{p1} and f_{p2} are the pumping light frequencies and f_{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,

$$M = \left(\frac{N^3 - N^2}{2}\right) \tag{3}$$

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

The time-averaged FWM power P_{ijk} generated at the end of fiber due to ineractions of channels at frequencies f_i, f_j *and* f_k is given by [4, 5],

$$P_{FWM} = \eta\left(\frac{1024\pi^6}{n^4\lambda^2c^2}\right)[D\chi_3]^2\left(\frac{L_{eff}}{A_{eff}}\right)^2 P_iP_jP_k\exp(-\alpha L) \tag{4}$$

Where L is the fiber length; η is the FWM efficiency; n is the refractive index of the core; λ 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 $f_i = f_j = f_k$, $f_i = f_j \neq f_k$, $f_i \neq f_j \neq f_k$; χ is the third-order nonlinear susceptibility; α is the fiber attenuation coefficient; A_{eff} is the effective area of the fiber core; P_i, P_j and P_k are the input pump powers launched into the fiber; $\Delta\beta$ is the propagation constant difference. Here β indiactes the propagation constant.

L_{eff} is the effective fiber length given as $L_{eff} = \dfrac{1-\exp(-\alpha L)}{\alpha}$

D_c is the fiber-chromatic dispersion value given by

$$D_c = -\left(\frac{\omega_k^2}{2\pi c}\right)\left[\frac{d^2\beta(\omega_k)}{d\omega^2}\right] \tag{5}$$

The propagation constant difference is given by

$$\Delta\beta = \left(\frac{2\pi\lambda_k^2}{c}\right)\Delta f_{ik}\Delta f_{jk}\left[D_c + \left(\frac{\lambda_k^2}{2c}\right)(\Delta f_{ik} + \Delta f_{jk})\left(\frac{dD_c(\lambda_k)}{d\lambda}\right)\right] \tag{6}$$

Where $\Delta f_{mn} = |f_m - f_n|$ *(m,n = i, j, k)* Generally, D_c dominates, and the contribution of $dD_c/d\lambda$ can be neglected at the wavelength far from zero chromatic dispersion wavelengths around 1.3 and 1.55 µm. At the zero chromatic dispersion wavelength $D_c = 0$ and the dispersion slope $dD_c/d\lambda$ must be included. The generated wave efficiency η with respect to phase mismatch $\Delta\beta L$ can be expressed as

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

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.

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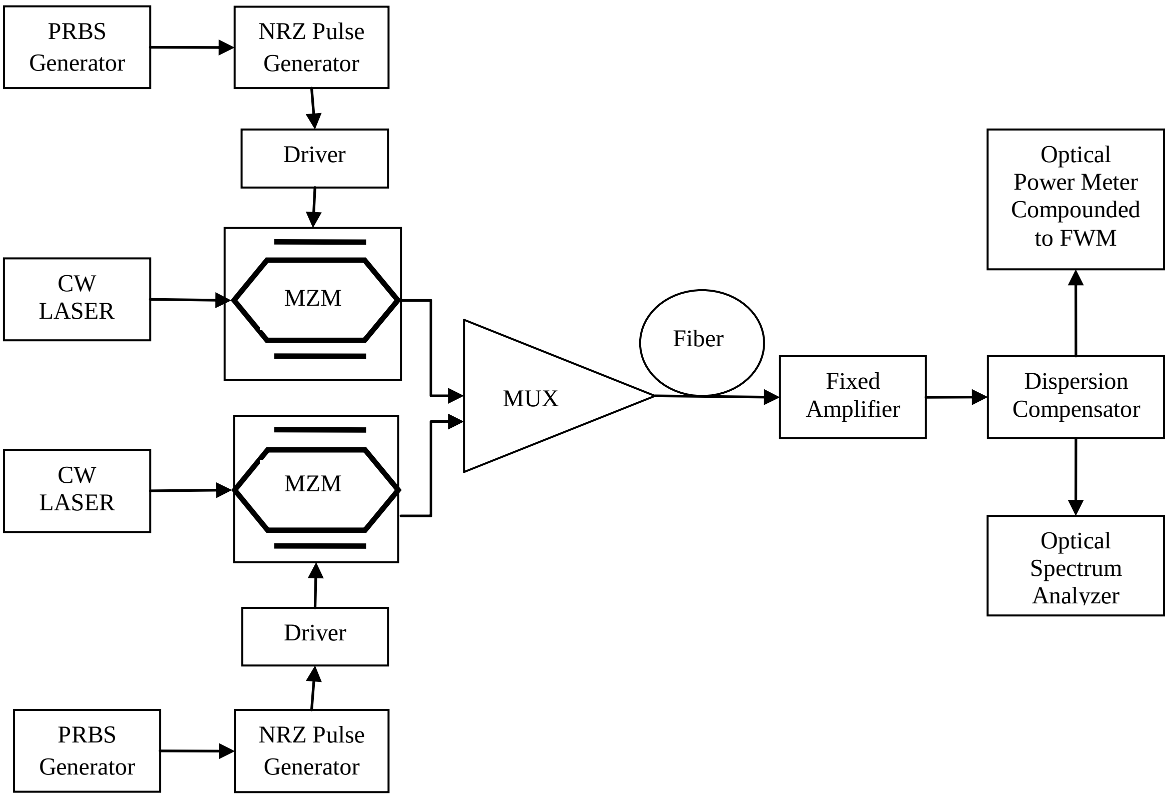

