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Four Wave Mixing Mitigation in Already Existing Dense Wavelength Division Multiplexing Networks

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***Abstract* - A Dense Wavelength Division Multiplexing (DWDM) network has been designed and built to investigate the mitigation of Four Wave Mixing (FWM) products. The system considered a real scenario faced by the optical network in locally and internationally DWDM-based networks. The optical links in such networks suffer from nonlinear effects especially FWM because it causes traffic flapping and service degradation. The simulated design contained 16 optical channels with 0.8 nm spacing and 10 Gbps data rate for each channel. The Q. factor, BER and optical power of this system were studied, and it was found that the FWM products generated by such system was limiting the system performance. The mitigation technique was based on changing the polarization of the optical channels to circular polarization and lowering the output power of the transmitted signals. The FWM products had an average power of -45 dBm and after employing circular polarizers and lowering the input power, this value dropped to -73 dBm which led to increase in Optical Signal to Noise Ratio (OSNR) values to about 50% while keeping the other parameters at an acceptable level.**
Keywords – Circular Polarization, DWDM, Four Wave Mixing, FWM Mitigation

INTRODUCTION

Optical fiber-based networks have become one of the most favorable telecommunication systems. Optical fibers provide excellent transmission bandwidth with slight delay. Those optical fibers have recently been the default choice for long haul and high data-rate transmission due to the exponential increase in bandwidth demand [1]. The capacity of optical communication has significantly increased thanks to modern enabling technologies such as Dense Wavelength Division Multiplexing (DWDM), Orthogonal Frequency-Division Multiplexing (OFDM), and Code Division Multiplexing (CDM) [2]. DWDM has been adapted by several internet service providers (ISPs) because of its flexibility, scalability, ease of installation and management of add/dropping of optical channels on-the-go whenever there is an increase on demand for more bandwidth [3]. One of the challenges, which is faced by the R&D (Research and Development) scientists and engineers, is how to maintain large optical networks with easy and cost-effective ways. One of the most troublesome situations that could face the maintenance engineers is the transmission impairments including linear and nonlinear ones. Linear effects such as attenuation and dispersion have been treated by using reduction and mitigation schemes which were developed over the years to compensate those impairments such us optical amplification, dispersion compensation and optical power management [4]. On the other hand, nonlinear effects in optical fibers may possibly degrade the performance of WDM networks. Such nonlinearities may limit the optical power on each channel, number of channels utilized by the system, and the maximum transmission rate, and constrain the channel spacing [5]. The most significant nonlinear effects are self-phase modulation (SPM), cross-phase modulation (XPM) and four wave mixing (FWM). Figure 1 shows the most common linear and nonlinear effects in current optical networking systems (ONS) [4].

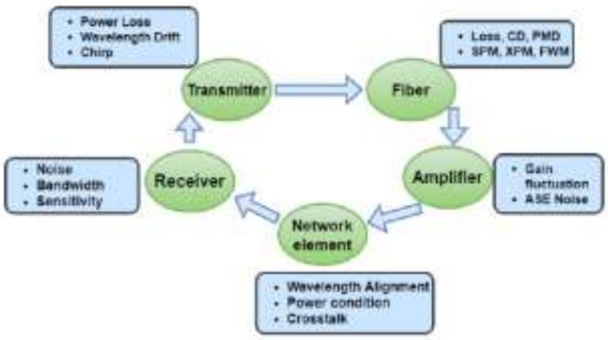

FIGURE 1
OVERVIEW OF VARIOUS OPTICAL IMPAIRMENTS WITHIN OPTICAL NETWORKING SYSTEM

FOUR WAVE MIXING

Nonlinear effects can be classified as second or third order parametric processes, depending on whether they are caused by the second order susceptibility $\chi(2)$ or the third order susceptibility $\chi(3)$. Second order processes such as second harmonic generation should not occur in silica fibers because $\chi(2)$ disappears for a material with inversion symmetry [6]. Third order parametric processes include nonlinear interaction between optical waves and include phenomena like FWM and third-harmonic generation [7]. The origin of FWM lies in the nonlinear response of bound electrons of a material to an electromagnetic field [1]. In DWDM systems, FWM is the most prominent effect which induces crosstalk and resulting in power penalties and limits the input power launched into the fiber [8], causing a reduction in OSNR and increasing BER which restrain the system performance [9]. The physical origin of FWM-induced crosstalk and the resulting system degradation can be understood by noting that FWM generates a new wave at the wavelength [10]:

$$\lambda_{ijk} = \lambda_i \pm \lambda_j \pm \lambda_k \qquad \dots (1)$$

whenever three signals at wavelengths λi, λj and λk copropagate inside the fiber. The worst combination wavelength resulting in degradation of WDM system is [10]

$$\lambda_{ijk} = \lambda_i + \lambda_j - \lambda_k \qquad \dots (2)$$

For an N-channels system, i, j, and k can be in a range from 1 to N, which result in a large combination of new wavelengths generated by FWM, as shown in the below equation [11]:

$$M = N2\ (N-1) / 2 \qquad \dots (3)$$

In the case of equally spaced channels, the new wavelengths coincide with the existing ones, leading to coherent in band crosstalk, but when channels are not equally spaced, most FWM components fall in between the channels and lead to incoherent out of band crosstalk. In both cases, the system performance is degraded because of a loss in the channel [12]. The average number of FWM crosstalks interfered every channel is N(N-1)/2 [13].

Figure 2 shows signal distortion of 40 Gbit/s signal with transmission over 480 km span (8x60 km spans) of a compensated SMF with 7 dBm launch power [14].

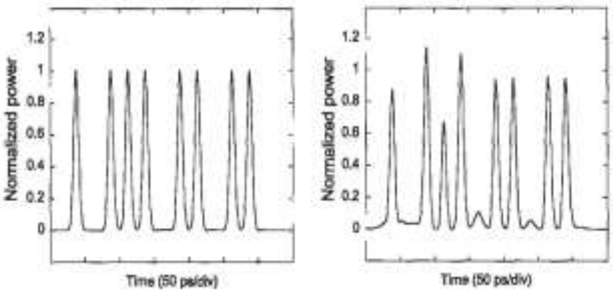

FIGURE 2

THE INPUT SIGNAL (LEFT) AND THE EFFECT OF FWM (RIGHT) AFTER TRANSMISSION

CIRCULAR POLARIZER

A circular polarizer composed of a metal-coated fiber polarizer and a λ/4 platelet fabricated on a birefringent fiber. A diagram of a fiber circular polarizer is shown in figure 3, consisting of fiber polarizer and stress-induced birefringent fiber parts [15]. The fiber polarizer is formed on a part of the birefringent fiber. The stress-inducing part of the fiber polarizer section is eliminated as shown in figure 3 to maintain the state of polarization. The circular polarizer changes the azimuthal polarization of incoming pulses of light into 90 and -90 degrees based on its orientation [16,17]. The azimuthal polarization is the polarization in which the polarization vector is tangential to the beam. This way electric field of adjacent pulses is at 180 degrees of each other, so the interaction of adjacent pulses is lower which leads to the reduction of FWM [18].

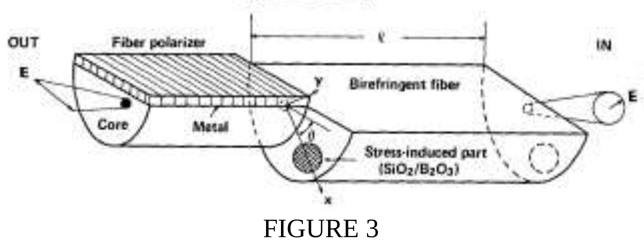

FIGURE 3
FIBER CIRCULAR POLARIZER DIAGRAM [15]

INITIAL SYSTEM DESIGN

A 16 optical channels DWDM system was designed and simulated using Optisystem ver. 15. Bit rate of 10 Gbps per channel was used so that the overall capacity will be 160 Gbps (10 Gbps x 16 channels). The built system contains a WDM transmitter consisting of 16 channels from 1530.33 nm to 1542.33 nm with 0.8 nm spacing and each having 0 dBm optical power and 100

MHz linewidth. The modulation was set to return-to-zero (RZ) as it has been reported by literature that this type help to reduce FWM products [12]. The transmitter outputs are connected to a multiplexer (MUX). The MUX is then linked to a single mode fiber (SMF) with a length of 100 km. The SMF is followed by a dispersion compensating fiber (DCF) of 26.4 km length. The DCF is then connected to 38 dB gain optical amplifier. On the receiver side a demultiplexer (DEMUX) was used followed by an optical receiver block. The receiver block contains an optical receiver and BER analyzer to analyze the received signal. Figure 4 shows the simulation setup.

