Effect of Four Wave Mixing Nonlinearity in Wavelength Division Multiplexing Radio over Fiber

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Abstract— **Optical networks are fast, robust and error free, however, there are nonlinear obstacles preventing from being perfect media. The performance of wavelength division multiplexing (WDM) in radio over fiber (RoF) systems is found to be strongly influenced by nonlinearity characteristics inside the fiber. The effect of four wave mixing (FWM) as one of the influential factors in the WDM for RoF. From the results obtained, it is found that the FWM effects have become significant at high optical power levels and have become even more significant when the capacity of the optical transmission line is increased, which has been done by either increasing the channel bit rate, and decreasing the channel spacing, or by the combination of both process. It is found that when the channel spacing is 0.1 nm, 0.2 nm and 0.5 nm the FWM power is respectively, becomes about -59 dBm, -61 dBm and -79 dBm. The simulation results obtained here are in reasonable agreement as compared with other numerical simulation results obtained, elsewhere, using different simulation tools.**

Keywords—Radio over Fiber (RoF); Wavelength Division Multiplexing (WDM); Nonlinearities; Four Wave Mixing (FWM)

I. INTRODUCTION

The next generation of access networks is rushing the needs for the convergence of wired and wireless services to offer end users greater choice, convenience, and variety in an efficient way. This scenario will require the simultaneous delivery of voice, data, and video services with mobility feature to serve the fixed and mobile users in a unified networking platform. In other words, new telecom systems require high-transmission bandwidths and long haul with reliable mobility [1]. Radio over Fiber (RoF) application has attracted much attention recently because of the increasing demand for capacity/coverage and the benefits it offers in terms of low-cost base station deployment in macro cellular system. RoF systems are now being used extensively for enhanced cellular coverage inside buildings such as office blocks, shopping malls and airport terminal. RoF is fundamentally an analog transmission system because it distributes the radio waveform, directly at the radio carrier frequency, from a central unit to a Radio Access Point (RAP) [2].

RoF is a technology used to distribute RF signals over analog optical links. In such RoF systems, broadband microwave data signals are modulated onto an optical carrier at a central location, and then transported to remote sites using optical fiber. The base-stations then transmit the RF signals over small areas using microwave antennas and. Such a technology is expected to play an important role in present and future wireless networks since it provides an end user with a truly broadband access to the network while guaranteeing the increasing requirement for mobility. In addition, since it enables the generation of millimeter-wave signals with excellent properties, and makes effective use of the broad bandwidth and low transmission loss characteristics of optical fibers, it is a very attractive, cost-effective and flexible system configuration.

Normally light waves or photons transmitted through RoF have little interaction with each other, and are not changed by their passage through the fiber (except for absorption and scattering). However, there are exceptions arising from the interactions between light waves and the material transmitting them, which can affect optical signals in RoF. These processes generally are called nonlinear effects because their strength typically depends on the square (or some higher power) of intensity rather than simply on the amount of light present. This means that nonlinear such as self-phase modulation (SPM), cross phase modulation (XPM), four wave mixing (FWM), stimulated raman scattering (SRS), and stimulated brillouin scattering effects (SBS) are weak at low powers, but can become much stronger when light reaches high intensities [3]. This can occur either when the power is increased, or when it is concentrated in a small area-such as the core of an optical fiber. Nonlinear optical devices have become common in RoF applications, such as to convert the output of lasers to shorter wavelengths by doubling the frequency. The nonlinearities in RoF are small, but they accumulate as light passes through many kilometers of fiber. Nonlinear effects are comparatively small in optical fibers transmitting a single optical channel. They become much larger when wavelength division multiplexing (WDM) packs many channels into a single fiber [4].

WDM puts many closely spaced wavelengths into the same fiber where they can interact with one another. It also multiplies the total power in the fiber. A single channel system may carry powers of 3 milliwatts near the transmitter. DWDM multiplies the total power by the number of channels, so a 40-channel system carries 120 mW. That's a total of 2 mW per square micrometer-or 200,000 watts per square centimeter [5]. Several nonlinear effects are potentially important in RoF, although some have produce more troublesome than others. Some occur in systems carrying only a single optical channel, but others can occur only in multichannel systems.