Fig 2: The Simulation Set up

5. RESULTS AND DISCUSSION

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. Below are the tables for parameters setting.

Table 1: Simulation parameters for FWM power

CW Laser 1 frequency	193.025 THz
CW Laser 2 frequency	193.075 THz
CW Power	-10 dBm
Optical Fiber Length	0-450 km
Initial Laser Phase Noise	0
Mach-Zehnder Modulator Bias Voltage (Vpi)	5 V

Figure 3(a)-3(e) shows the optical spectrum for the optical signal received at the receiver through PIN photodiode. It can be seen that four wave mixing components are also received alongwith the transmitted optical frequencies. Two FWM components are dominant in the spectrum corresponding to 192.975 THz and 193.125 THz. The power level for 192.975 THz and 193.125 THz is 18 dBm, -8 dBm, -28 dBm, -48 dBm and -58 dBm for optical fiber length of 100 km, 200 km, 300 km, 400 km and 450 km respectively.

The results obtained at the end of the fiber when the power level is set at 0 dBm and the optical transmission distance is varied from 0 to 450 km as shown in Figures from 3 (a) to 3 (e). 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.

Fig 3(a) shows that Two FWM components are dominant in the spectrum corresponding to 192.975 THz and 193.125 THz with power level of 18 dB at length of 100 km.

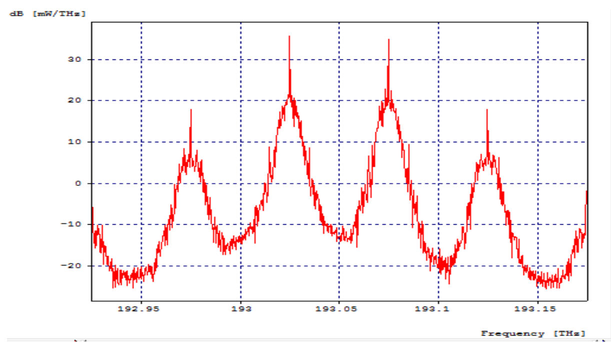

Fig 3(a): Optical spectrum including FWM component for length =100 km

Fig 3(b) shows that Two FWM components are dominant in the spectrum corresponding to 192.975 THz and 193.125 THz with power level of -8 dB at length of 200 km.

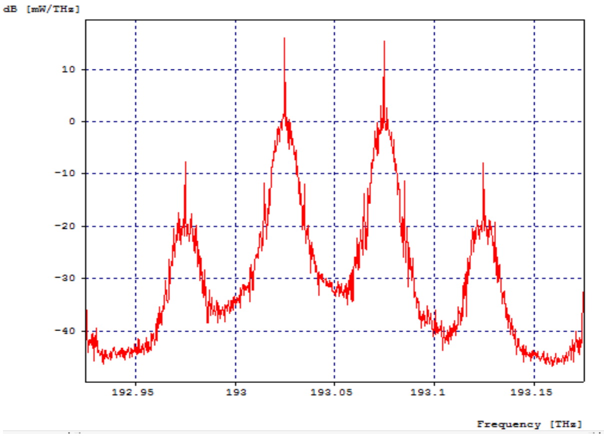

Fig 3(b): Optical spectrum including FWM component for length = 200 km

Fig 3(c) shows that Two FWM components are dominant in the spectrum corresponding to 192.975 THz and 193.125 THz with power level of -28 dB at length of 300 km.

