FOUR WAVE MIXING NONLINEARITY EFFECT IN WAVELENGTH DIVISION MULTIPLEXING RADIO OVER FIBER SYSTEM

BY

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ABSTRACT

The integration of wireless and optical networks is a potential solution for the increasing capacity and mobility as well as decreasing costs in the access networks. Optical networks are fast, robust and error free, however, there are nonlinearity obstacles preventing them 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 in side the fiber. The effect of four wave mixing (FWM) as one of the influential factors in the WDM for RoF has been studied here using Optisystem and Matlab. 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 becomes about -59dBm to -79dBm respectively. This result confirms that the fiber nonlinearities play decisive role in the WDM for RoF system. The simulation results obtained here are in reasonable agreement as compared with other numerical simulation results obtained, elsewhere, using different simulation tools.

1. Introduction

In the past, dating back to the beginning of the human civilization, communication was done through signals, voice or primitive forms of writing and gradually developed to use signaling lamps, flags, and other semaphore tools. As time passed by, the need for communication through distances, to pass information from one place to another, became necessary and the invention of telegraphy brought the world in to the electrical-communication[Guo,kao andChing2009]. The major revolution that affected the world however was the invention of the telephone in 1876. This event has drastically transformed the development of communication technology. Today's long distance communication has the ability to transmit and receive a large amount of information in a short period of time. Since the development of the first-generation of optical fiber communication systems in the early 80's [Rober 2004], the optical fiber communication technology has developed fast to achieve larger transmission capacity and longer transmission distance, to satisfy the increased demand of computer network. Since the demand on the increasing system and network capacity is expected, more bandwidth is needed because of the high data rates application, such as video conference and real-time image transmission, and also to achieve affordable communication for everyone, at anytime and place [Hamed 2011]. The communication capabilities allow not only human to human communication and contact, but also human to machine and machine to machine interaction. The communication will allow our visual, audio, and touch sense, to be contacted as a virtual 3-D presence [Govind 2001]. To keep up with the capacity increasing requirement, new devices and technologies with high bandwidth are greatly needed by using both electronic and optical technologies together to produce a new term Radio over Fiber (RoF). The progress made so far has been impressive, where information rate at 1 terabits/s can be handled by a single fiber [Yannis 2010].

RoF technology entails the use of optical fiber links to distribute RF signals from a central location (headend) to Remote Antenna Units (RAUs). In narrowband communication systems and Wireless Local Area Network (WLANs), most of signal processing (including coding, multiplexing, RF generation, modulation, etc) are made in central stations (CS- s) rather than in the base station (BS -s) [Anthong 2005]. The signal between CS and BS is transmitted in the optical band via a RoF network. This architecture makes design of BS-s quite simple. In the simplest case, the BS consists mainly from optical-to -electrical (O/E) and electrical-to -optical (E/O) converters, an antenna and some microwave circuitry (two amplifiers and a diplexer). The centralization of Radio Frequency (RF) signal processing functions enables equipment sharing, dynamic allocation of resources, and simplifies system operation and maintenance. These advantages could be translated into major system installation and operational savings, especially in wide-coverage broadband wireless communication systems, where a high density is necessary.

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 [Takuo and Kazuro 2011]. 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 [Antti 2003]. The origin of the nonlinearities is the refractive index of the optical fiber, which is 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 [Marcus 1991]. 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.

2. Simulation Modeling

This section highlights the techniques and methods employed to study the nonlinear effects of FWM in WDM for RoF as well as to analyze the modeling results obtained. Details of the methods will be given in the proceeding sections. Using Optisystem software, two types of simulation models have been developed to study FWM effects. The two models are with external modulated signal and without external modulated signal as shown in the Figure 1 and 2, respectively. 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 [Caiqin andXiupu 2006].

The simulation models were modified according to the related parameters or components for different types of simulation process as given below:

- Effect of channel spacing.
- Effect of different Power Level of the signals Sources
- Effect of increase dispersion of the Fiber Optic
- Effect of Increase Effective Area of the Fiber optic

a. Simulation of the Four Wave Mixing effect

Each component in both simulation models, shown in **Figures 1 and 2**, has its own role, to play in the process. The continues wave (CW) Generator is a generator of continuous-wave millimeter-wave optical signals. The spectral line-width 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 used in the simulation is a single mode fiber (SMF-28), where the dispersive and nonlinear effects are taken into account by a direct numerical integration of the modified nonlinear Schrödinger (NLS) equation. Besides the above components there are three types of components, which used for visualizing purposes:

i. Optical Power Meter Visualizer
ii. Optical Spectrum Analysis
iii. WDM analyzer

b. Simulation of FWM for higher number of channels

Sources in the simulation model were increased to three or four channels. **Figures 3 and 4** show the sources increased in the new simulation model based on direct modulation [Ooi 2007].

c. Effect of Different Power Level of the Signals Sources

The main requirement from a wireless communication system is that the transmitted electro magnetic (EM) wave must reach the receiver with ample power to allow the receiver to distinguish the wave from the background noise. Another common property used to describe signal strength is the S/N ratio. The S/N ratio does not describe the absolute power in the signal, but instead describes the power of the signal in comparison to the power of the background noise. The higher the S/N ratio, the better or more powerful the signal. Since the S/N ratio accounts for the level of background noise, it is a very valuable and widely used indicator of signal strength. In the simulation process, the power at the simulation model sources was varied from 20 dBm to -10 dBm with step of -10 dBm to in order try different simulations.

d. Effect of Increase dispersion of the Fiber Optic

Wavelength dispersion, is a signal dispersion, which occurrs primarily in single mode fiber. A significant amount of the light launched into the fiber is leaked into the cladding. This leaked amount is wavelength dependent and also influences the speed of propagation. High volume communication lines have carefully timed spacings between individual signals. Fortunately, wavelength dispersion can be minimized by careful designation of fiber refractive index. The dispersion parameter of the fiber optic in the simulation model was varied from 1 ps/nm/km to 16.75 ps/nm/km. This has been done in order to compare the results with different dispersion parameters and the power level of sources set at 0 dBm.

e. Effect of Increase Effective Area of the Fiber optic

The effective area (A_{eff}) of the single-mode fiber is an important measurement parameter. It is the area of the cross section of the beam arrived into the fiber. The effective area evaluation requires the measurement of the field distribution in the fundamental mode. The effective area parameter of the fiber optic in the simulation model has been changed from 64 μm^2 to 76.5 μm^2, in order to compare the results with different effective area parameters as the power level of sources set at 0 dBm..

3. Modelling the Effect of FWM

Matlab program is used to develop the analytical model of the effect of FWM in WDM for RoF. The modeling is meant to study the nonlinear effects due to the FWM in WDM for RoF when the light passing through the medium. Figure 4 shows the steps that will be followed in the modeling process. The total polarization P is nonlinear with respect to the electric field E, however, it can be written as:

$$p = \varepsilon_o(\chi^1.E+\chi^2.E.E+\chi^3.E.E.E+\cdots) \quad (1)$$

Where $\varepsilon_\circ$ is the vacuum permittivity and X^1 (j=1,2,……..)is jth 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 χ(1) represents the linear term, and nonlinearities can have strong effects in fibers at the third order susceptibility χ(3). So, only the nonlinear effects in the optical fibers, which originate from the third-order susceptibility χ(3), will be considered and the other terms will be neglected. The programming will start from the third- order susceptibility χ(3). Thus the electric field of the signal can be written as [6]:

$$E(r,t) = \sum_{i=1}^{N} E_i \cos(\omega_i t - \beta_i z) \quad (2)$$

Where β i s the propagation constant , and ω i s angular frequencies Substituting Equation 2 into Equation 1, and if only the term of the third order susceptibility is taken into account, the nonlinear dielectric polarization (PNL(r,t))can written as [6]:

$$P_{NL}(r,t) = \varepsilon_o \chi^3 \sum_{i=1}^{n}\sum_{j=1}^{n}\sum_{k=1}^{n} E_i \cos(\omega_i t - \beta_i z) E_j \cos(\omega_j t - \beta_j z) E_k \cos(\omega_k t - \beta_k z)$$

$$= \frac{3\varepsilon_\circ \chi^3}{4} \sum_{i=1}^{n} [E_i^2 + 2\sum_{j=1}^{n} E_i E_j] E_i \cos(\omega_i t - \beta_i z) \quad \text{(term 1)}$$

$$+ \frac{\varepsilon_\circ \chi^3}{4} \sum_{i=1}^{n} E_i^3 \cos(3\omega_i t - 3\beta_i z) \quad \text{(term 2)}$$

$$+ \frac{3\varepsilon_o \chi^3}{4} \sum_{i=1}^{n}\sum_{j=1}^{n} E_i^2 E_j \cos((2\omega_i t - 3\beta_i z)t - (2\beta_i - \beta_{j)} z) \quad \text{(term..3)}$$

$$+ \frac{3\varepsilon_o \chi^3}{4} \sum_{i=1}^{n}\sum_{j=1}^{n} E_i^2 E_j \cos((2\omega_i t + 3\beta_i z)t - (2\beta_i + \beta_j) z) \quad \text{(term…4)}$$

$$+ \frac{3\varepsilon_o \chi^3}{4} \sum_{i=1}^{n}\sum_{j>i}^{n}\sum_{k>j}^{n} E_i E_j E_k$$

$$\cos(\omega_i + \omega_j + \omega_k)t - \cos(\beta_i + \beta_j + \beta_k) z \quad \text{(term….5)}$$

$$+\cos(\omega_i + \omega_j + \omega_k)t - \cos(\beta_i + \beta_j - \beta_k) z \quad \text{(term…6)}$$

$$+\cos(\omega_i - \omega_j + \omega_k)t - \cos(\beta_i - \beta_j + \beta_k) z \quad \text{(term…7)}$$

$$+\cos(\omega_i - \omega_j - \omega_k)t - \cos(\beta_i - \beta_j - \beta_k) z \quad \text{(term..8)} \qquad (3)$$

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,…). Term 1, in the above equation represents the effects of SPM and XP

Terms 2, 4 and 5 can be neglected, due to lack of phase matching. 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 4.4 [6]:

$$P_{ijk} = \left(\frac{\omega_{ijk}\, d_{ijk}\, \chi^{3}}{8\, A_{eff}\ n_{eff}\ c}^{2}\right) \quad P_i\, P_j\, P_k\, L^2 \qquad (4)$$

Where n_{eff} is the effective index ,A_{eff} is the effective area, P_i ,P_j ,and P_k are the input powers at ω_i, ω_j, and ω_k the factor d_{ijk} depends on the number of channels affecting FWM.