The rapid development of the wireless communication networks has increased the need of the optical signal processing. The link lengths have grown to thousands of kilometers without need to convert optical signals back and forth to electric form, and the transmission speeds of terabits per second are feasible today [6]. This ever-growing demand for the high speed communication has forced to use higher bit rates as well as transmission powers. Nonlinear effects on communication have become significant at high optical power levels and have become even more important since the development of erbium-doped fiber amplifier (EFDA) and DWDM systems. By increasing the capacity of the optical transmission line, which can be done by increasing channel bit rate, decreasing channel spacing or the combination of both, the fiber nonlinearities come to play even more decisive role.

The origin of the nonlinearities is the refractive index of the optical fiber, which varies with the intensity of the optical signal. This intensity-dependent component of the refractive index includes several nonlinear effects, such as SPM, XPM, FWM, SRS, and SBS, and becomes significant when high powers are used. Although the individual power in each channel may be below the level needed to produce nonlinearities, the total power summed over all channels can quickly become significant. The combination of high total optical power and large number of channels at closely spaced wavelengths is a source for many kinds of nonlinear interactions.

Form the above-mentioned reasons, this study is aimed to gain insight into nonlinear effect caused specifically by FWM in the WDM for RoF system and measure the coefficient behind these nonlinear effects. Nonlinear coefficient of the RoF may become an important parameter, when new optical long-haul transmission lines and networks are being deployed.

II. FOUR WAVE MIXING CRITERIA

FWM is a phenomenon that occurs in the case of DWDM systems in which the wavelength channel spacing are very close to each other. This effect is generated by the third order distortion that creates third order harmonics. These cross products interfere with the original wavelength and cause the mixing. In fact, these spurious signals fall right on the original wavelength which results in difficulty in filtering them out. In case of 3 channel system, there will be 9 cross products, where 3 of them will be on the original wavelength. This is caused by the channel spacing and fiber dispersion. If the channel spacing is too close, then FWM occurs. If the dispersion is lesser, then FWM is higher since dispersion is inversely proportional to mixing efficiency. The cross product lies right on the original signal which poses problem when filtering. In general, for N wavelengths input channel there will be M cross mixing products and are given by [7]:

$$M = \frac{N^2}{2}(N-1) \tag{1}$$

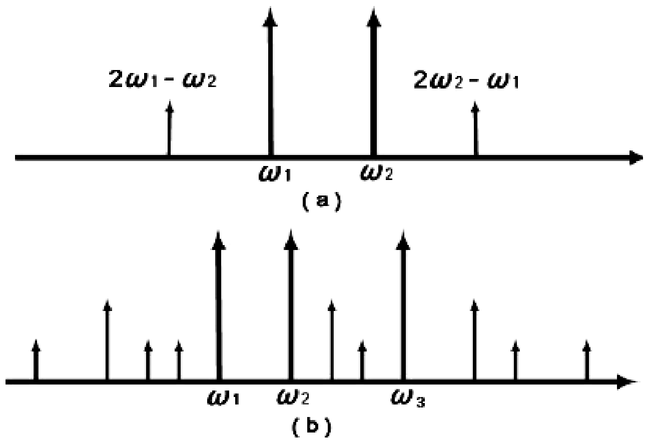


Fig. 1. (a) Two input signals ω_1, ω_2 (b) Two input signals ω_1, ω_2 and ω_3 and the arising new frequency components due to FWM

If the WDM system is considered as a sum of *N* monochromatic plane waves, it is possible to solve the arising channels angular frequencies. Considering a simple three wavelength (λ_1, λ_2 and λ_3) system that is experiencing FWM distortion, nine cross products are generated near λ_1, λ_2 and λ_3 see Fig. 1 that involve two or more of the original wavelengths. There are additional products generated, however they fall well away from the original input wavelengths.

If Assuming that the input wavelengths are λ_1= 1551.72 nm, λ_2= 1552.52 nm, and λ_3= 1553.32 nm. The interfering wavelengths generated around the original three wavelength system are: $\lambda_1+\lambda_2-\lambda_3$ =1550.92 nm, $\lambda_1-\lambda_2+\lambda_3$ =1552.52 nm, $\lambda_2+\lambda_3-\lambda_1$ =1554.12 nm, $2\lambda_1-\lambda_2$ =1550.92nm, $2\lambda_1-\lambda_3$ =1550.12nm, $2\lambda_2-\lambda_1$ =1553.32nm, $2\lambda_2-\lambda_3$ =1551.72nm, $2\lambda_3-\lambda_1$ =1554.92nm, $2\lambda_3-\lambda_2$=1554.12nm.