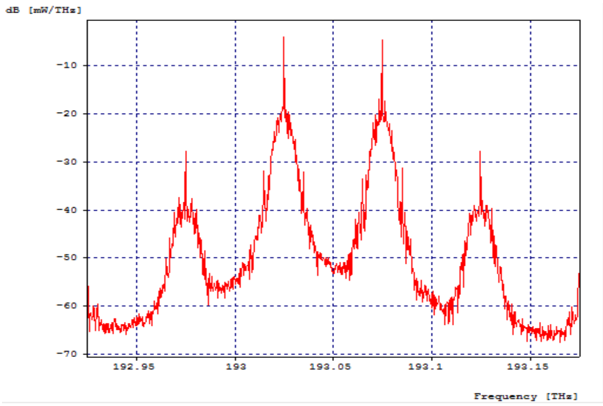

Figure 3(c): Optical spectrum including FWM component for length = 300 km

Fig 3(d) shows that Two FWM components are dominant in the spectrum corresponding to 192.975 THz and 193.125 THz with power level of -48 dB at length of 400 km.

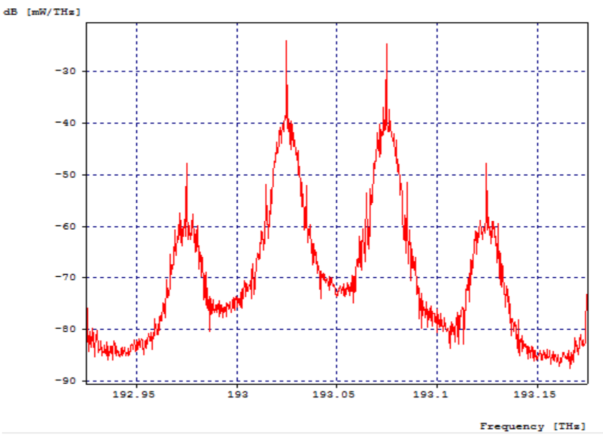

Fig 3(d): Optical spectrum including FWM component for length = 400 km

Fig 3(e) shows that Two FWM components are dominant in the spectrum corresponding to 192.975 THz and 193.125 THz with power level of -58 dB at length of 450 km.

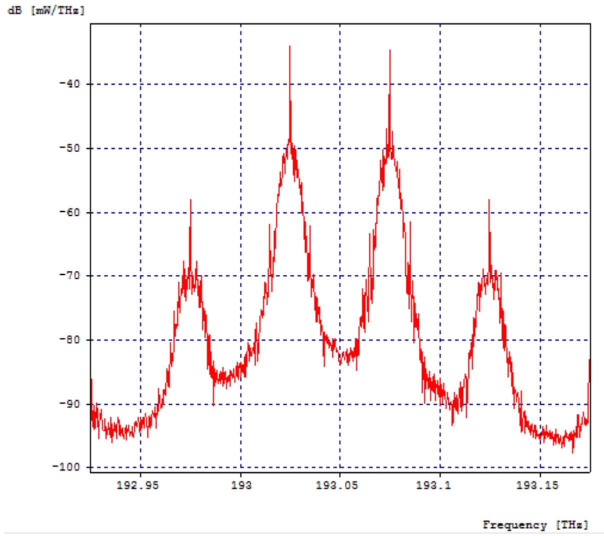

Fig 3(e): Optical spectrum including FWM component for length = 450 km

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.

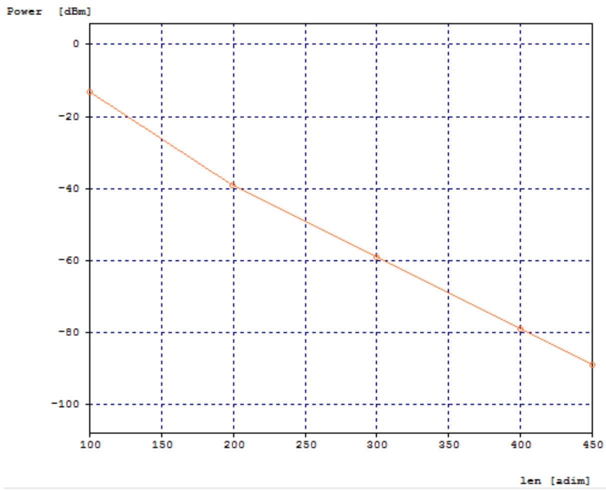

Fig 4: Output optical power vs length for FWM component

6. CONCLUSION

In this paper we investigate Four Wave Mixing (FWM) effect by varying parameter of optical transmission length from 100 km to 450 km. The performance analysis of four wave mixing in optical communication system for different values of fiber length 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. It can be seen from the graphs that as value of fiber length increases, FWM component almost reduces to zero. 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.

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