The efficiency of FWM and noise performance are analyzed ,taking into account the effects of difference channel spacing . Equation 5 is presented to evaluate the efficiency of the FWM [6] .

$$\eta = \left[\frac{n_2}{A_{eff}\, D\, (\Delta\lambda)^2}\right]^2 \qquad (5)$$

Equation 6 is used to investigate the relationship between the efficiency and power of the FWM [6].

$$P_{ijk} = \left(\frac{\gamma^2}{9}\right)\left(d_{ijk}\right)^2 \left(P_i\ \ P_j\, P_k\right) \exp(-\alpha L) L_{eff}^2\, \eta \qquad (6)$$

Where L_{eff} is effective length , which can be calculated by using equation (7)

$$L_{eff} = \frac{1-e^{-\alpha L}}{\alpha} \qquad (7)$$

Where ω is the angular frequency ,d is the degeneracy factor , $X^3$is third order considered as zero, thus ,their effects on FWM modeling are neglected. Term 1 representing XPM &SPM will be considered as of zero effect and will be neglected too.
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 4.8 satisfies the condition of phase matching

$$\Delta\beta = \beta(\omega 1\ ) + \ \beta(\omega 2\ ) - \beta(\omega_3\ ) - \beta(\omega_4) \qquad (8)$$

Where β_j is the propagation constant .If $\Delta\beta = 0$ the phase matching condition is satisfied otherwise mismatching occurs. The model in this study will use only two wave lengths , therefore the phase matching condition will be $\Delta\beta = \beta(\omega_2) - 2\beta(\omega_1) = 0$ in order to satisfy the phase matching.

4. Calculation Results and Analysis

In this section presents and discusses the results obtained from the simulation model by using Optisystem as numerical simulation and Matlab as analytical simulation. The numerical simulation is simulated accordingly as mentioned in the previous sections, with and without external modulated laser.

a. Simulation of the Four Wave Mixing Effect

In the FWM simulation model layout, two types of visualiser tools have been used. The optical spectrum analyzer and the WDM analyzer 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 whereby the WDM analyzer has been used to display signal power (dBm), noise power (dBm) and OSNR (dB).

b. Simulation Results without the External Modulated Signal

In this simulation two CW lasers were used as signals sources, the frequencies were set at 1550 and 1550.1 nm, where as 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. Figure 5 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 Figure 6. From this figure, the FWM effect is obviousl because the simulation without external modulated laser is simpler compared to the simulation model with external modulated laser. The interfering wavelengths generated around the original two wavelength systems are 1549.9 nm and 1550.2 nm, thereby the power of the each FWM sideband is approximately -59 dBm

Figure 7 shows the signal at the input channel when the channel spacing is set at 0.2 nm.

When the channel spacing is increased to 0.2 nm, the result obtained from the simulation is depicted in Figure 8. The interfering wavelengths generated around the original two wavelength system are 1549.8 nm and 1550.4 nm, thereby the power of the each FWM sideband is approximately -61 dBm.

Similarly, **Figures 9** shows the signal at the input channel when the channel spacing is increased to 0.5 nm.

Figure 10 shows the interfering wavelengths generated around the original two wavelength system of 1549.5 nm and 1551 nm; thereby the power of each FWM sideband is approximately -71 dBm.

Therefore, as the spacing between channels is increased the effect of the FWM is decreased.

Figure 11 optical spectrum at the output of the fiber when input power is set at 20 dBm.

The result obtained from the simulation when the input source power is set at 10 dBm is depicted in Figure 12.

The result obtained from the simulation when the input source power is set at -10 dBm is depicted in Figure 13.

From the result s, 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 Figure 11. As the power level of the signal sources is decreased to -10 dBm the FWM becomes less effective, as shown in the Figure 13, therefore, the FWM becomes significantly effective at high optical power levels.

The effect of dispersion parameter of fiber optic was changed from 1.0 ps/nm/km to16.75 ps/nm/km, at input power of 0 dBm. The results were taken at the end of the fiber optic. Simulation results at dispersion of 16.75 ps/nm/km at input power of 0 dBm is shown in Figures 14.

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 as shown in Figure 14, was compared with the result obtained at the same power level and dispersion of 1 ps/nm/km as shown in Figure 8, these result show that the FWM products were reduced when the dispersion parameter is increased. It is important to mention that the dispersion parameter can not be set at too high value because it does bring limitation in bandwidth in the WDM model.

4.1 Simulation Results with the External Modulated Signal

In this simulation two CW lasers were used as signals sources, the frequencies were set at 1550 and 1550.1 nm, where as the power was set at 0 dBm, 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.

4.1.1 Effect of Channel Spacing variation

Figure 15 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 Figure 16. The FWM effect is not quite obvious because the external modulation produce sideband.

From Figures 18, the FWM effect is quite obvious when the channel spacing is increased to 0.2. The power of the FWM sideband is approximately -72 dBm

Figure 19 shows the signal at the input channel when the channel spacing is set at 0.5 nm.

Also in Figure 20, 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

Therefore, as the spacing between channels is increased the effect of the FWM is decreased.

4.1.2 Effect of Different Power Level of the Signals 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 Figure 21.

The result obtained from the simulation when the input source power is set at 0 dBm is depicted in Figure 22.

The result obtained from the simulation when the input source power is set at -10 dBm is depicted in Figure 23.

From the result s, 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 Figure 21. As the power level of the signal sources is decreased to -10 dBm the FWM becomes less effective, as shown in the Figure 23, 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.

4.1.3 Effect of Increase Dispersion of the Fiber Optic

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 Figures 24.

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 as shown in Figures from 24. were compared with the result obtained at the same power level and dispersion of 1 ps/nm/km as shown in Figure 16, these result show that the FWM products were reduced when the dispersion parameter is increased. It is important to mention that the dispersion parameter can not be set at too high value because it does bring limitation in bandwidth in the WDM model.

4.1.4 Effect of Increase Effective Area of the Fiber Optic

Simulation results with the use of the external modulated laser at effective area of 76.5 μm^2 at input power of 0 dBm are shown in Figure 25.

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 Figure 25 is compared with Figure 16 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.

4.2 Simulation of Four Wave Mixing for Higher Number of Channels

This section presents the simulation results as the number of channels is increased to four in the simulation model, with or without the use of external modulated laser.

4.2.1 Simulation Results for Four Signal Source without External Modulated Signal

The simulation results for four channels, without use of external modulated laser, Figure 26 shows input signal when number of channels is increased to four and the channel spacing is set at 0.1 nm.

The result obtained from the simulation when the number of channel is increased is depicted in Figure 27. The number of FWM also is increased.

The result obtained from the simulation when the number of channel is increased and the channel spacing is set at 0.5 nm is depicted in Figure 28. The number of FWM also is increased.

4.2.2 Simulation Results for Four Signal Source with External Modulated Signal

The simulation results for four channels, when using External modulated Laser, at different channel spacing. Figure 29 shows input signal when number of channels is increased to four and the channel spacing is set at 0.1 nm.

The result obtained from the simulation when the number of channel is increased and the channel spacing is set at 0.1 nm is depicted in Figure 30. The number of FWM is also increased.

The result obtained from the simulation when the number of channel is increased and the channel spacing is set at 0.5 nm is depicted in Figure 31. The number of FWM is also increased but with less effect.

5. Discussions

Based on the results presented , The FWM effects increase as the number of channels is increased. The number of spurious signals due to FWM increase geometrically and given by:

$$M = (N^3 - N^2)/2 \qquad (8)$$

where N is the number of channels and M is the number of the newly generated sidebands. The new generated mixing products have high possibilities fall directly on the original signal , this could produce crosstalk. Therefore, as the spacing between channels is reduced or remained equal the effect of the crosstalk is found to become greater. When the spacing between the channels is unequal, showed that the mixing products have low power level and highly possible not to falls on the original signal, which makes them easy to be filtered, and in turn improve the system performance. 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 are shown in Figures 14. It is found that the OSNR obtained is better than before increasing the effective area as shown in Figure 8. As general, the increase of the effective area can reduce the FWM effect and give higher OSNR value compared to the simulation result obtained with the same power level. The effective area refers to the equivalent area of the fiber in which the optical power is transmitted. In the case of single mode fiber, this is roughly proportional to the core area. Fiber with a large effective area offers reduced optical power density, which raises the power threshold for the FWM penalties. In addition, the effective area parameter and the dispersion parameter can be used to calculate the FWM efficiency as follows:

$$\eta = n_2/(A_{eff} \text{ X } D \text{ X } \Delta\lambda^2) \qquad (9)$$

where η is the FWM efficiency, n_2 is the nonlinear index coefficient, A_{eff} is the effective area, D is the dispersion and $\Delta\lambda$ is the spectral width.

5.1 Analytical Modelling

Matlab based program has been developed in order to design analytical model which 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 Figures 32 and 33.

These results show that when power per channel is increased the spurious power increase, too. 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 Figure 32 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 Figure 33.

5.2 Four Wave Mixing Reduction

One way to combat the FWM process is to use unequal channel spacing, so that the mixing products do not coincide with signal frequency, and to use low input power, or high effective area. Fiber dispersion management is a very effective way, helpful not for FWM but also is the case of other nonlinear phenomena, that degrade transmission performance in the fiber, also FWM can be mitigated by increasing the effective area of the fiber [13].

5.2.1 Effect of Unequal Channels

Figure 34 shows input signal when the channel spacing is unequal.

When the spacing between the channels is unequal, showed that the mixing products have low power level and highly possible not to falls on the original signal, which makes them easy to be filtered, and in turn improve the system performance. As shown Figure 35.

5.2.2 Effect of Increase Effective Area of the Fiber Optic

The effective area parameter of fiber optic has been changed from 64 μm^2 to 76.5 μm^2 at the power level set at 0 dBm. The results were taken at the end of the fiber optic. Simulation results at effective area of 76.5 μm^2 at input power of 0 dBm are shown in Figures 36.

Results obtained at the end of fiber where the power level is set at 0 dBm, and the effective area is increased to 76.5 μm^2 as shown in Figure 36. It is found that the increasing of the effective area can reduce the FWM effect.

6. Conclusions

Future wireless systems it will be targeting towards providing broadband access and personal area multimedia services to large number of subscribers. Radio over fiber (RoF) network accompanied with wavelength division multiplexing (WDM) can provide a simple topology, easier network management, and an increased capacity by allocating different wavelengths to individual remote nodes. The performance of WDM networks is strongly influenced by nonlinearity characteristic inside the fiber. Therefore the nonlinearity effects of fiber optics pose additional limitation in WDM systems. It is well known that FWM in WDM for RoF signals are mostly generated by non-degenerate FWM process regardless of the number of input signals. In this study only two and four input signals were launched into the optical fiber. The FWM effect has been investigated analytically and numerically simulated. Simple equations to determine the spectral linewidth, the FWM power due to channel spacing and the power of the FWM components due to the input power have been deduced. The numerical simulation results obtained have shown the spectral characteristics of the FWM in WDM for RoF where the effects of FWM are pronounced with decreased channel spacing of wavelengths or at high signal power levels.