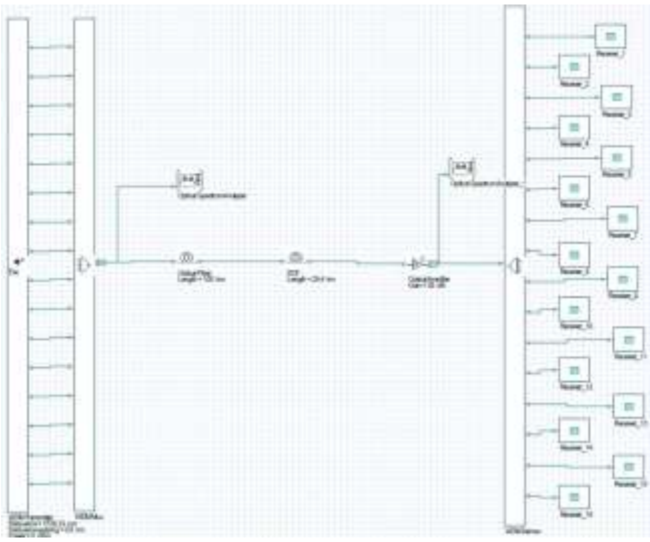

FIGURE 4
SIMULATION SETUP OF DWDM SYSTEM

All the above-mentioned values were selected based on the design parameters of an original case study parameters in a local ISP company except for the DCF which was calculated as follows.

Dispersion Compensating Planning

Signal: 10 Gbps, CD_{limit}: ±1000 ps/nm,

Length: 100 km, SMF with Dispersion equals to 16.75 ps/(nm.km) at λ = 1550 nm

First, dispersion compensation was calculated

$CD_{SMF} = Dispersion\ x\ Length$ … (4)

$CD_{SMF} = 16.75 \times 100$

$CD_{SMF} = 1675\ ps/nm$

And since dispersion limit for this system is:

$CD_{limit} = \pm 1000$ ps/nm, then dispersion compensation was needed.

From Table (1) [19], for this system the CDSMF must be:

$CD_{limit} - CD_{DCF} \geq CD_{SMF}$ … (5)

to compensate the dispersion.

Now, the positive and negative limit was calculated to select a suitable DCF for dispersion compensation.

$CD_{DCF} \leq 1000 - 1675 = -675$ ps/nm → Positive limit

CDDCF ≥ -1000 – 1675 = -2675 ps/nm → Negative limit

Thus, the CDDCF will be:

$$-2675 \text{ ps/nm} \leq \text{CDDCF} \leq -675 \text{ ps/nm}$$

The DCF38 fiber has dispersion -38.0 ps/(nm.km), so two segments of 13.2 km length should be used to completely compensate the dispersion.

$CD_{DCF} = 2 \times L_{DCF} \times CD_{DCF38}$ … (6)

$= 2 \times 13.2 \times -38$

$= -1003.2\ ps/nm$

The total dispersion is then:

$CD_{total} = CD_{DCF} + CD_{SMF}$ … (7)

$= -1003.2 + 1675$

$CD_{total} = 671.8\ ps/nm$,

which is below the dispersion compensation limit.

TABLE (1)
THORLABS DCF38 CHROMATIC DISPERSION COEFFICIENT

Bit Rate/ Channel (Gbps)	SDH	SONET	CD_{limit} (ps/nm)
2.5	STM-16	OC-48	12000 – 16000
10	STM-64	OC-192	800 – 1000
40	STM-256	OC-768	60 – 100

RESULTS

After running the simulation shown in figure (4), the following results were obtained from the OSA before and after transmission. Figure (5) shows the optical spectrum of the transmitted optical channels before and after passing through the optical link. After passing through the fiber, the power levels of the transmitted channels were decreased and FWM products emerged, with an average value of -45 dBm which must be mitigated to eliminate any crosstalk that could occur that would hinder the system performance. The FWM products were created because of the high input power of the optical channels and the narrow channel spacing. Table (2) shows the obtained results from WDM analyzer and BER analyzer for channels 1, 2, 4, 8 and 15, 16.