Fig. 2 shows that the number of the interfering products rapidly becomes a very large. Since there is no way to eliminate the products that falling on top of the original signals, the priority is to prevent them from forming in the first place.

Therefore two factors strongly influence the magnitude of the FWM products, referred to as the FWM efficiency. The first factor is the channel spacing; where the mixing efficiency increases dramatically as the channel spacing becomes closer. Fiber dispersion is the second factor, and the mixing efficiency is inversely proportional to the fiber dispersion, being strongest at the zero-dispersion point. In all cases, the FWM mixing efficiency is expressed in dB, and more negative values are better since they indicate a lower mixing efficiency.

Fig. 3 shows the magnitude of FWM mixing efficiency versus fiber dispersion and channel spacing. If a system design uses NDSF with dispersion of 17 ps/nm/km and the minimum recommended International Telecommunication Union (ITU) DWDM spacing of 0.8 nm, then the mixing efficiency is about -48 dB and will have little impact. On the other hand, if a system design uses DSF with a dispersion of 1 ps/nm/km and a non-standard spacing of 0.4 nm, then the mixing efficiency becomes -12 dB and will have a severe impact on the system performance, perhaps, making the recovery of the transmitted signal impossible. The magnitude of the mixing efficiency will vary widely as these parameters vary. The data presented is intended to illustrate the principles only.

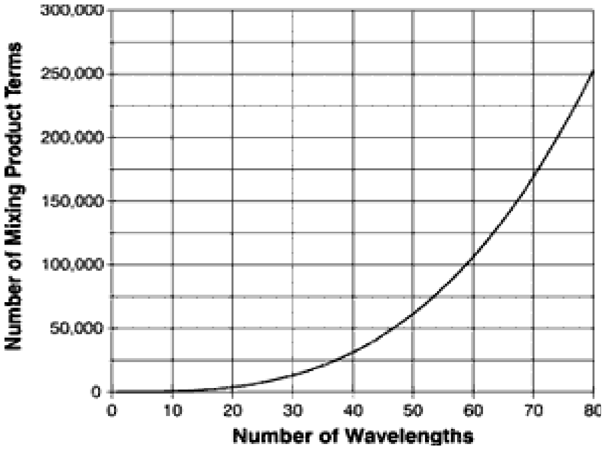


Fig. 2. FWM products versus channel count [7]

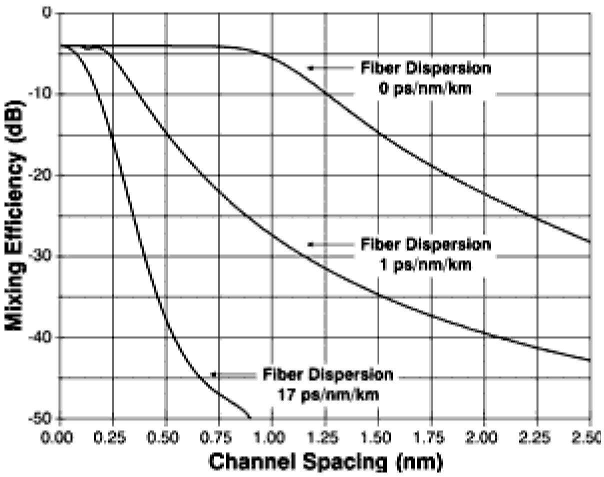


Fig. 3. FWM efficiency in single-mode fibers [7]

FWM is independent of the used bit rate; however, it is critically dependent on channel spacing and chromatic dispersion. Therefore, the effects of FWM must be considered even at moderate-bit-rate systems, if the channel spacing is small or the chromatic dispersion of the fiber is low. Thus, it is possible to minimize the effects of FWM by increasing the channel spacing and the chromatic dispersion of the fiber.

