Software Simulation FWM in WDM Optical Communication Systems

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Abstract

A serious issue for WDM systems is the presence of resonant four wave mixing (FWM) terms, as a result of interactions between different channels. FWM presents a major source of non-linear cross talk. In multichannel systems, third order distortion mechanisms generate third order cross harmonics and a gamut of cross products. These cross products cause the most problems since they often fall near or on top of the desired signals .So the best solution is to avoid the FWM generation from early design stages. This paper describes the sources of FWM in WDM systems. In order to test the FWM generation with different frequency ranges, and different bit rates, different layout has been designed and strategies for getting around this limitation have been proposed. The experiments have been tested both on low and high bit rates, using optical signals with different frequency ranges. Proposed are solutions to avoid FWM for both low rate and high rate optical communication systems

Introduction

In its simplest term, fiber optics is a medium for carrying information from one point to another in the form of light. Unlike the copper form of transmission, fiber optics is not electrical in nature. A basic fiber optic system consists of a transmitting device, which generates the light signal; an optical fiber cable, which carries the light; and a receiver, which accepts the light signal transmitted. The fiber itself is passive and does not contain any active, generative properties.

Since its invention in the early 1970s, the use and demand of optical fiber has grown tremendously. The uses of optical fiber today are quite numerous. The most common are telecommunications, medicine, military, automotive, and industrial. Telecommunications applications are widespread, ranging from global networks to local telephone exchanges to subscribers' homes to desktop computers. These involve the transmission of voice, data, or video over distances of less than a meter to hundreds of kilometers, using one of a few standard fiber designs in one of several cable designs.

Companies such as AT&T, MCI, and U.S. Sprint use optical fiber cable to carry plain old telephone service (POTS) across their nationwide

networks. Local telephone service providers use fiber to carry this same service between central office switches at more local levels, and sometimes as far as the neighborhood or individual home.

Optical fiber is also used extensively for transmission of data signals. Private networks are owned by firms such as IBM, Rockwell, Honeywell, banks, universities, Wall Street firms, and more. These firms have a need for secure, reliable systems to transfer computer and monetary information between buildings to the desktop terminal or computer, and around the world. The security inherent in optical fiber systems is a major benefit.

Cable television or common antenna television (CATV) companies also find fiber useful for video services. The high information-carrying capacity, or bandwidth, of fiber makes it the perfect choice for transmitting signals to subscribers.

Once upon a time, the world assumed that fiber possessed infinite bandwidth and would meet mankind's communication needs into the foreseeable future. As the need arose to send information over longer and longer distances, the fiber optic community developed additional wavelength "windows" that allowed longer transmission. The 1550 nm region, with a loss of only 0.2 dB/km seemed like the answer. Millions of kilometers of fiber were installed around the world creating a high-speed communication network. As requirement changed, the industry responded with wavelength-division multiplexing (WDM), which sends many distinct signals per fiber increasing transmission capacity. However, the need of using WDM left the researchers huge task to deal with fiber nonlinearities.

Fiber non-linearities
1- Basics concepts

The response of any dielectric to light becomes nonlinear for intense electromagnetic fields, and optical fibers are no exception. Even though silica is intrinsically not a high non linear material, the waveguide geometry that confines light to a small cross section over long fiber lengths makes nonlinear effects quite important in the design of modern light wave systems.

The following are some well known fiber nonlinearities:
- SBS Stimulated Brillion Scattering.
- SRS Stimulated Raman Scattering.
- FWM Four wave mixing.
- SPM self phase modulation.
- XPM cross phase modulation.
- Inter modulation (mixing).

They represent the fundamental limiting mechanisms to the amount of data that can be transmitted on a single fiber. This paper will concentrate on evaluating the FWM, which is represents one of the most general but nonetheless important phenomena in nonlinear optics. In this process, two or more waves interact in a nonlinear medium to produce an output at various sum or difference frequencies.

Four-wave mixing can take place in any material. It refers to the interaction of four waves via the third order nonlinear polarization. This process results from the nonlinear index of refraction.

2- Relation between fiber non-linearity and Refractive index.

Refractive index of the glass is dependent on the optical power going through the material; the power dependence has its origin from the third order non-linear susceptibility.

$$N = n_o + n_2 . P/A_{eff} \qquad \qquad \dots (1)$$

n_o - is the refractive index of the fiber core at low optical level

n_2- is the nonlinear refractive index coefficient

P is the optical power

A eff - is the effective area of the fiber core in square meters

It is clear from equation 1, that the nonlinearities could be eliminated by min. P or maximizing the effective area of the fiber core.

The recent technologies are considering maximizing A_{eff}

Wave Division Multiplexing

Wavelength division multiplexing (WDM) 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 result is a link with an aggregate band width that increases with the number of wavelengths employed. In this way WDM technology can maximize the use of the fiber optic infrastructure that is available what would normally require two or more fiber links instead requires only one.

The fiber optic industry first deployed single wavelength transmission on links. As requirement changed, the industry responded with wavelength-division multiplexing (WDM), which sends two distinct signals per fiber doubling transmission capacity. WDM corresponds to the scheme in which multiple optical carriers at Different wavelengths are modulated by using independent electrical bit streams and are then transmitted over the same fiber.

The optical signal at the receiver is de-multiplexed into separate channels by using an optical technique. WDM has the potential for exploiting the large bandwidth offered by optical fibers. For example, hundreds of 10-Gbps channels can be transmitted over the same fiber when

channel spacing is reduced to below 100 GHz. WDM is used to upgrade the capacity of installed point-to-point transmission systems, typically by adding two, three, or four additional wavelengths. WDM systems that use 16 wavelengths at OC-48 and 32 wavelengths at OC-192 to provide aggregate rates up to 40 and 320 Gbps, respectively, are available, fig (1) shows WDM channels which is like different color of light (Sawsan et al, 2005).


Fig. (1): shows WDM channels is like different color of light

Two important considerations in WDM device are crosstalk and channel separation. Crosstalk, also called directivity, refers to separation of de-multiplexed channels. Each channel should appear only at its intended port and not at any other output port. The crosstalk specification expresses how well a coupler maintains this port-to-port separation. One of the major problems related to WDM optical communication systems is FWM (Four wave mixing) (Abeer, 2005).