TABLE (2)
WDM AND BER ANALYZERS OUTPUT AFTER TRANSMISSION

Wavelength (nm)	Signal Power (dBm)	OSNR (dB)	Q. Factor	BER
1530.33	4.34	49.73	8.21	1.04E-16
1531.13	4.30	49.69	8.30	4.88E-17
1532.73	4.30	54.55	7.43	5.43E-14
1535.93	4.30	57.24	7.77	3.97E-15
1541.53	4.29	49.68	7.58	1.61E-14
1542.33	4.30	49.69	7.34	1.02E-13

The values of the OSNR for the leading and trailing wavelengths (1530.33, 1531.13, 1541.53 and 1542.33 nm) are the lowest because of the impact of FWM products on them as its clearly shown in figure (5). Because of the presence of the FWM effect, the values of BER, OSNR and Q. Factor differ from one wavelength to the other.

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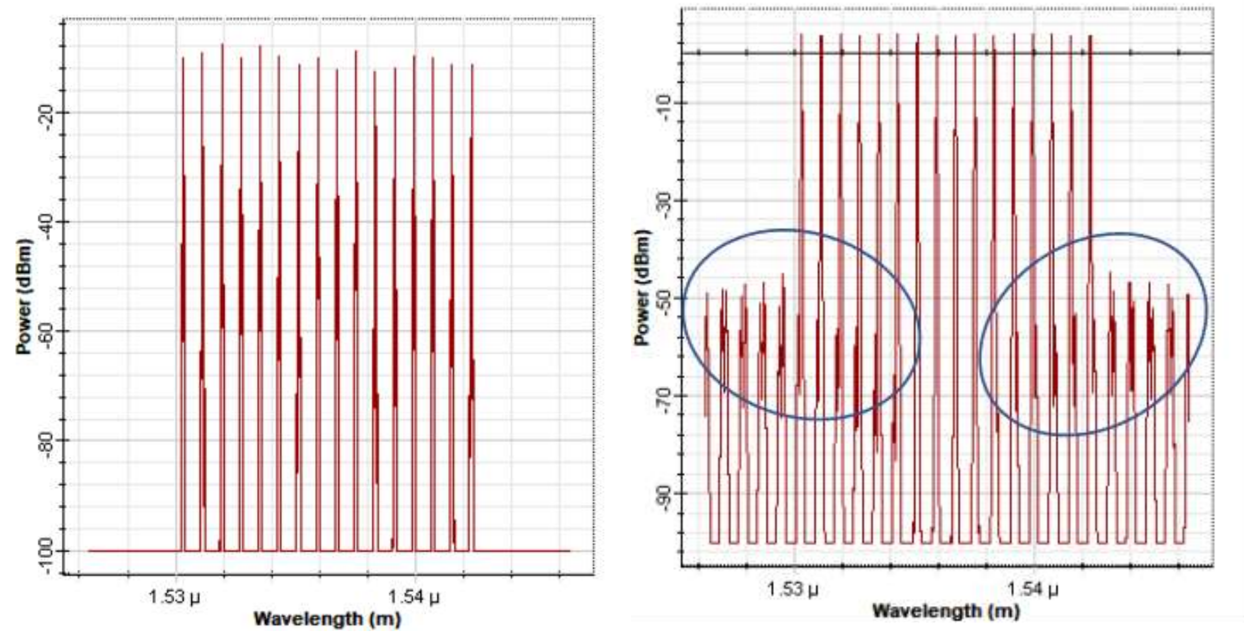


(a) (b)

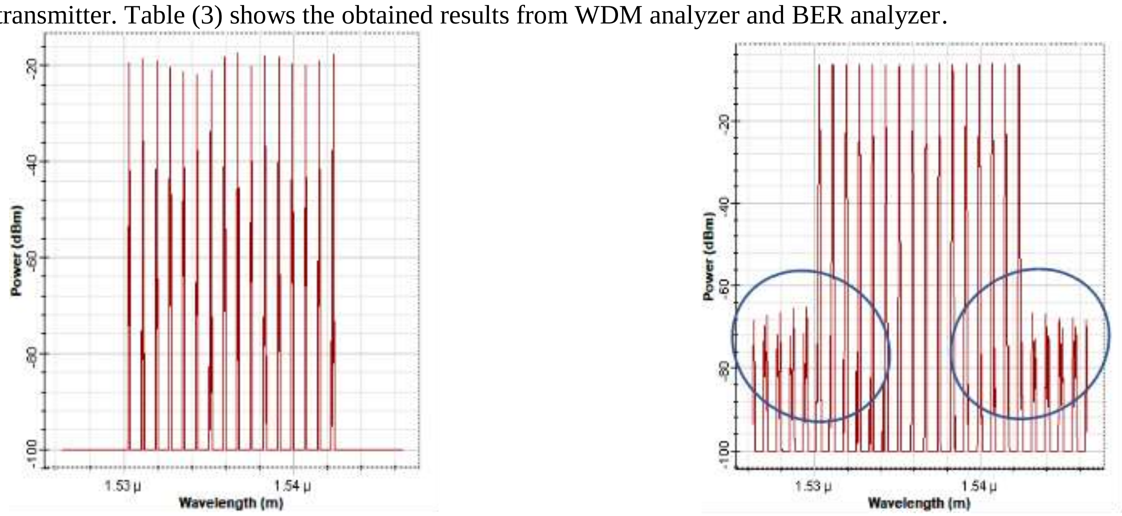
FIGURE 5
OPTICAL SPECTRUM a) BEFORE AND b) AFTER TRANSMISSION SHOWING THE FWM PRODUCTS IN BLUE CIRCLES