The numerical simulation model results and the analytical model results were compared. The numerical simulated results clearly demonstrate that the degradation due to FWM can be minimized by ensuring that the phase matching does not occur. This has been achieved by increasing the channel separation and supplying low signal power level. The high effective area is also found to the decrease FWM effect. It is noticed that the FWM also causes inter-channel cross talk for equally spaced WDM channels. Thus, FWM can be mitigated using unequal channel spacing. It could be concluded that results obtained from this study will provide useful information for identifying the fundamental limit of the capacity of the WDM systems.

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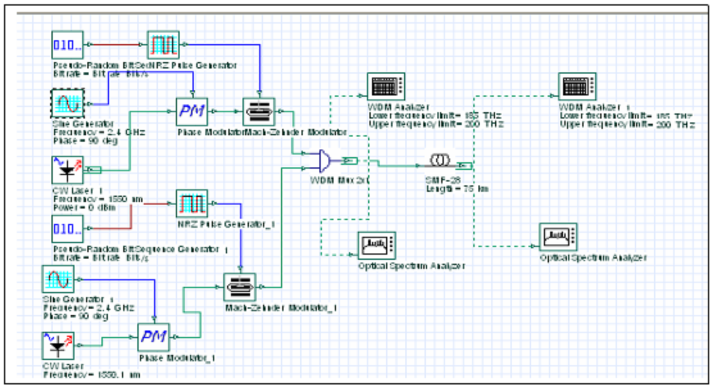


Figure 1 Simulation model with external modulated signal

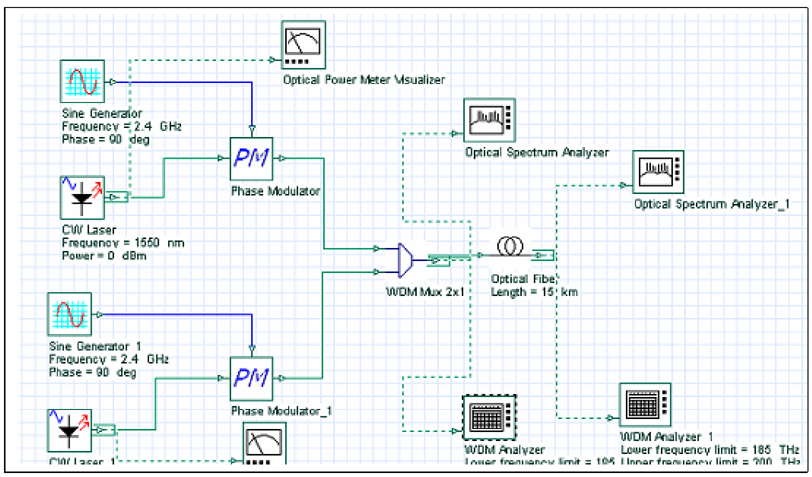


Figure 2 Simulation model without external modulated signal

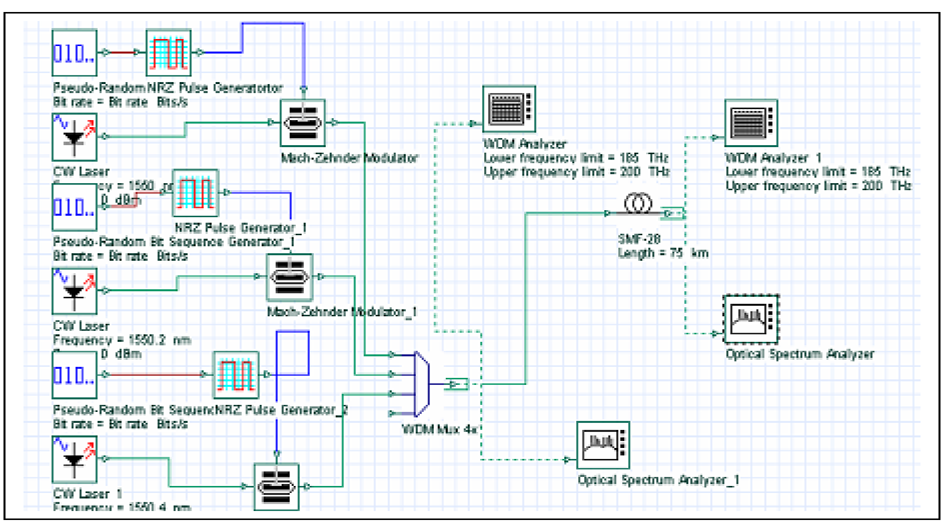


Figure 3 Simulation model with three channels

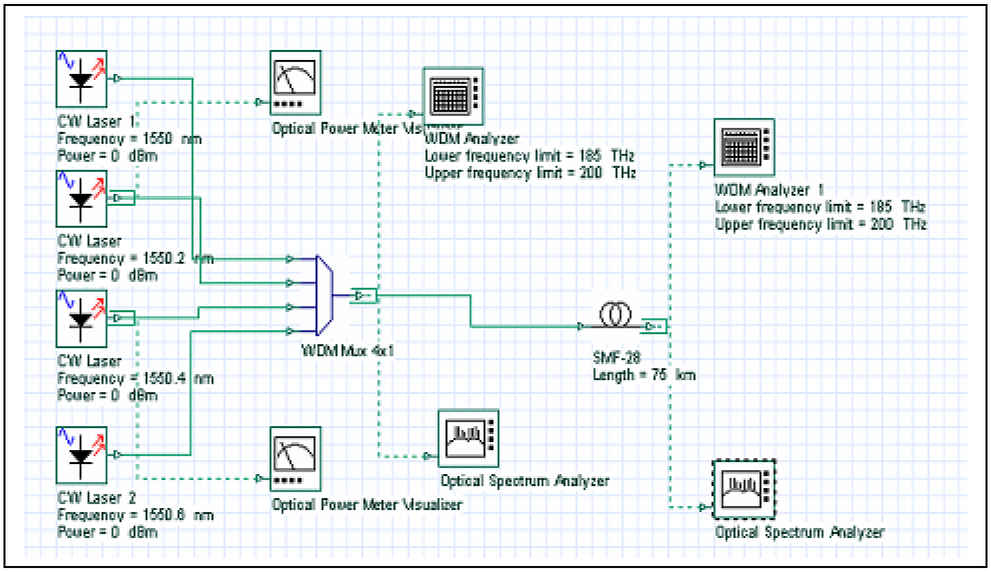


Figure 4 Simulation model with four channels

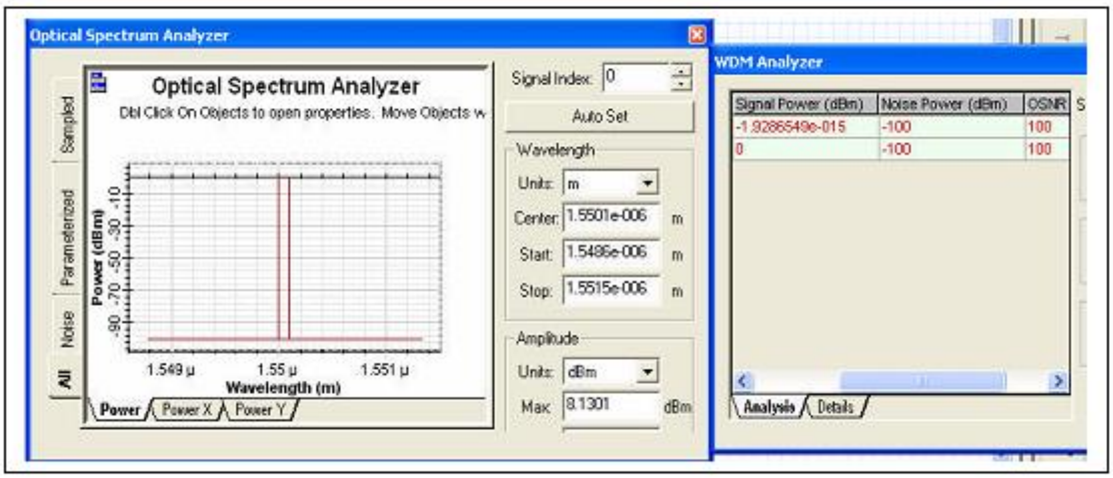


Figure 5 Optical spectrum at the input of the fiber when channel spacing is set at 0.1 nm

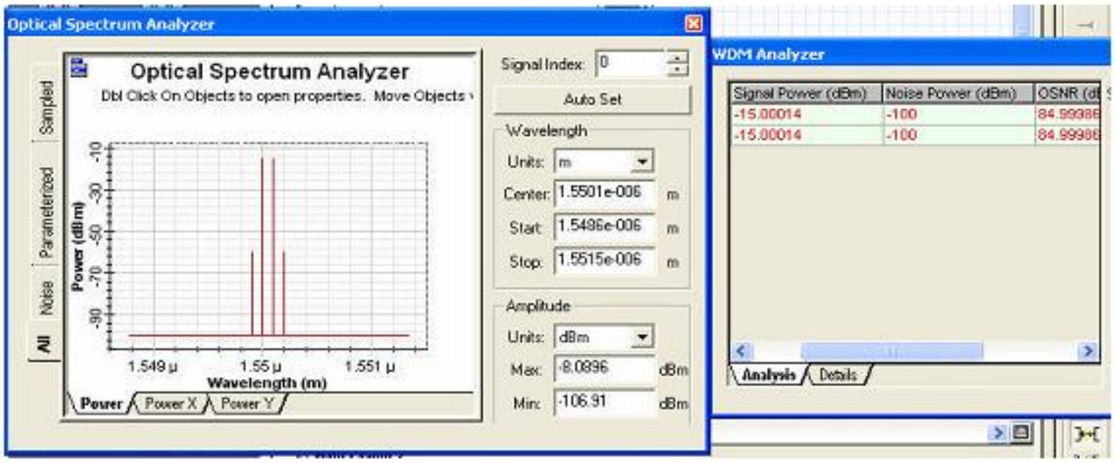


Figure 6 Optical spectrum at the output of the fiber when channel spacing is set at 0.1 nm