Four wave mixing

Four wave mixing is caused by non linear nature of the refractive index of the optical fiber it self, and is classified as third order distortion phenomenon. In multichannel systems, third order mechanisms generate third order harmonics and gamut of cross products. These cross products cause the most problems since they can fall near or on top of the desired signals (David, 2002). FWM is the major source of nonlinear cross-talk for WDM communication systems. It can be understood from the fact that beating between two signals generates harmonics at difference frequencies. If the channels are equally spaced new frequencies coincide with the existing channel frequencies. This may lead to nonlinear cross-talk between channels. When the channels are not equally spaced, most FWM components fall in between the channels and add to overall noise (Agrawal, 2001; Agrawal, 2001).

Here we consider a simple three-wavelength (λ_1, λ_2 and λ_3) that are experiencing FWM distortion. In this simple system, nine cross products are generated near λ_1, λ_2 and λ_3 that involve two or more of the original

wavelengths. Note that three are additional products generated, but they fall well away from the original input wavelengths.

Let us assume that the input wavelengths are: $\lambda_{1=\,1550.92\,nm}$, $\lambda_{2=\,1552.52\,nm}$, $\lambda_{3=\,1553.32\,nm}$

As shown in fig (2), three of the interfering products fall right on top of the original three signals. The remaining six products fall outside of the original three signals. The six products can be filtered out. But the three products which fall on top of the original ones can not be filtered out, by any means. The number of the interfering products is calculated according to

$$M= \tfrac{1}{2}(N^{3}-N^{2}) \qquad\qquad\qquad ... (2)$$

Where N is the number of the original products, and M is the number of mixing products

$\lambda_1 + \lambda_2 - \lambda_3 = 1550.92$ nm $\qquad$ $\lambda_1 - \lambda_2 + \lambda_3 = 1552.52$ nm $\qquad$ $\lambda_2 + \lambda_3 - \lambda_1 = 1554.12$

$2\lambda_1 - \lambda_2 = 1550.92$ nm $\qquad$ $2\lambda_1 - \lambda_3 = 1550.12$ nm $\qquad$ $2\lambda_2 - \lambda_1 = 1553.32$

$2\lambda_2 - \lambda_3 = 1551.72$ nm $\qquad$ $2\lambda_3 - \lambda_1 = 1554.92$ nm $\qquad$ $2\lambda_3 - \lambda_2 = 1554.12$
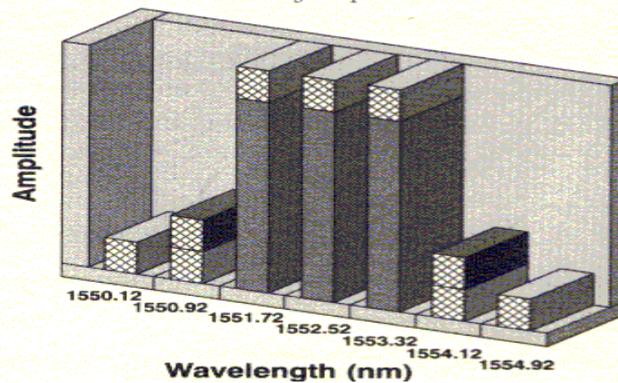
Fig. (2): Shows FWM Generation, where three tall solid bars are the three original signals. Nine cross –hatched bars represent nine interfering products (David, 2002).

Two factors strongly influence the magnitude of FWM products, referred to as (The mixing efficiency), expressed in dB.

1. Channel spacing, mixing efficiency increases with channel spacing becomes closer.
2. Fiber dispersion, mixing efficiency is inversely proportional to fiber dispersion, being strongest at zero-dispersion point.

Some of the measurement results are shown in figure (2), where it can be seen, that with high dispersion like in NDSF (17ps/nm.km), the mixing efficiency will be very low (- 48dB), while using DSF with low dispersion of 1ps/nm.km will cause high mixing efficiency of (- 12 db).
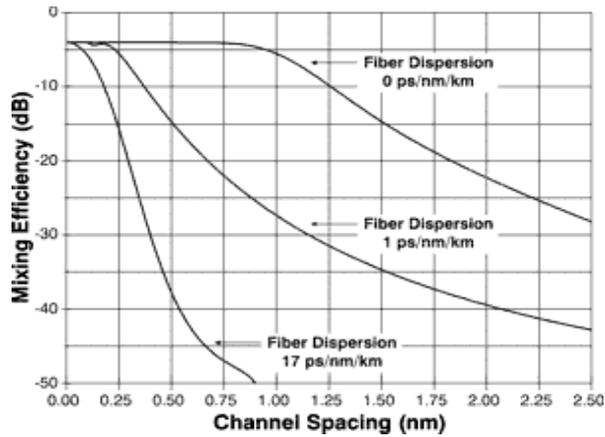
Fig. (3): FWM Efficiency in single – mode fibers

To reduce the effect of FWM to the system performance, one can use either uneven channel spacing or use dispersion-management technique (David, 2002).

Now, given inputs f1, f2, and f3, co-propagate inside the optical fiber, the nonlinear system will generate a fourth field whose frequency is *f*4, related to other frequencies by a relation $f_1 \mp f_2 \mp f_3$.

With the most damaging signals to system performance calculated as:

$$f_{ijk} = f_i + f_j - f_k, where, i \neq j \neq k \qquad \text{… (3)}$$

In principle, several frequencies corresponding to different plus and minus signs combinations are possible. In practice, the frequency combinations of the form:

$$f_4 = f_1 + {}_2 - f_3 \qquad \text{… (4)}$$

Are most troublesome.

According to equation 1and 3, one should expect to see 9 mixing products and for 4 WDM system one should expect to see 24 mixing product. Since there is no way to eliminate products that fall on top of the original signals, the only hope is to prevent them from forming in the first place.