DECREASING LASER OUTPUT POWER

The OSNR is degraded when FWM products fall on the frequency grid. Due to the fact that FWM output is proportional to the cube of optical carrier power, even a tiny increase in fiber-launched power decreases the OSNR dramatically [16]. Therefore, the suggested laser power was reduced to -10 dBm (0.1 mW). The resulted spectrum is shown in figure (6).

RESULTS

Figure (6) clearly shows that the FWM products were dropped to an average value of -65 dBm after decreasing the output power of the laser in the transmitter. Table (3) shows the obtained results from WDM analyzer and BER analyzer.



(a) (b)

FIGURE 6
THE OPTICAL SPECTRUM AFTER LOWERING THE INPUT POWER OF THE LASER a) BEFORE AND b) AFTER SHOWING THE FWM PRODUCTS IN BLUE CIRCLES

TABLE (3) WDM AND BER ANALYZERS OUTPUT AFTER DECREASING THE POWER (POWER PER CHANNEL = -10 dBm)

Wavelength (nm)	Signal Power (dBm)	OSNR (dB)	Q. Factor	BER
1530.33	-5.66	61.92	7.99	6.85E-16
1531.13	-5.69	61.88	8.00	5.84E-16
1532.73	-5.70	67.10	7.53	2.41E-14
1535.93	-5.69	68.65	7.61	1.30E-14
1541.53	-5.70	61.90	7.80	3.04E-15
1542.33	-5.70	61.90	7.76	4.27E-15

Comparing the above table with table (2), the value of the signal power decreased without affecting the system performance since they are still within the acceptable levels. On the other hand, the OSNR values increased (about 24%) because of the drop in FWM products power.

ADDING CIRCULAR POLARIZERS

Circular polarizers (CPs) were added to the transmitter side to alter the polarization of input pulses into left and right-handed circular polarization. The same previous system was used without altering or modifying any parameter. Figure (7) shows the new system setup.

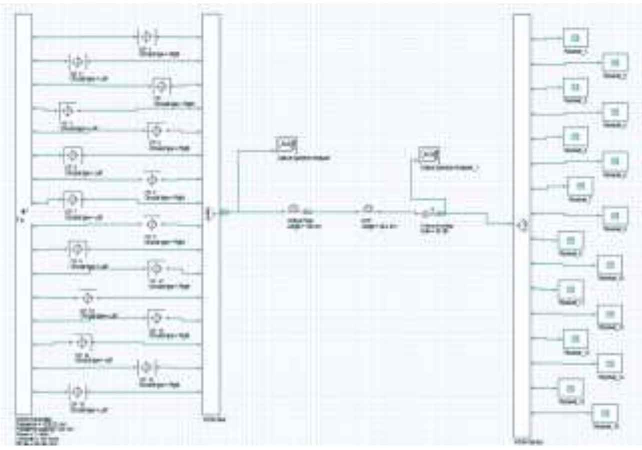


FIGURE 7
SYSTEM SETUP AFTER ADDING CPs

TABLE (4)
SIMULATION RESULTS AFTER EMPLOYING CPs

Wavelength (nm)	**Signal Power (dBm)**	**OSNR (dB)**	**Q. Factor**	**BER**
1530.33	-8.6636646	72.561982	6.2149	2.50E-10
1531.13	-8.7026312	72.523016	6.9249	2.07E-12
1532.73	-8.7059856	73.076293	6.28843	1.54E-10
1535.93	-8.7059187	76.731502	6.33337	1.16E-10
1541.53	-8.7028518	72.505152	6.18952	2.85E-10
1542.33	-8.7089762	72.499028	5.93784	1.40E-09

RESULTS

The FWM products were further reduced after employing the CPs, as shown in figure (8). The FWM signals now have an average value of -79 dBm while maintaining acceptable values of BER, Q. Factor and OSNR as shown in table (4).