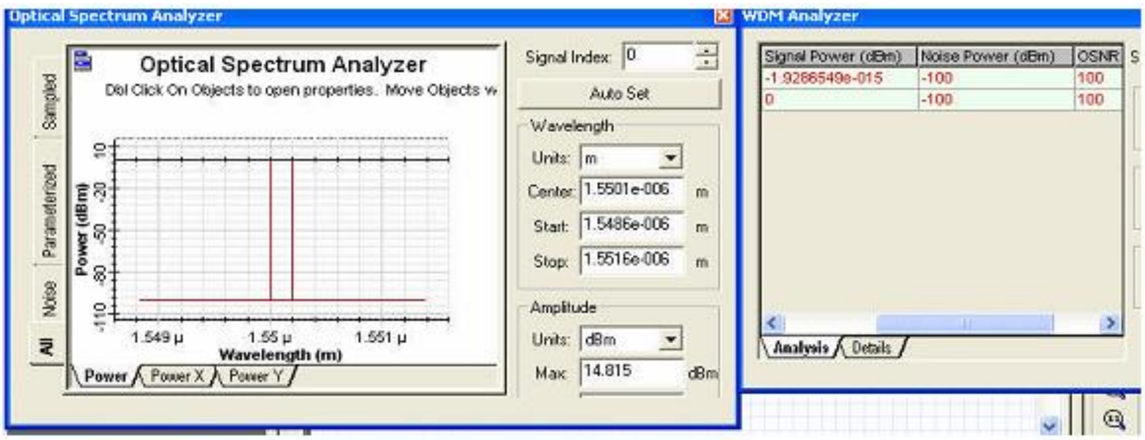


Figure 7 Optical spectrum at the input of the fiber when channel spacing is set at 0.2 nm

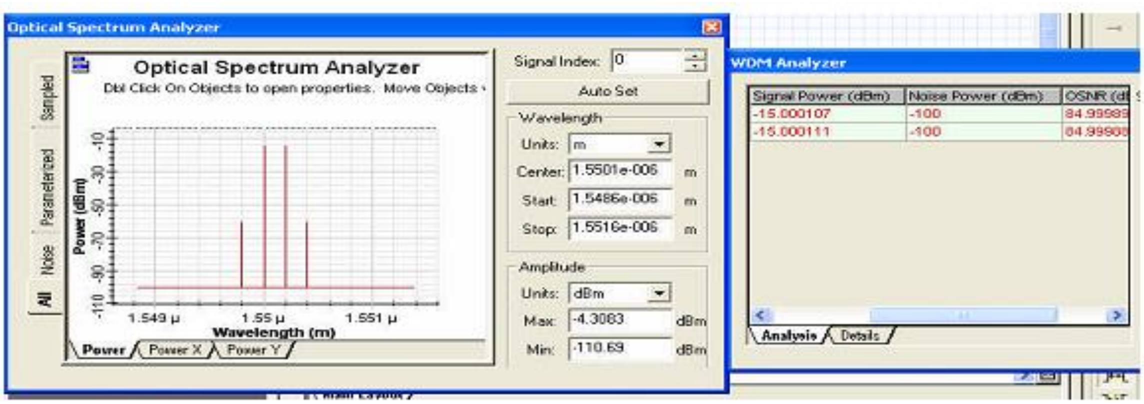


Figure 8 Optical spectrum at the output of the fiber when channel spacing is set at 0.2 nm

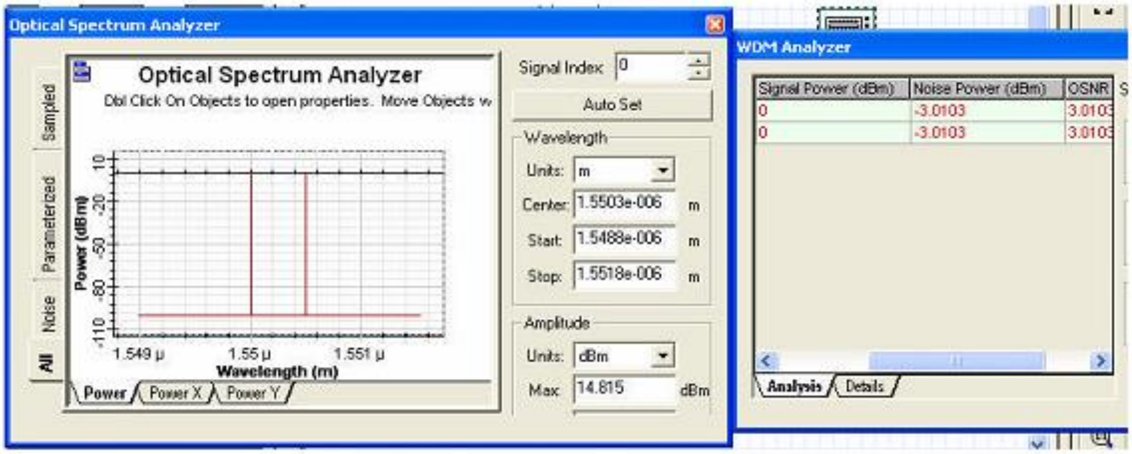


Figure 9 Optical spectrum at the input of the fiber when channel spacing is set at 0.5 nm

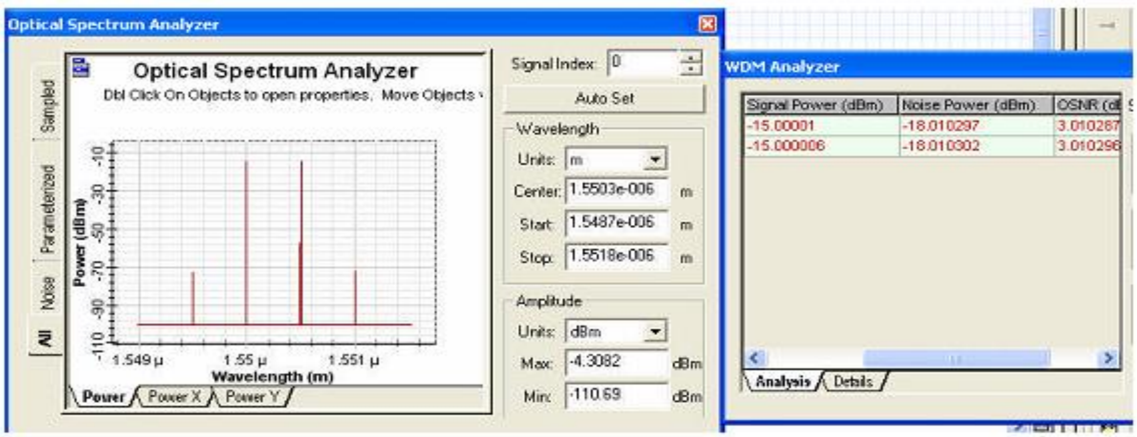


Figure 10 Optical spectrum at the output of the fiber when channel spacing is set at 0.5 nm

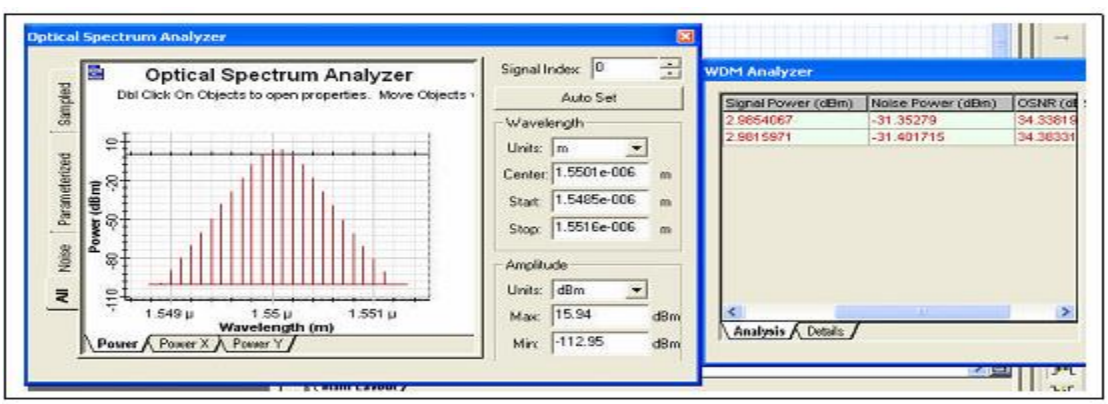
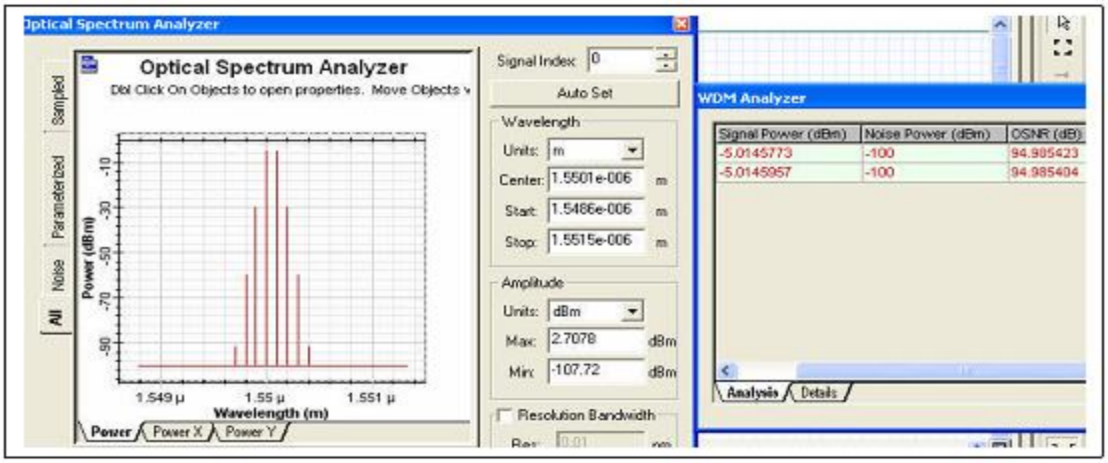
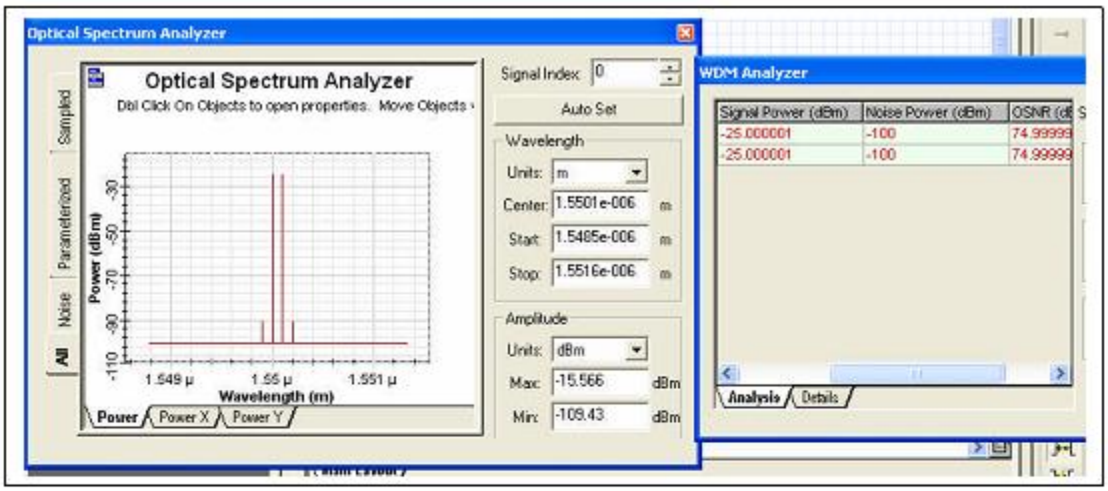