On a fundamental level FWM can be viewed as a scattering process in which two photons of energies $h\omega_1$ and $h\omega_2$ are destroyed and their energy appears in the form of two new photons of energies $h\omega_3$, and $h\omega_4$. The phase matching condition is a requirement of momentum conservation.
The phase mismatch is the main reason behind FWM. It can be the channel spacing and the fiber dispersion is the two factors affecting the FWM.

SM Optical fiber classes

1- NDSF, Non Dispersive Shifted Fiber:

To be used near the window 1310 nm (zero dispersion point). Such fiber has very high dispersion near 1550 nm. SMF-28 manufactured by corning

is good sample. Commonly referred to as single-mode silica fiber, this optical fiber also known as non-dispersion shifted fiber (NDSF). SMF-28, made by corning, is among the most popular NDSF deployed today. NDSF has an operating wavelength for zero chromatic dispersion (called $\lambda\circ$) of 1310 nm. Chromatic dispersion causes a pulse to spread out as it travels a long a fiber due to the fact that different wavelength components that constitute the pulse travel at slightly different speed in the fiber, fig (4) illustrate the four important windows(David, 2002).
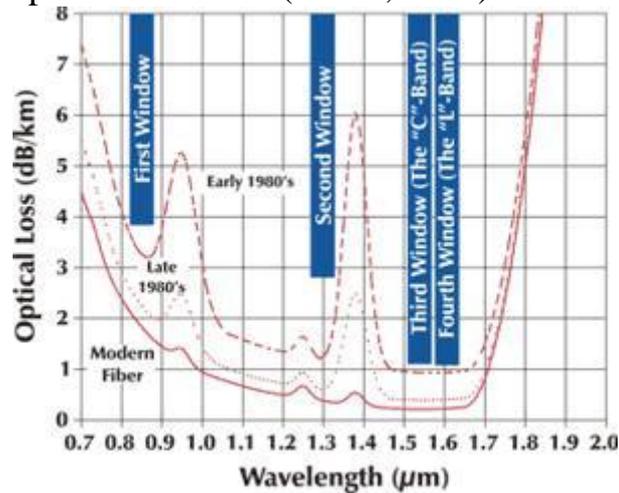
Fig. (4): The four important windows (David R., 2002).

2- DCF Dispersion compensation Fiber:

Dispersion Management means Designing the fiber and compensating elements in the transmission path to keep the total accumulated dispersion to a small number. It based on the idea that an optical pulse subjected to positive dispersion will see its longer wavelength components travel slower than its shorter components. The optical pulse subjected to negative dispersion will see its longer wavelength components travel faster than its shorter components. In modern fiber optic systems, dispersion management element are placed every 100km. DSC - dispersion slope compensator is used to assure long distance systems by dispersion compensation, which is AWG (arrayed waveguide grating) based.

CAD for photonics

The design of a fiber-optic communication system involves using a large number of Active and Passive components such as transmitters, optical fibers, in-line amplifiers, and receivers. The power and the rise-time budgets are only useful for obtaining a conservative estimate of the transmission distance (or repeater spacing) and the bit rate. Simple approach fails for modern high-capacity systems designed to operate over long distances using optical amplifiers. An alleviative approach uses

computer simulations and provides a much more realistic modeling of fiber-optic communication systems. The computer-aided design (CAD) techniques are very helpful to design the whole system and can provide the different tools verify and calculate values of various system parameters, such that the design objectives are met at a minimum. Therefore, to reduce cost, time of practical work firstly, secondly for high accuracy, and third for testing physical effects, the design should be examined first by using the CAD. Optisystem4.0, which is the emerging world leader in photonic design automation design, a license product of Optiwave corroboration a Canadian base company, is used in this paper (Optiwave Corporation, 2002; Optiwave Corporation, 2005).

FWM measurements

The FWM measurements have been done using Optisystem4.0; with the following parameters:

1. Global parameter set up, 2.5Gbit /s up to 40Gbit/s.
2. Using two and four Channels.
3. Multiplexer (Nx1), where N is the number of channels.
4. Using SMF-28 fiber type as fiber link.
5. Using Dispersion Compensation Fiber (DCF), to compensate the fiber dispersion.

First-Experiments with 2.5Gbit /s bit rats.

Case 1:

Two channels (1540 and 1540.5) nm were chosen with small channel spacing (0.5nm).Both Channels were Multiplexed, and sent via 75 Km SMF-28 fiber. FWM will be generated, as shown in fig (5):
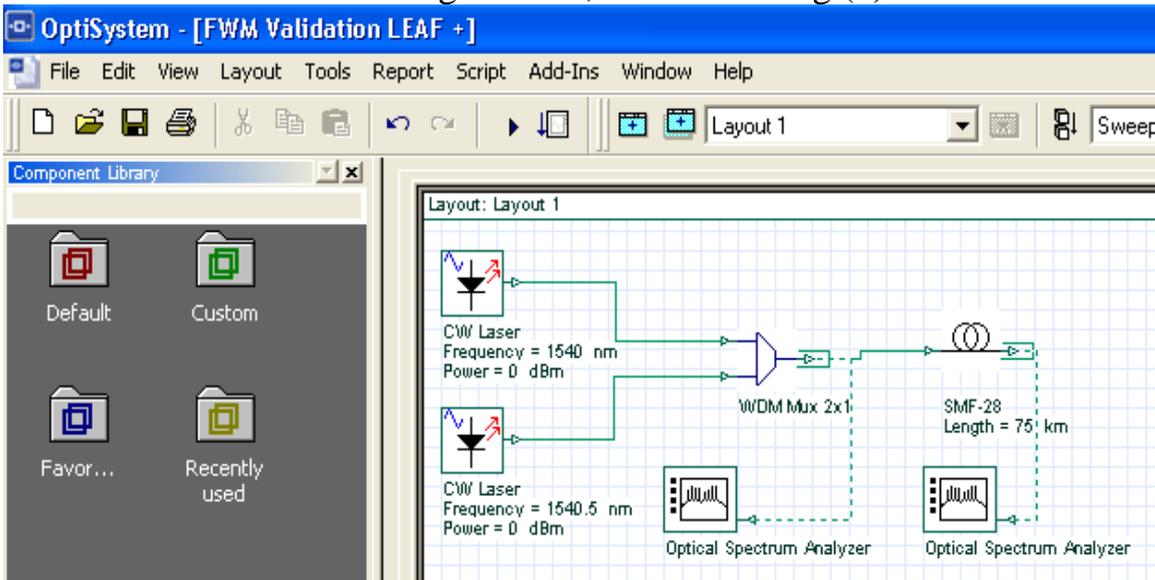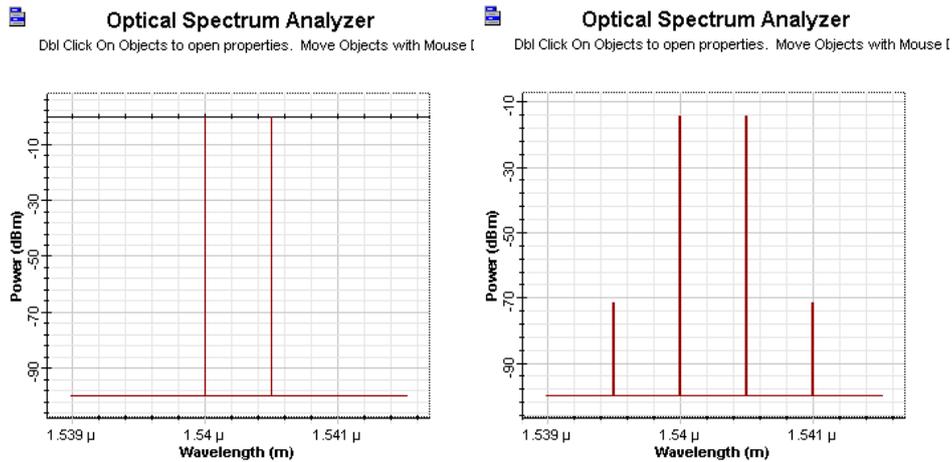
Fig. (5): two channels (1540 and 1540.5) nm with FWM

Case 2: With small channel spacing (1 nm), four channels (1540, 1541, 1542, and 1543) nm, were Multiplexed and sent via the same Fiber. FWM will be generated rats (2.5 Gbit/s) as shown in fig (6):
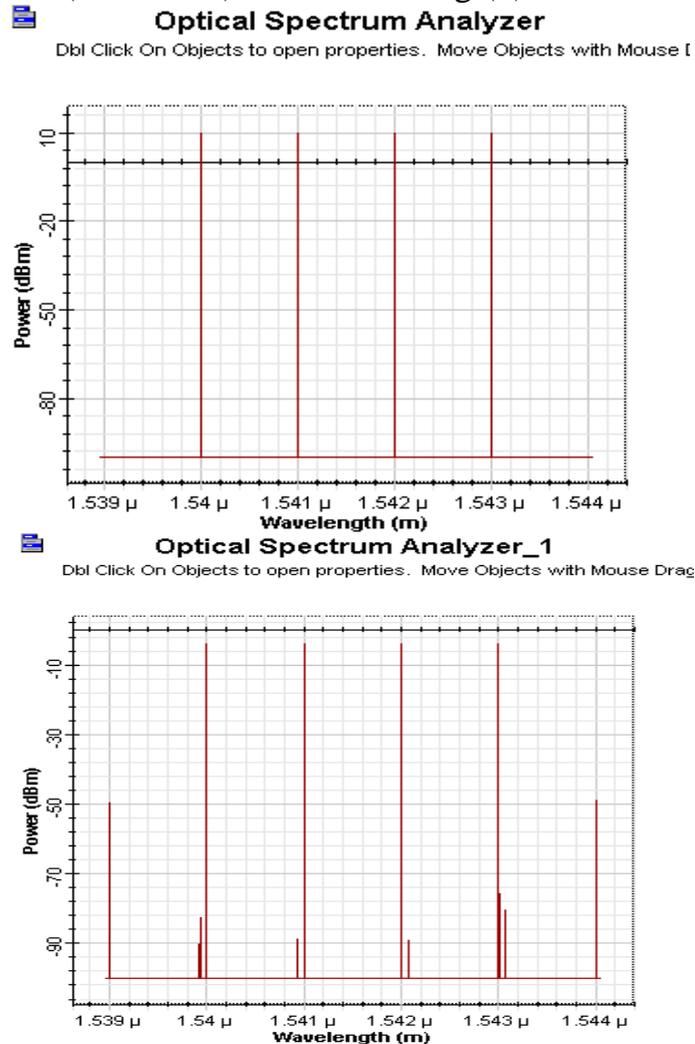

Fig .(6 , A): shows the input four signals to the SMF Figure 6B shows the four signals at the output of SMF Fiber Fiber, affected by FWM.

Case 3:

Using four equally spaced channels (1540, 1550, 1560 and 1570) nm, with large channel spacing (10nm). FWM will not be generated as shown in fig (7 A), and (7B).
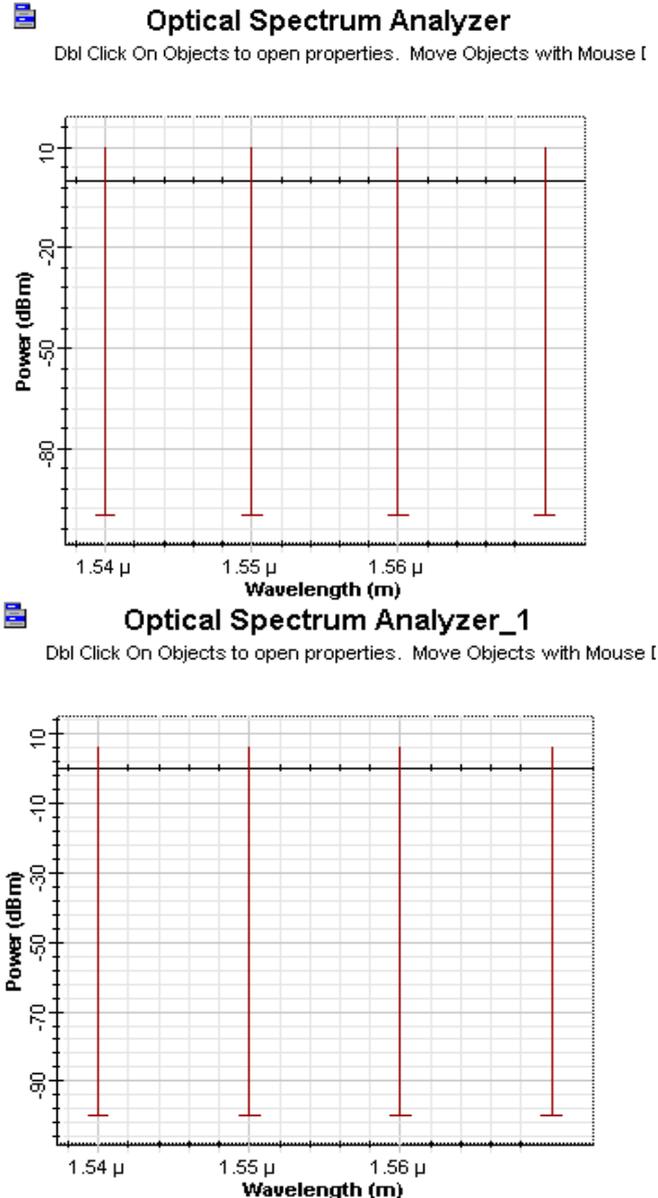
Fig. (7, A): Four channels at the input of the fiber Fig (7B) Four channels at the output of the fiber,

Case 4:

The FWM effects can be avoided by using small unequal channel spacing. The channel spacing should be predefined according to ITU standard (ITU-T-10, 1998) Fig.(8), introduces the design where 4 unequally spaced channels, will solve the problem of FWM as:

The channel spacing is to be at lease 200GHz.

The wave lengths to be between 1531-1540nm
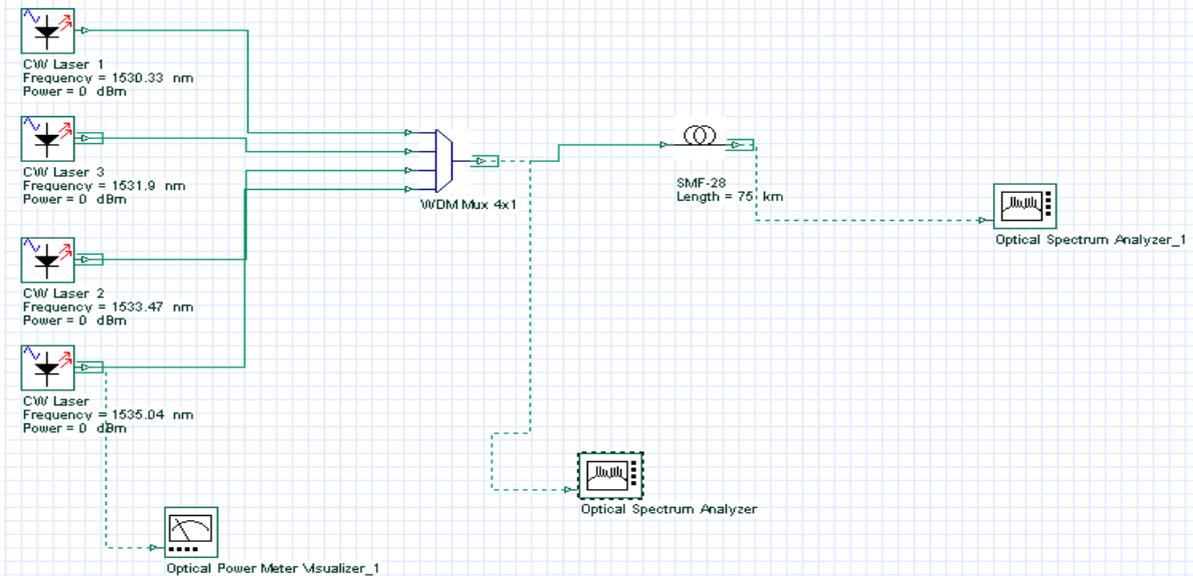
Fig (8): four unequally-spaced frequencies (1530.33, 1531.90, 1533.47, and 1535.04) nm without FWM.