III. MODELLING THE EFFECT OF FWM

The modelling is meant to study the nonlinear effects due to the FWM in WDM for RoF when the light passing through the medium. The total polarization P is nonlinear with respect to the electric field E, however, it can be written as:

$$\mathrm{P} = \varepsilon_0 (\chi^{(1)}\mathrm{E} + \chi^{(2)}\mathrm{EE} + \chi^{(3)}\mathrm{EEE} + ...) \qquad (2)$$

Where ε_0 is the vacuum permittivity and $\chi^{(j)}$ (j =1, 2, …) is j^{th} order susceptibility. When light propagates in a transparent medium, its electric field causes some amount of polarization in the medium. While at low light intensities the polarization is linear with the electric field, nonlinear contributions become important at high optical intensities, so the polarization equation consists linear terms as well as nonlinear terms. The first order susceptibility $\chi^{(1)}$ represents the linear term, and nonlinearities can have strong effects in fibers at the third order susceptibility $\chi^{(3)}$. So, only the nonlinear effects in the optical fibers, which originate from the third-order susceptibility $\chi^{(3)}$, will be considered and the other terms will be neglected. The programming will start from the third-order susceptibility $\chi^{(3)}$**.** Thus the electric field of the signal can be written as [8]:

$$\mathrm{E(r,t)} = \sum_{i=1}^{N} E_i \cos(\omega_i t - \beta_i z) \qquad (3)$$

Where β is the propagation constant and ω is angular frequency. Substituting equation 3 into equation 2, and if only the term of the third order susceptibility is taken into account, the nonlinear dielectric polarization can be written as [8]:

$$\begin{aligned}
P_{NL}(r,t) &= \varepsilon_0 \chi^{(3)} \sum_{i=1}^{n}\sum_{j=1}^{n}\sum_{k=1}^{n} E_i \cos(\omega_i t - \beta_i z) \\
& E_j \cos(\omega_j t - \beta_j z)\, E_k \cos(\omega_k t - \beta_k z) \\
&= \frac{3\varepsilon_o \chi^{(3)}}{4} \sum_{i=1}^{n} [E_i^2 + 2\sum_{j=1}^{n} E_i E_j] E_i \cos(\omega_i t - \beta_i z) \\
&+ \frac{\varepsilon_o \chi^{(3)}}{4} \sum_{i=1}^{n} [E_i^3 \cos(3\omega_i t - 3\beta_i z) \\
&+ \frac{3\varepsilon_o \chi^{(3)}}{4} \sum_{i=1}^{n}\sum_{j=1}^{n} E_i^2 E_j \cos((2\omega_i t - 3\beta_i z)t - (2\beta_i - \beta_j)z) \\
&+ \frac{3\varepsilon_o \chi^{(3)}}{4} \sum_{i=1}^{n}\sum_{j=1}^{n} E_i^2 E_j \cos((2\omega_i t + 3\beta_i z)t - (2\beta_i + \beta_j)z) \\
&= \frac{3\varepsilon_o \chi^{(3)}}{4} \sum_{i=1}^{n}\sum_{j>i}^{n}\sum_{k>j}^{n} E_i E_j E_k \\
& (\cos(\omega_i + \omega_j + \omega_k)t - \cos(\beta_i + \beta_j + \beta_k)z \\
& + \cos(\omega_i + \omega_j - \omega_k)t - \cos(\beta_i + \beta_j - \beta_k)z \\
& + \cos(\omega_i - \omega_j + \omega_k)t - \cos(\beta_i - \beta_j + \beta_k)z \\
& + \cos(\omega_i - \omega_j - \omega_k)t - \cos(\beta_i - \beta_j - \beta_k)z
\end{aligned} \qquad (4)$$

The nonlinear susceptibility of the optical fiber generates new waves at the angular frequencies $\omega r \pm \omega s \pm \omega t$ (r, s, t = 1, 2,…). The remaining terms can satisfy the phase matching condition. The power transferred due to the FWM to new frequencies after light has propagated distance L in the fiber can be estimated from equation 5:

$$P_{ijk} = (\frac{\omega_{ijk} d_{ijk} \chi^{(3)}}{8 A_{eff} n_{eff} c})^2 \cdot P_i P_j P_k L^2 \qquad (5)$$

where n_{eff} is the effective index, A_{eff} is the effective area, Pi, Pj and Pk are the input powers at ωi,ωj and ωk. The factor $d$ijk depends on the number of channels affecting the FWM. The efficiency of FWM and noise performance are analyzed, taking into account the effects of difference channel spacing. Equation 6 is presented to evaluate the efficiency of the FWM [9].