Figure 11 Optical spectrum at the output of the fiber when input power is set at 20 dBm



Figures 12 Optical spectrum at the output of the fiber when input power is set at 10 dBm



Figures 13 Optical spectrum at the output of the fiber when input power is set at -10 dBm

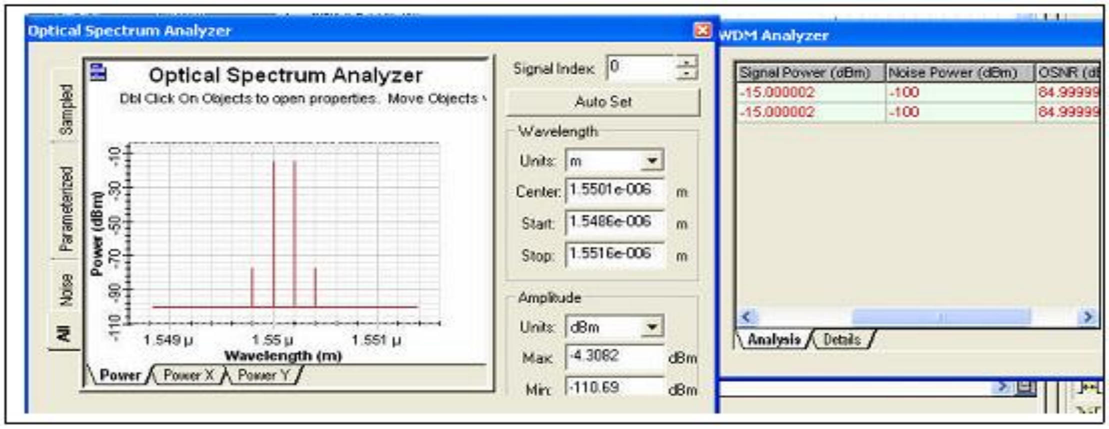


Figure 14 Optical spectrum at the output of the optical when the dispersion of fiber optic is set at 16.75 ps/nm/km

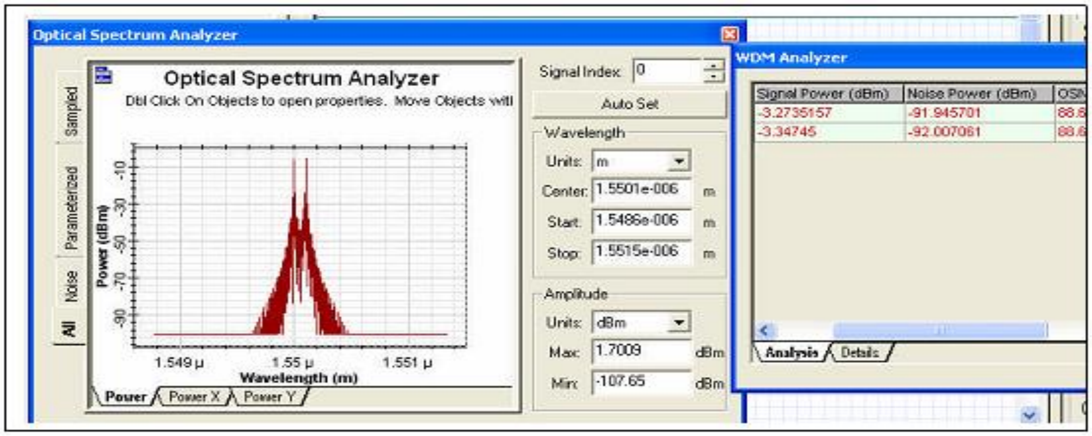


Figure 15 Optical spectrum at the input of the fiber when the channel spacing is

set at 0.1 nm

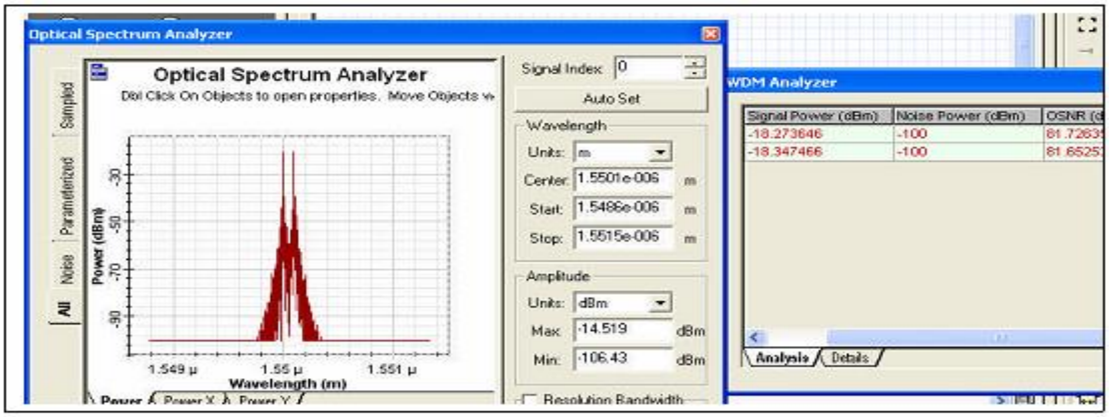


Figure.16 Optical spectrum at the output of the fiber when the channel spacing

is set at 0.1 nm

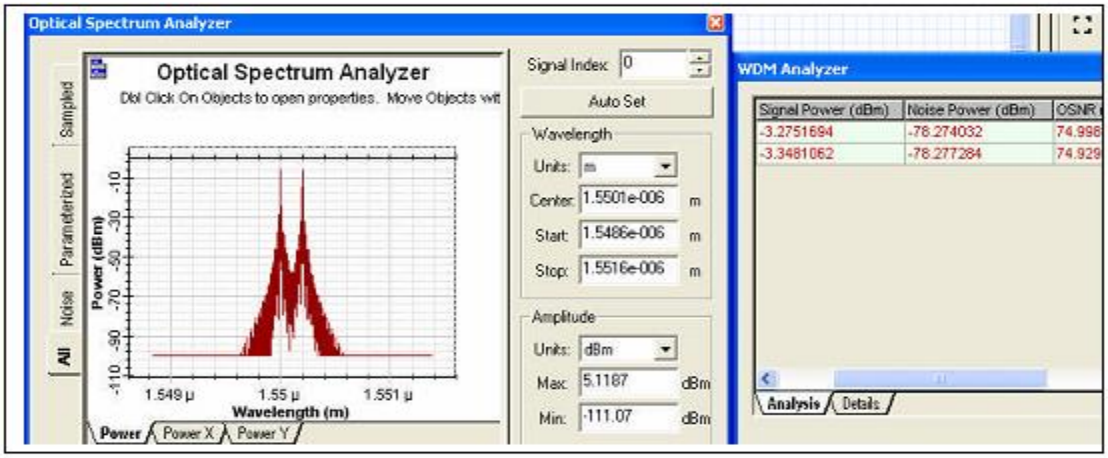


Figure 17 shows the signal at the input channel when the channel spacing is set at 0.2 nm.

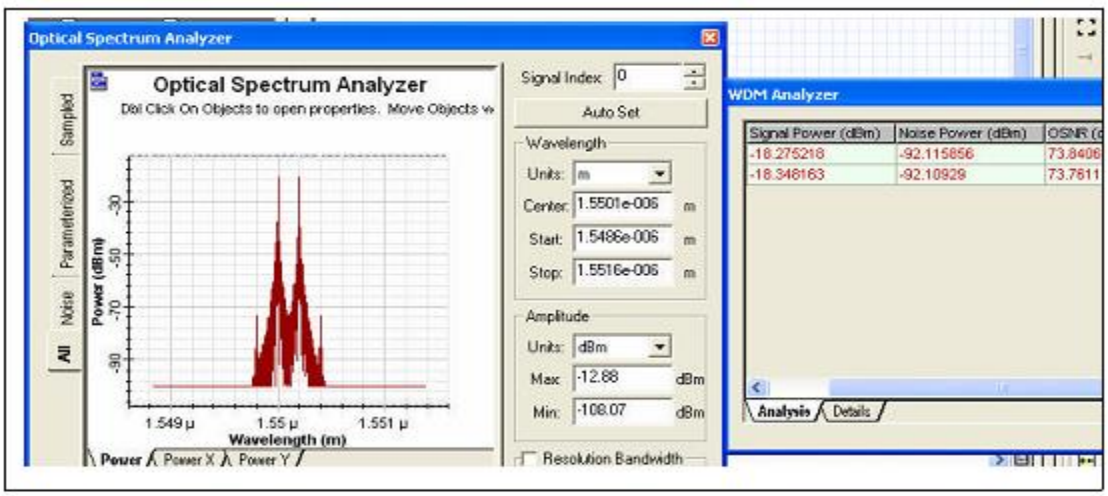


Figure 18 Optical spectrum at the output of the fiber when the channel spacing is set at 0.2 nm

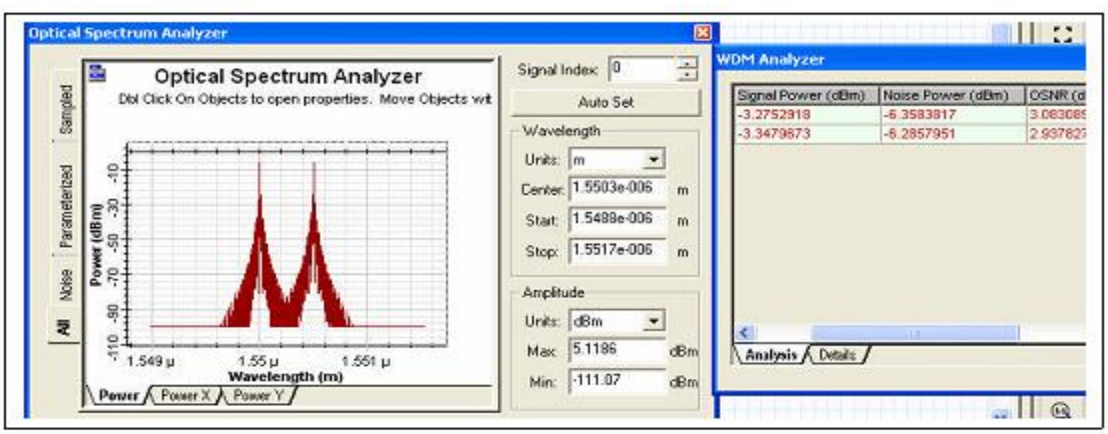


Figure 19 Optical spectrum at the input of the fiber when the channel spacing is set at 0.5 nm