The above unequally-spaced frequencies (1530.33, 1531.90, 1533.47 and 1535.04) nm are chosen due to the condition of ITU-T from table IV.1/ G.692. The SMF-28 fiber characteristics as attenuation and dispersion are downloaded from the software, as shown in fig (9):
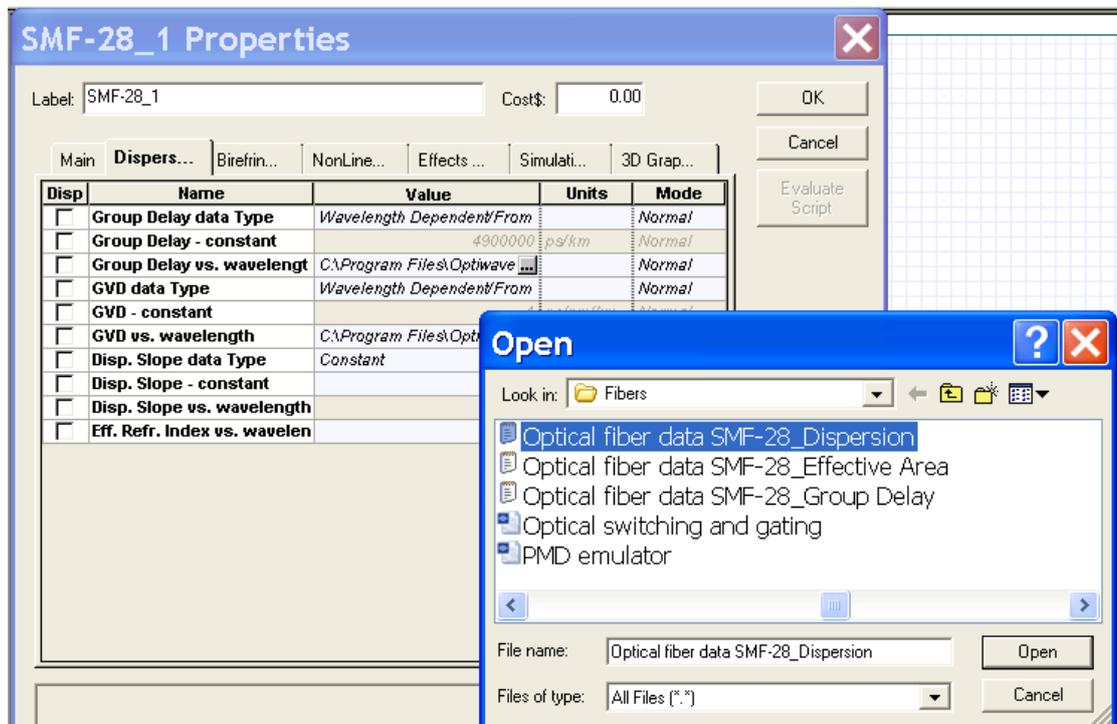
Fig. (9): SMF-28 fiber type characteristic
**The input and output of this system are shown in figure (10A and 10B)**
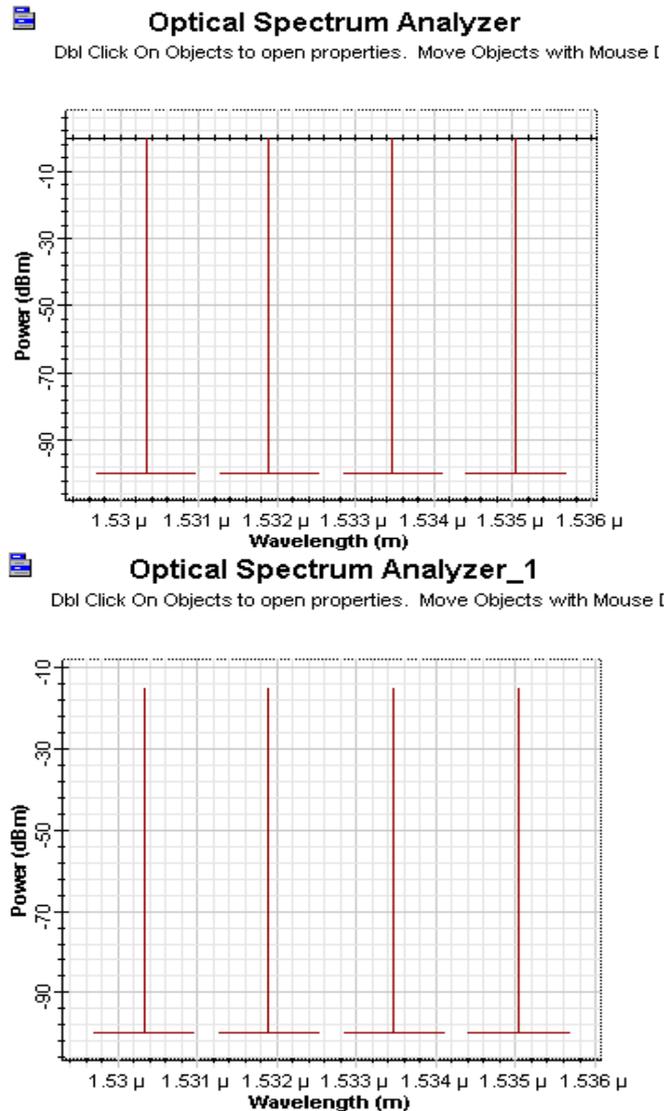
Fig. (10, A): the input and output of four unequally spaced Fig. (10, B): The output of the system, not Frequencies (1530.33, 1531.90, 1533.47, and 1535.04) nm affected by FWM

Second set Experiments with 40Gbit /s bit.

Case 5:

Today 40Gbit/s is the more used bit rates that Optical Communication System, therefore the system shown in figure (10) is recalculated with the same conditions from case 4, but with bit rate of 40Gbit/s. Unlike the design with 2.5 Gbit/s, the output channels experienced FWM, even when using unequally spaced channels predefined by ITU as shown in fig.11
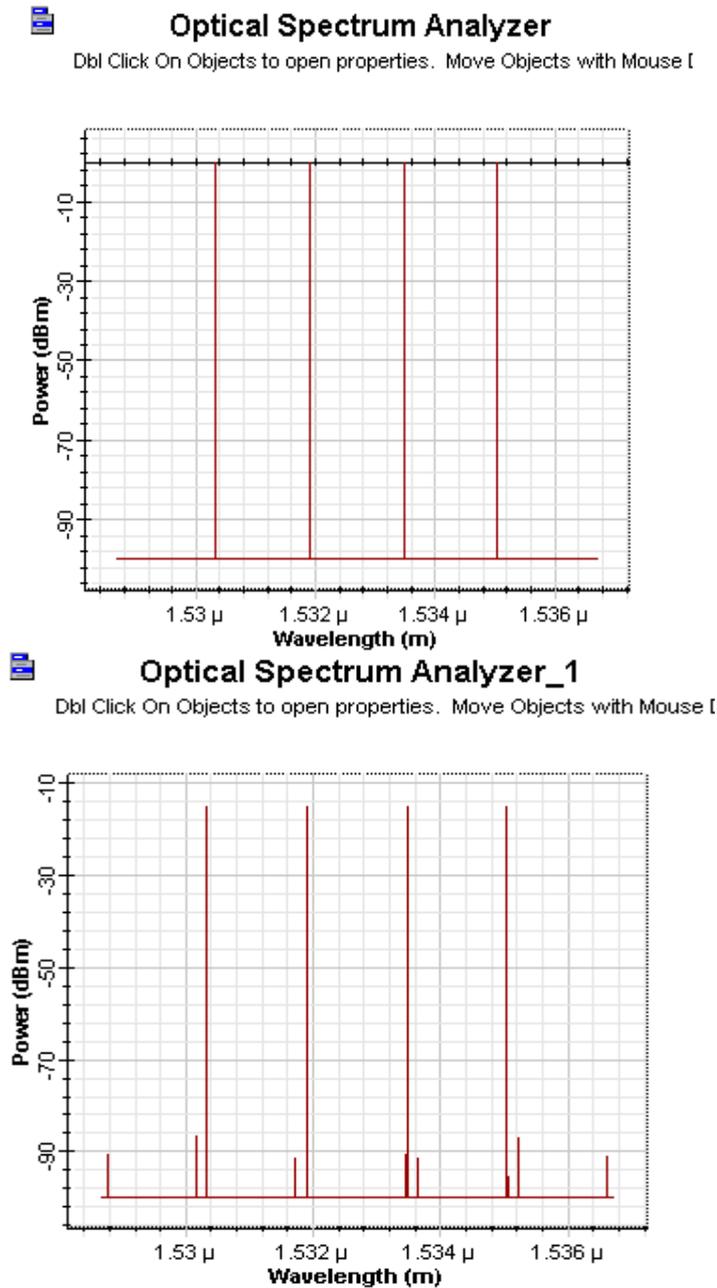
Fig. (11): with 40Gbit/s, the output with FWM is shown