$$\eta = [\frac{n_2}{A_{eff} D(\Delta\lambda)^2}]^2 \tag{6}$$

Equation 7 is used to investigate the relationship between the efficiency and the power of the FWM [9].

$$P_{ijk} = (\frac{\gamma^2}{9})(d_{ijk})^2 (P_i P_j P_k) \exp(-\alpha L) L_{eff}^2 \eta \tag{7}$$

Where L_{eff} is effective length, which can be calculated by using equation 8.

$$L_{eff} = \frac{1-e^{-\alpha l}}{\alpha} \tag{8}$$

where ω is the Angular frequency, d is the degeneracy factor, $\chi^{(3)}$ is the third order susceptibility, A_{eff} is the effective Area, n2 is the nonlinear reflective index, c is the speed of light, D is the dispersion, Δλ is the channel space, α is the fiber loss coefficient and L is total fiber length. The third order susceptibility χ(3), which includes self-phase modulation (SPM) and cross-phase modulation (XPM) as well as four-wave mixing (FWM). Therefore, the SPM and XPM will be considered as zero, thus, their effects on FWM modeling are neglected. The four-wave mixing, require the phase matching to be efficient. Essentially this is mean to ensure a proper phase relationship between the interacting waves. FWM will be a peak at the phase matching spectrum. Equation 9 satisfies the condition of phase matching:

$$\Delta\beta = \beta(\omega_1) + \beta(\omega_2) - \beta(\omega_3) - \beta(\omega_4) \tag{9}$$

Where βj is the propagation constant. If Δβ= 0 the phase matching condition is satisfied, otherwise mismatching occurs. The model in this study will use only two wavelengths, therefore the phase matching condition will be $\Delta\beta = \beta(\omega_2) - 2\beta(\omega_1) = 0$ in order to satisfy the phase matching requirement as shown in Fig. 4.

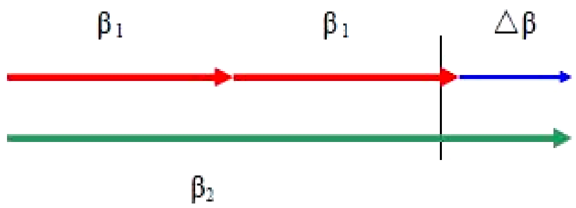


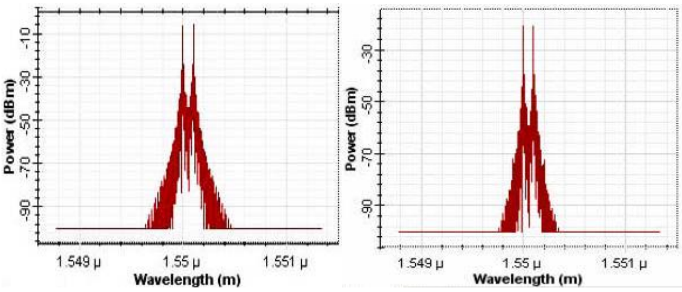
Fig. 4. The phase matching condition of two different wavelength

IV. SIMULATION AND RESULT

In this paper the results obtained from the simulation model by using Optisystem as numerical simulation and Matlab as analytical simulation. In this simulation two CW lasers were used as signals sources, the frequencies were set at 1550 and 1550.1 nm, whereas the power was set at 0 dBm. The linewidth has been set at 0, due to the interest in measuring only the total power of the sideband frequencies, where the shape of the spectrum is not required. The input signals have propagated through 25 km of nonlinear fiber.