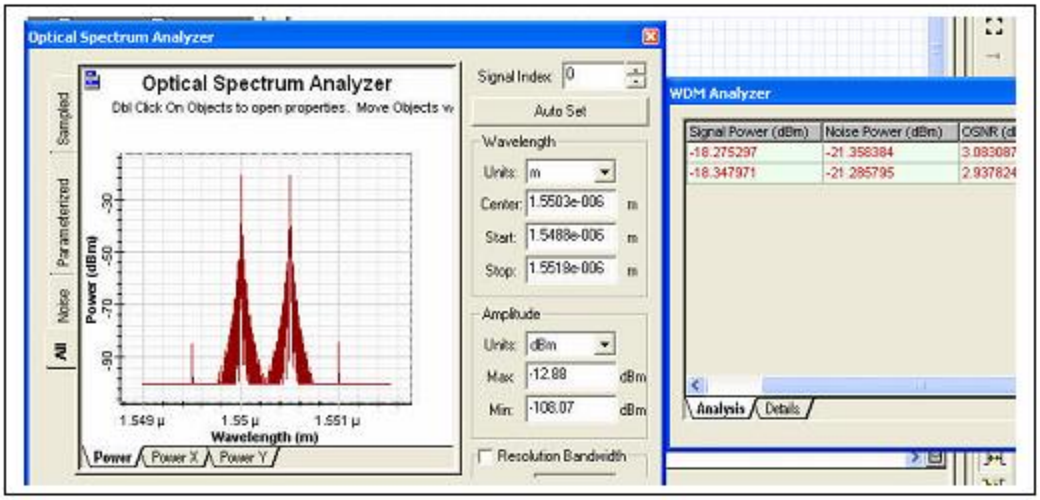


Figure 20 Optical spectrum at the output of the fiber when the channel spacing is set at 0.5 nm

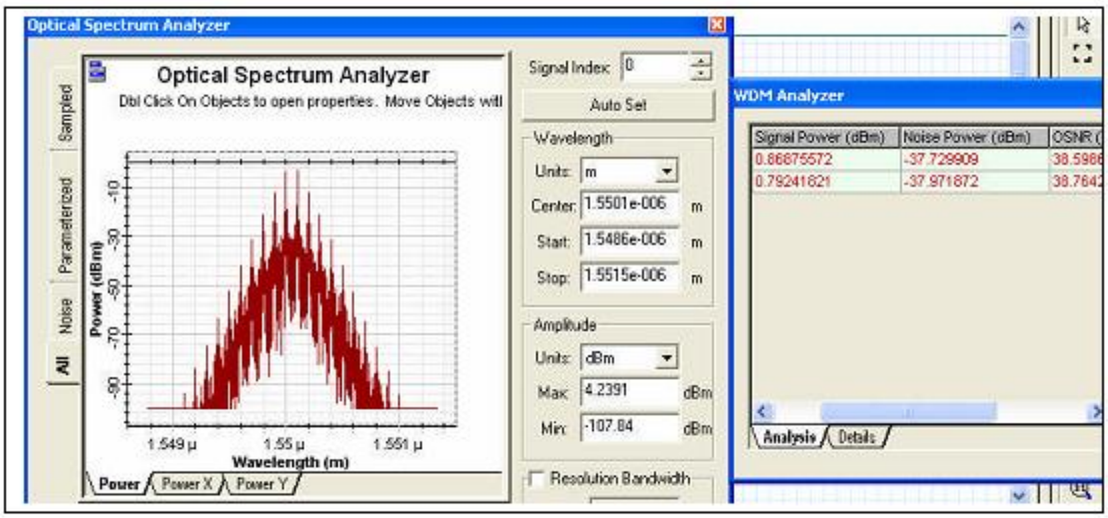


Figure 21 Optical spectrum at the output of the fiber when input power is set at 20 dBm

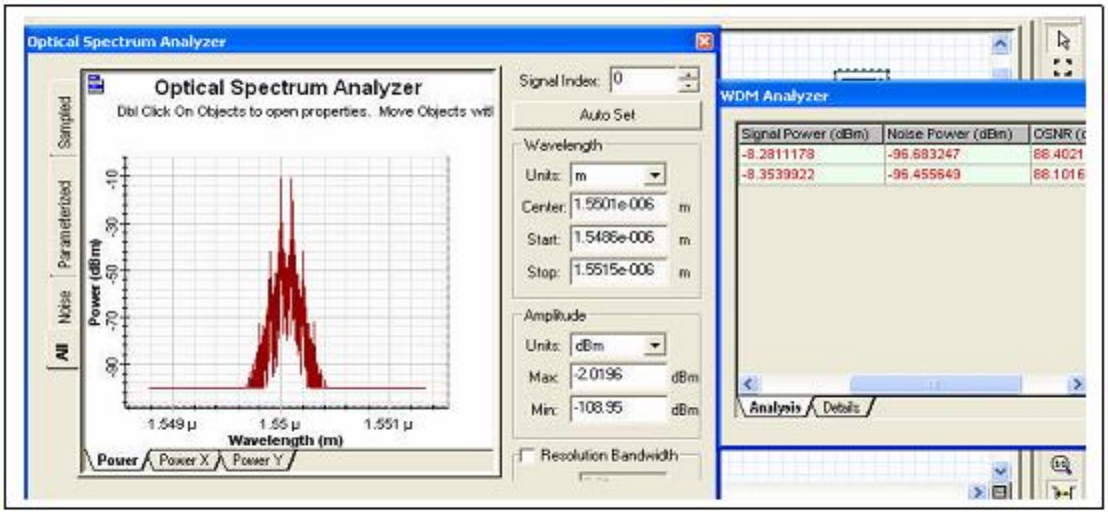


Figure 22 Optical spectrum at the output of the fiber when input power is set at 10 dBm

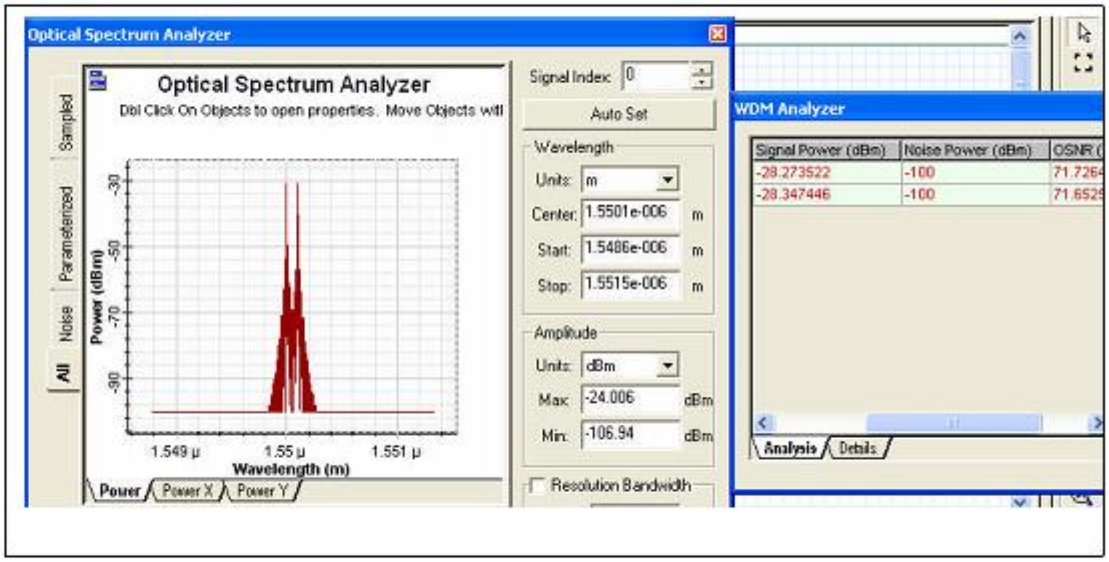


Figure 23 Optical spectrum at the output of the fiber when input power is set at -10 dBm

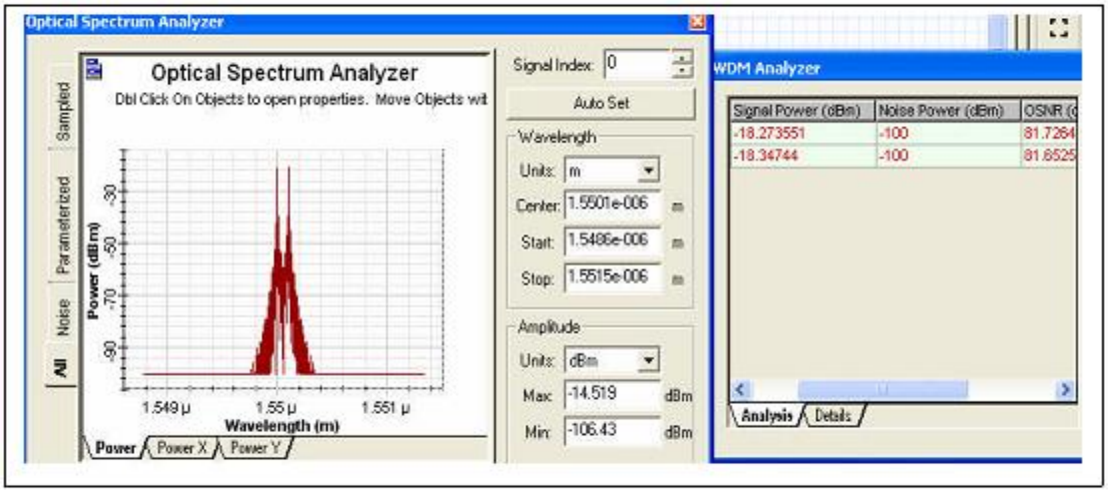


Figure 24 Optical spectrum at the output of the fiber when input power is set at 0 dBm