Case 6:

To overcome the FWM effects associated with high bit rats (40Gbit/s), DCF (Dispersion Compensating Fiber) was inserted after the SMF -28 fiber. Optical fiber data, DCF_ Dispersion and Optical fiber data DCF_ Attenuation are loaded from Optisystem 4.0 library, in order to eliminate the FWM components as shown in Fig.12.
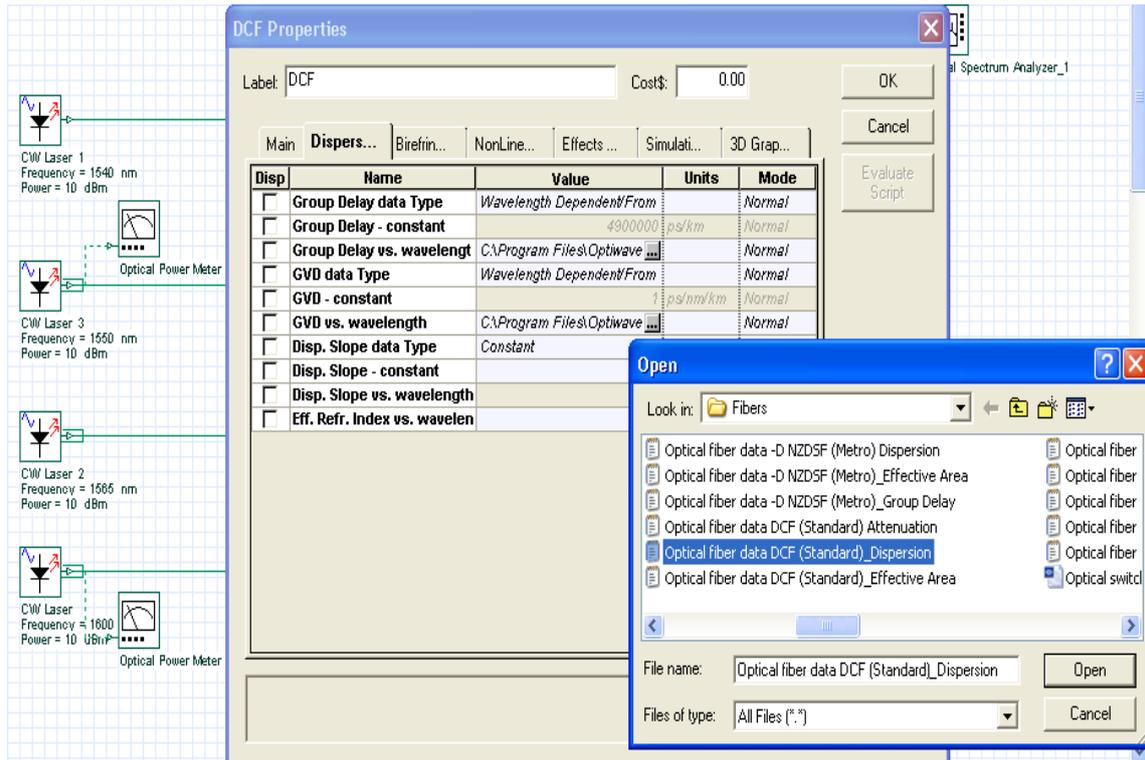
Fig. (12): optical fiber data DCF_ Dispersion and optical fiber data DCF _ Attenuation are loaded from the library of Optisystem 4.0

While Fig. (13, A) shows the signals at the input of the SMF fiber. The output of the SMF, and the input of DCF fiber, was affected by FWM, as shown in fig. (13, b). Fig. (13, C) shows the signals at the output of the DCF, where the FWM have been compensated.
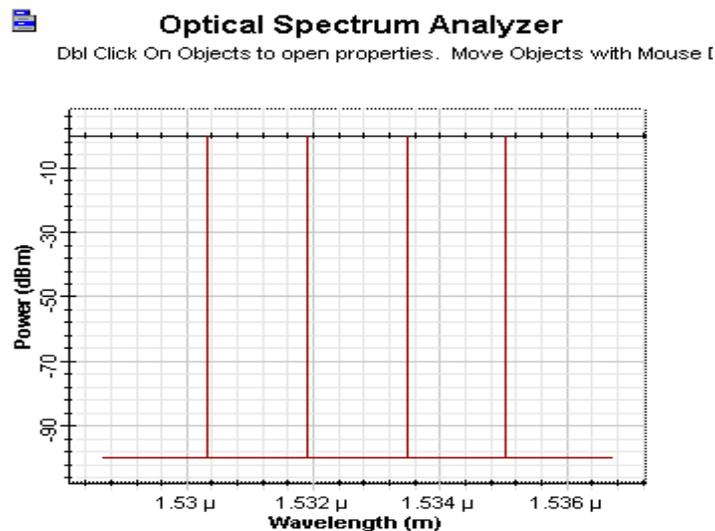