Figure (8) clearly shows how the leading and trailing FWM products were reduced, and the middle products have been completely removed and OSNR values also increased about 52% over the first proposed system.

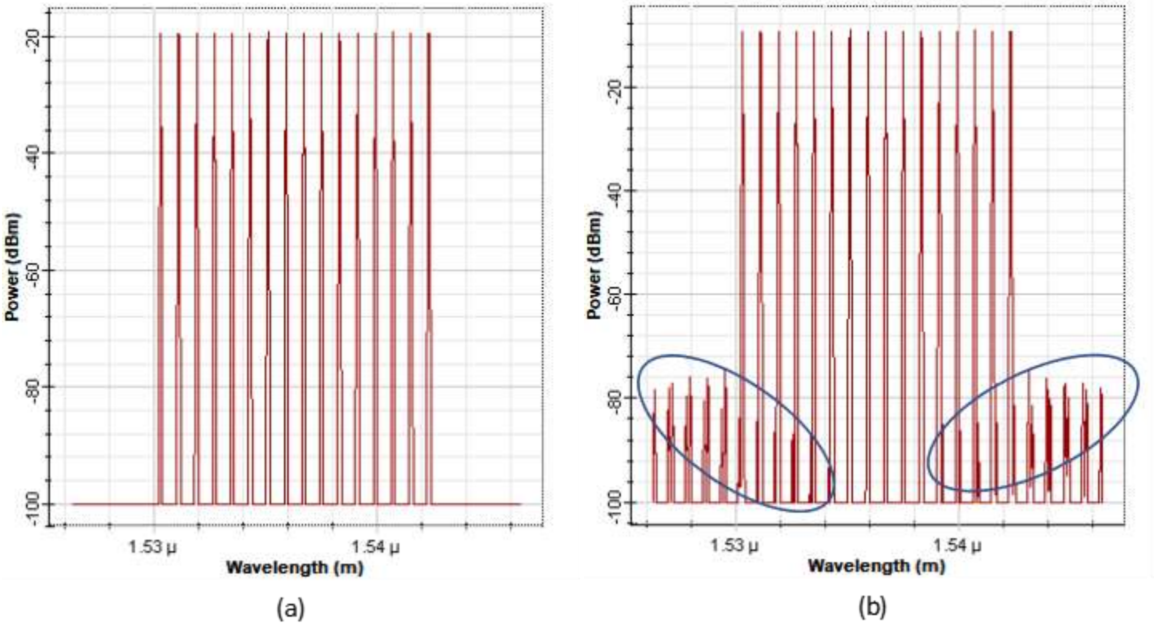


FIGURE 8
OPTICAL SPECTRUM AFTER EMPLOYING CPs a) BEFORE AND b) AFTER TRANSMISSION SHOWING THE FWM PRODUCTS IN BLUE CIRCLES

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CONCLUSION

The transmission performance of the proposed optical network system has been investigated. The investigation has focused on the system performance key parameters: Q. factor, BER, Signal power, OSNR and FWM products values. Simulation results have been reported for laser input power of 0 dBm and -10 dBm and compared to the results after employing the circular polarizers. The investigation revealed the following main conclusions:

- In the absence of the circular polarizer, the Q. factor, BER, Signal power and OSNR were all within the acceptable ranges, but the system suffers from FWM which causes intrachannel crosstalk which leads to loss in the carried traffic. The obtained value of FWM was about -49 dBm.
- Decreasing the output power of the laser before transmitting the signals into the fiber helped reducing the FWM products to an average value of -65 dBm.
- The circular polarizer played a great role in reducing the effect of FWM by decreasing the value of the products to about -80 dBm which resulted in a 50% increase in OSNR value.

The suggested techniques can be easily implemented to already existing networks with the need to modify the original system parameters. Decreasing the output power of the laser can be done by adding passive optical attenuators directly per channel and circular polarizers can also be added to the transmitted channels on the transmitter side.

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