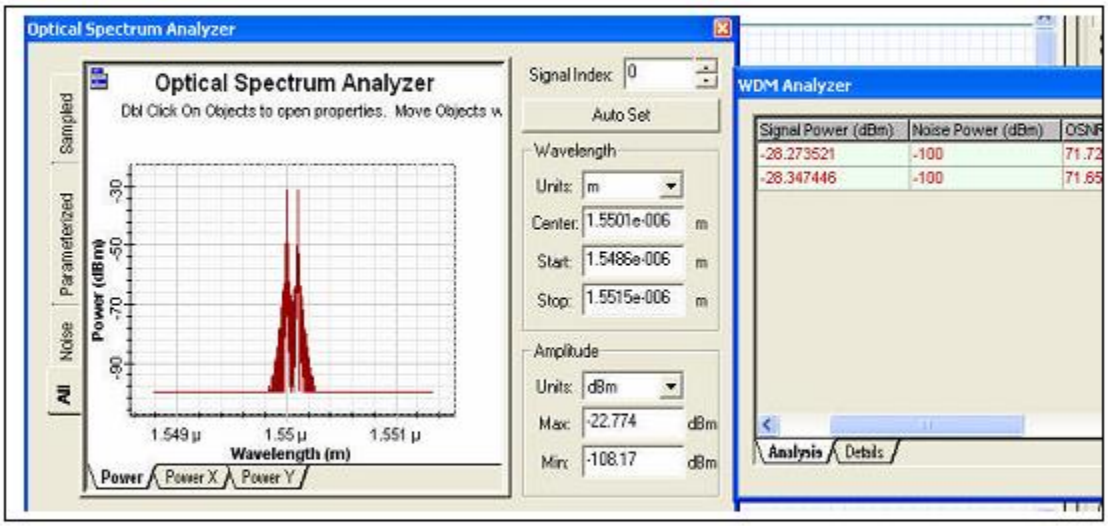


Figure 25 Optical spectrum at the output of the fiber when the effective area of the fiber optic is set at 76.5 μm^2

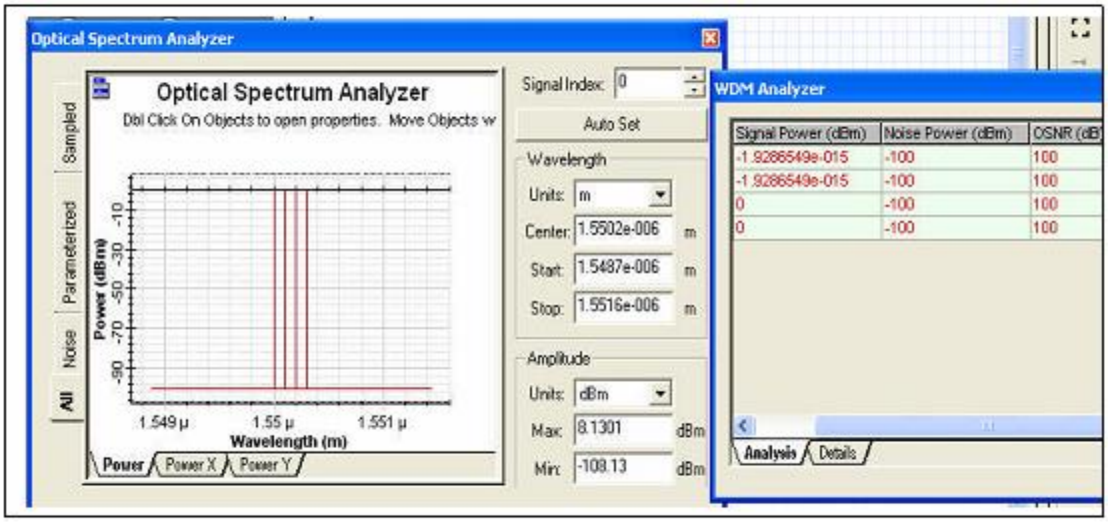


Figure 26 Four optical spectrum at the intput of the fiber when the channel spacing is set at 0.1 nm

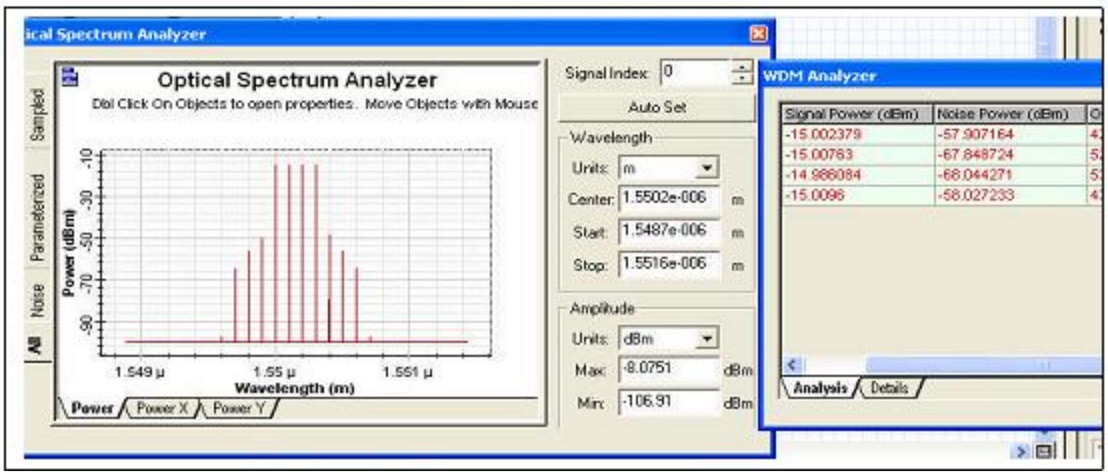


Figure 27 Four output optical spectrum channels when the channel spacing is set at 0.1 nm

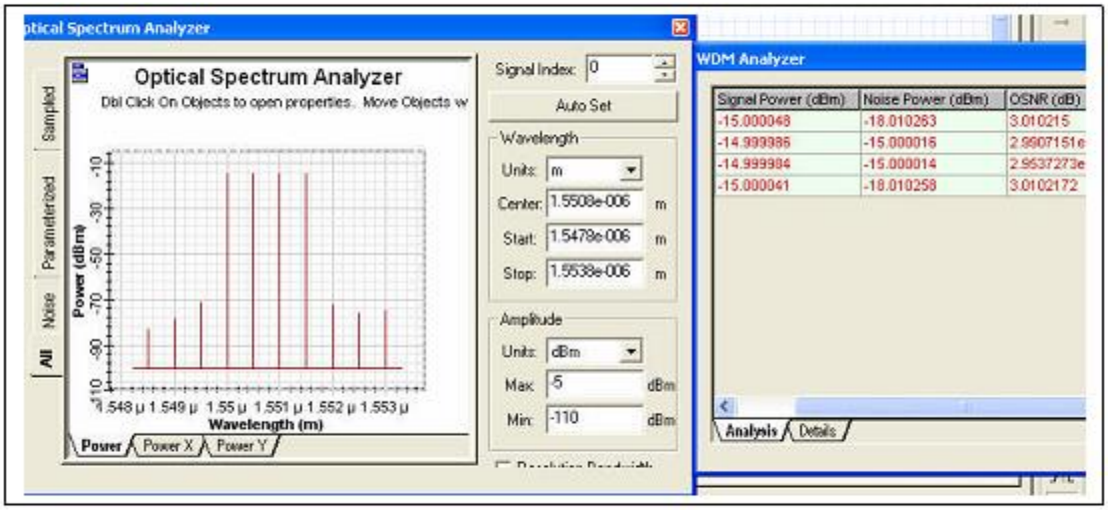


Figure 28 Four output optical spectrum channels when the channel spacing is set at 0.5 nm

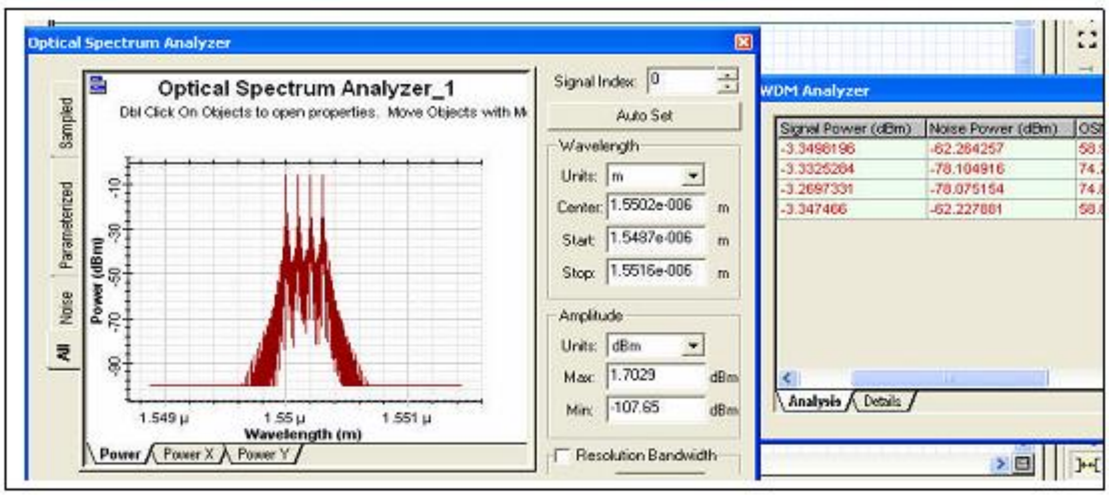


Figure 29 Four Input optical spectrum channels when the channel spacing is set at 0.1 nm

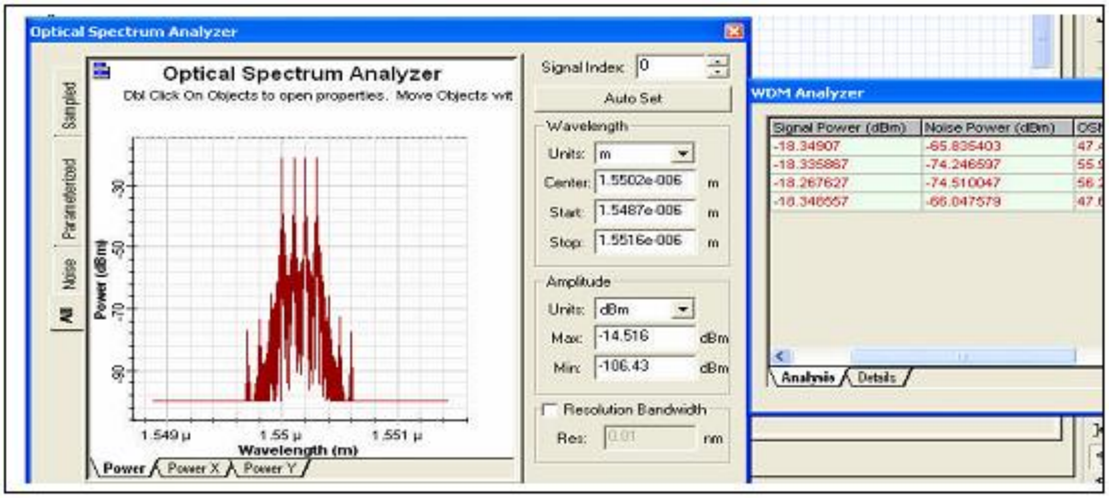


Figure 30 Four output optical spectrum channels when the channel spacing is set at 0.1 nm