**Fig. (13, A): shows the input signals before SMF fiber**
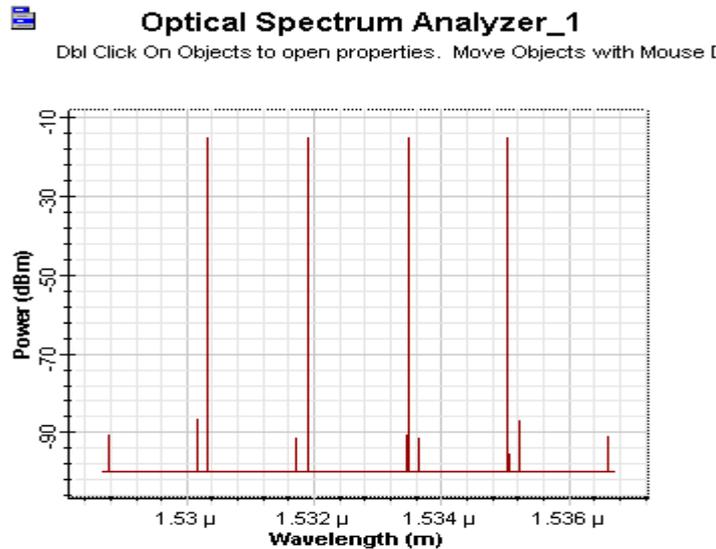
**Fig. (13, B) shows the signals at the output of SMF fiber**
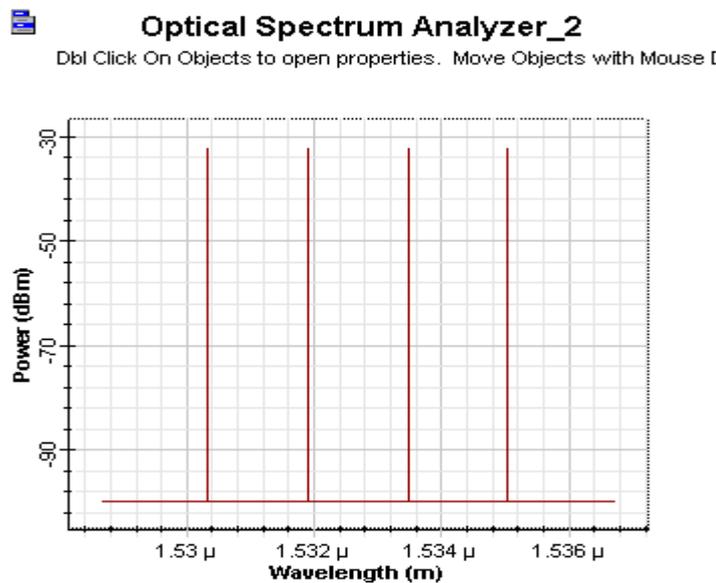
Fig. (13, C): Shows the signals at the output of DCF without FWM

Results

Two bit rate was used to configure FWM effect, 2.5Gbit/s and 40Gbit/s. Two sets of experiments with six cases were used to demonstrate how it will be generated. Also indicated are the conditions necessary to be taken into consideration to avoid FWM generation. Different sets of channels with different channel spacing (small and large), were tested.

Good results were achieved and FWM generation was prevented both in Low and high rate Optical communication systems.

A. In low rate systems, the unwanted FWM were prevented, by using unequally spaced channels predefine according to ITU standard.

B. It has been proved that high bit rate systems can cause FWM generation. Solution to over come this FWM was proposed, where DCF fiber was used to treat unwanted FWM re-appeared with high bit rate systems

Conclusions

FWM is one of the nonlinearity negative effects that characterize multi channel communication systems performance especially with dens WDM. Therefore it must treat within design stage i.e. to overcome FWM the system design must depends on special calculations.

1- System bit rate. For low rate systems (2.5 Gbit/s), conditional choice of unequal channel spacing should be taken into consideration. The unequal spacing should be ranged between 1530-1536nm.

2- For high rate systems, DCF should be used to compensate the high desperation.

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محاكاة برمجية لمازج الموجات الرباعية في أنظمة الاتصالات الضوئية لمازج الرباعي المقسم

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الخلاصة

من القضايا المهمة في منظومات الــ(WDM) هو ظهور مركبات المزج ألمــوجي الربــاعي (FWM) كنتيجة للتأثير المشترك بين القنوات الضوئية المختلفة. وتعتبر (FWM) مصدر رئيسي لظاهرة التداخل الغيــر خطي.في المنظومات المتعددة القنوات، ميكانيكيات التشوهات الثلاثية المستوى تولد توافقيات من المستوى الثالث وتسبب التداخل.

هذه المركبات المتداخلة المتولدة تسبب أغلبية المشاكل حيث انه في الغالب تقع المركبات المتولدة قرب أو فــوق الإشارات المطلوبة، لذا أفضل حل هو تجنب تولد الــ (FWM).

هذه الورقة البحثية تصف مصادر الــ(FWM) في منظومات الــ(WDM)، ولاختبار كيفية توليد(FWM) في مديات مختلفة من الترددات ونسبة ترددات مختلفة،تم تصميم مختلف التصاميم وعرض اســتراتيجيات التغلــب على هذه المشكلة.تجارب البحث أعدت باستخدام النسخة الأخيرة من برنامج التصميم الهندســي للضــوئيات (CAD for photonics)تم فحص تولد الــ (FWM)في حالتي المسافات الترددية المتساوية وغير المتساوية في منظومات الــ (WDM) ، وباستخدام نوعين من الليف الضــوئي (SMI-28, DCF). ولتجنــب توليــد (FWM)في منظومات المسافات الترددية الغير متساوية، اقترحت حلول خاصة ومحددة.

التصميم اختيرت باستخدام نسبة قطع واطئ وعالي مع إشارات ضوئية ذات مدى ترددات مختلفة، وتقديم حلول لتجنب الــ (FWM) في منظومات الاتصالات الضوئية ذات نسبة القطع الواطئ والعالي.