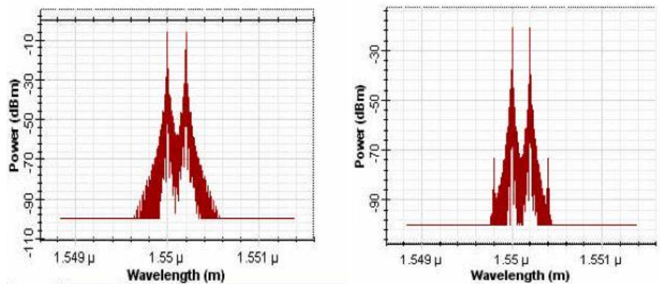
A. Effect of Channel Spacing Variation

Fig. 5 (a) shows the signal at the input channel when the channel spacing is set at 0.1 nm. The result obtained from the simulation is depicted in Fig. 5 (b). The FWM effect is not quite obvious because the external modulation produce sideband. Fig. 6 (a) shows the signal at the input channel when the channel spacing is set at 0.2 nm. From Fig. 6 (b) the FWM effect is quite obvious when the channel spacing sideband is approximately -72 dBm. Fig. 7 (a) shows the signal at the input channel when the channel spacing is set at 0.5 nm. Also in Fig. 7 (b), the FWM effect is quite obvious when the channel spacing is increased to 0.5 nm. The power of the FWM sideband is approximately 87 dBm.



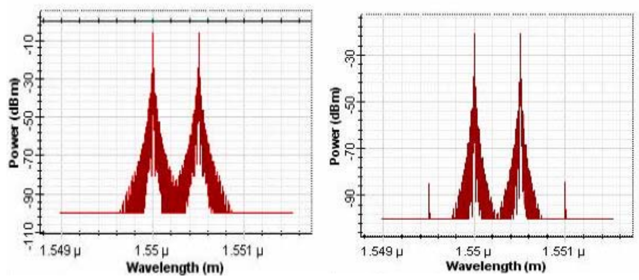
(a) (b)

Fig. 5. (a) Optical spectrum at the input channel (b) optical spectrum at the output channel when the channel spacing is set at 0.1 nm



(a) (b)

Fig. 6. (a) Optical spectrum at the input channel (b) optical spectrum at the output channel when the channel spacing is set at 0.2 nm



(a) (b)

Fig. 7. (a) Optical spectrum at the input channel (b) optical spectrum at the output channel when the channel spacing is set at 0.5 nm

B. *Effect of Different Power Levels of the Signal Sources*

In the following process, the power level of the input sources was varied from 20 dBm to -10 dBm with step -10 dBm while other parameters such as the dispersion and the effective area were kept unchanged. The result obtained from the simulation when the input source power is set at 20 dBm is depicted in Fig. 8 (a). The result obtained from the simulation when the input source power is set at 10 dBm is depicted in Fig. 8 (b). And the result obtained from the simulation when the input source power is set at -10 dBm is depicted in Fig. 8 (c). From the results, given it is clear that when the power level is increased to 20 dBm the effect of the FWM becomes very severe as shown in the Fig. 8 (b). As the power level of the signal sources is decreased to -10 dBm the FWM becomes less effective, as shown in the Fig. 8 (c), therefore, the FWM becomes significantly effective at high optical power levels. The new generated mixing products have high possibilities of falling directly on the original signal, which produce crosstalk.

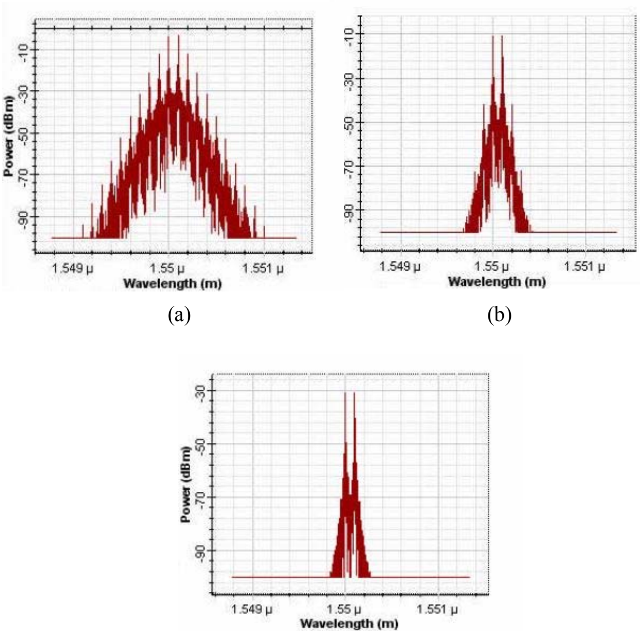


Fig. 8. Optical spectrum at the output of the fiber when input power is set at (a) 20 dBm (b) 10 dBm (c) -10 dBm