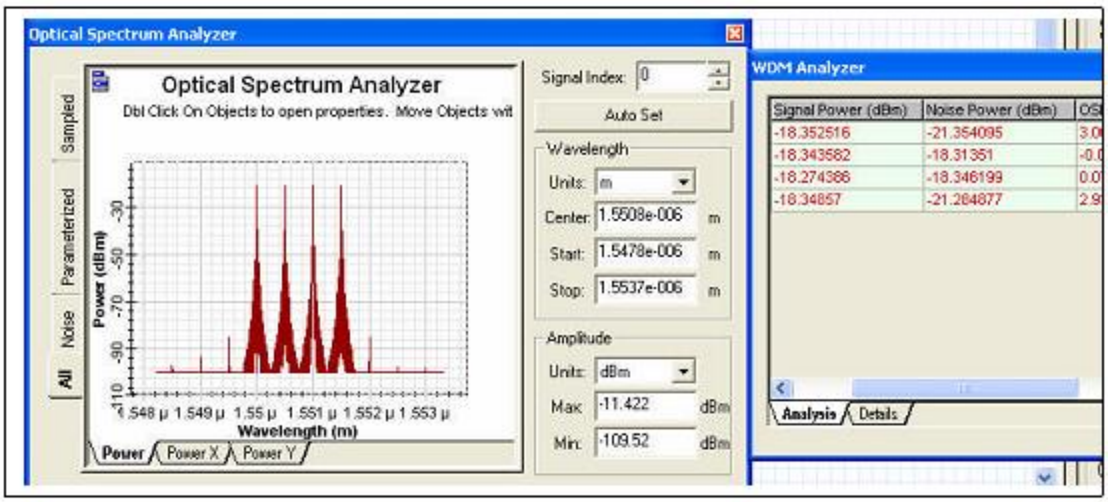


Figure 31 Four output optical spectrum channels when the channel spacing is set at 0.5 nm

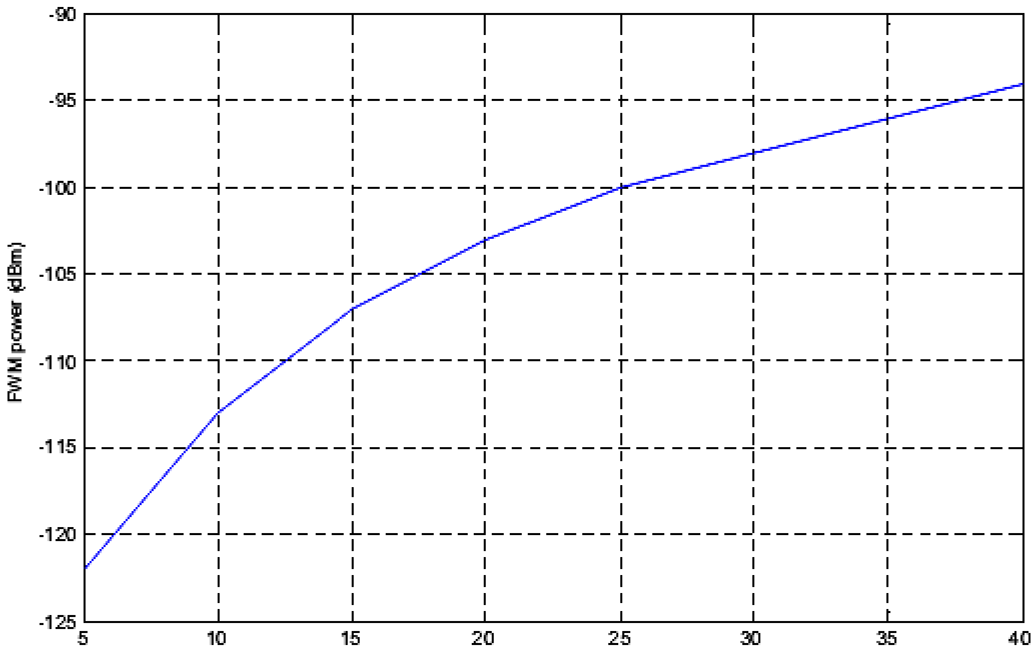


Figure 32 Power per channel vs. FWM power

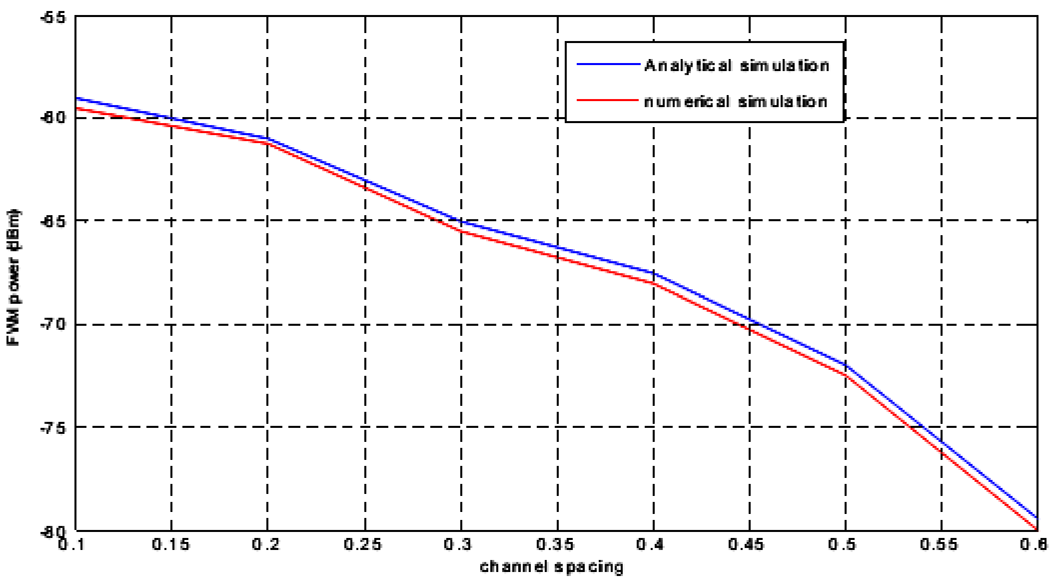


Figure 33 Channel spacing versus FWM power

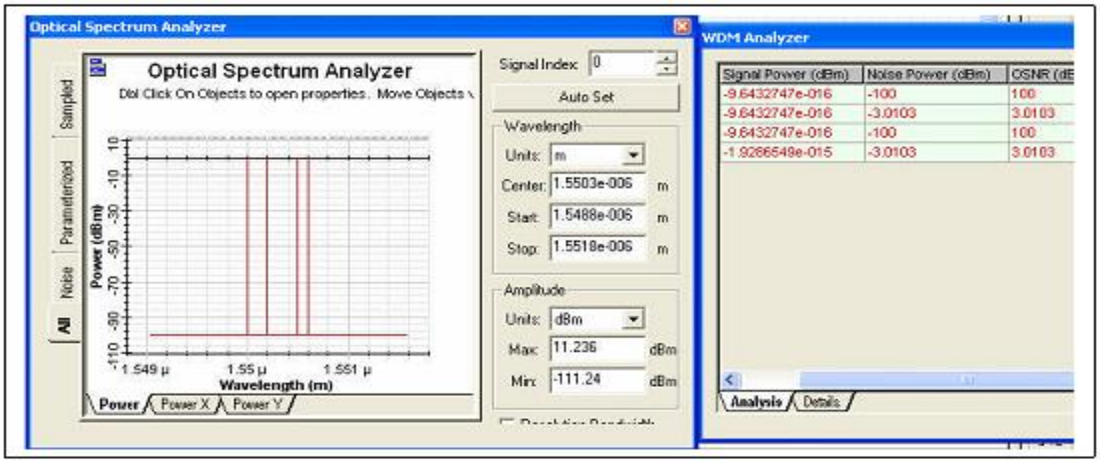


Figure 34 Optical spectrum at the input of the fiber when the channel spacing is unequal

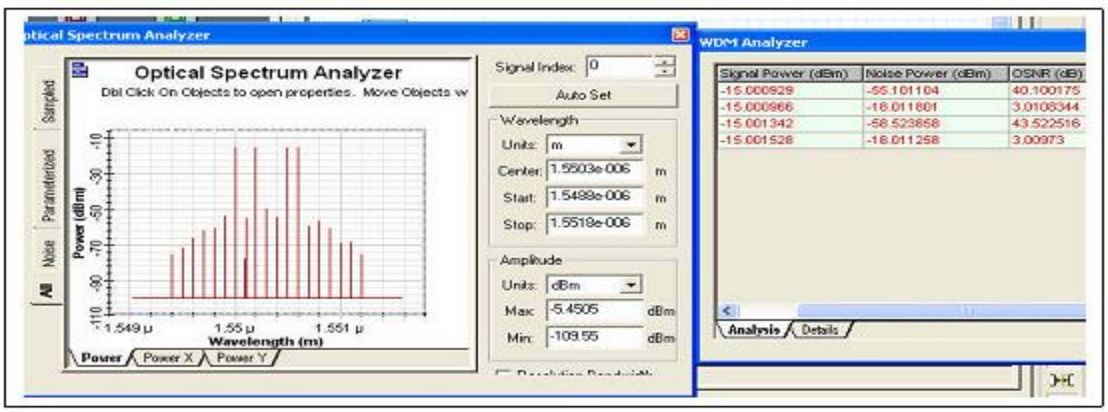


Figure 35 Optical spectrum at the output of the fiber with unequal channel spacing

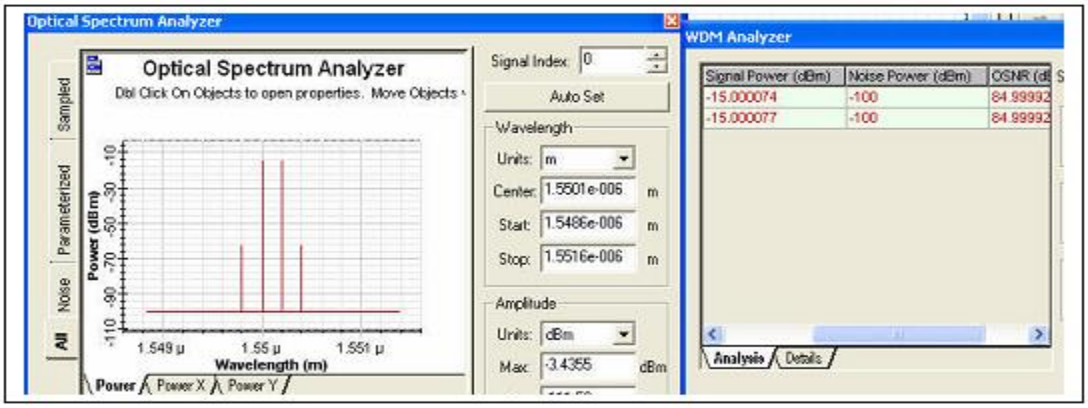


Figure 36 Optical spectrum at the output of the fiber when the effective area of the fiber optic is set at 76.5 μm^2