C. *Effect of Increase Dispersion of the Fiber Optic*

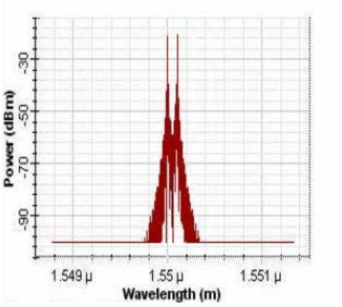


Fig. 9. Optical spectrum at the output of the fiber when input power is set at 0 dBm

Simulation results with the use of the external modulated laser at dispersion of 16.75 ps/nm/km at input power of 0 dBm is shown in Fig. 9. The results obtained at the end of the fiber when the power level is set at 0 dBm and the dispersion is set at 16.75 ps/nm/km were compared with the result obtained at the same power level and dispersion of 1 ps/nm/km. These results show that the FWM products were reduced when the dispersion parameter is increased. It is important to mention that the dispersion parameter cannot be set at too high value because it does bring limitation in bandwidth in the WDM model.

D. *Effect of Increase Effective Area of the Fiber Optic*

Results obtained at the end of fiber where the power level is set at 0 dBm, and the effective area is increased to 76.5μm^2 is shown in Fig. 10 is compared with Fig. 5 (b) which the effective area is set at 64 μm^2. It is found that the increasing of the effective area can reduce the FWM effect.

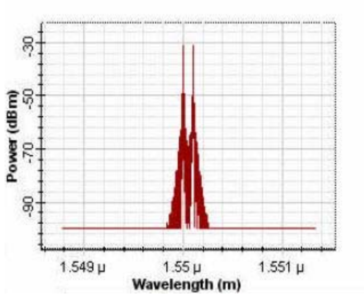


Fig. 10. Optical spectrum at the output of the fiber when the effective area of the fiber optic is set at 76.5μm^2

E. *Analytical Modelling*

Analytical model assists to predict the expected FWM power in different channel spacing. The designed model can give the expectation value of the FWM power in different input signal power level. The analytical results have been compared to the results obtained from the numerical simulation, as shown in Fig. 11 and Fig. 12.

These results show that when power per channel is increased the spurious power increase, too.

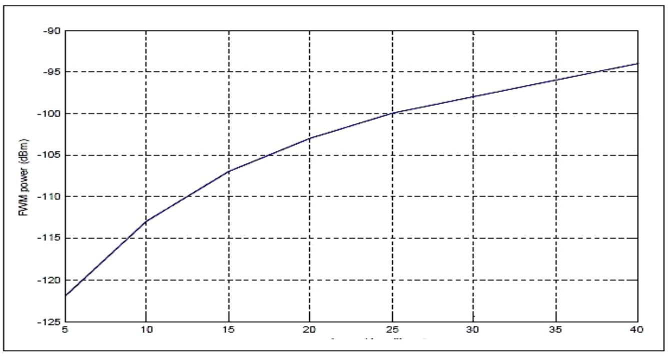


Fig. 11. Power per channel vs. FWM power

The power of the FWM produced is found to be inversely proportional to the square of the channel spacing, when all channels have the same input power. Furthermore, the FWM effects increase exponentially as the level of the optical power from the signal sources is increased, as shown in the Fig. 11. Based on results presented, it is clear that when the channel spacing is smaller the FWM effect becomes more significant due to the phase matching, as shown in Fig. 12.

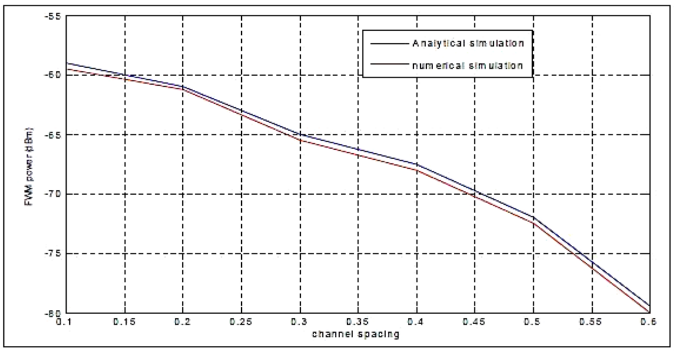


Fig. 12. Channel spacing vs. FWM power

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