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Suppression of Four-Wave Mixing in WDM Systems using Bessel Optical Filter

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ABSTRACT: -

The nonlinear effect reduces the system performance of optical fiber communications (OFC). Nonlinear effects tend to surface themselves when optical power is very high, hence, they become relevant in wavelength division multiplexing (WDM) systems. Four-wave mixing (FWM) is one of the prominent degradation effects in WDM systems. FWM is a parametric process in which different frequencies interact and by frequency mixing generate new spectral components. FWM can have significant deleterious effects in OFC systems, particularly in the context of WDM where it can cause crosstalk between different wavelength channels. From obtained results, the proposed Bessel Optical Filter (BOF) system help minimize the noise in the system from -61dBm to -100dBm compared to previously obtained value from -18dBm to -88dBm while employing duobinary modulation. Hence, this paper presents the design, performance analysis and reduction of FWM effect on the basis of output spectrums and threshold value of input power using BOF.

Keywords: WDM, Four-Wave Mixing, Bessel Optical Filter, Optisystem.

I. INTRODUCTION

Nonlinearities in optical fiber can lead to distortion, interference and excess attenuation of the optical signals, resulting in performance degradation. The most popular optical nonlinear effect of importance in optical fiber communication systems results from the nonlinear fiber refractive index. The nonlinearity in the refractive index is known as Kerr nonlinearities. The Kerr nonlinearity gives rise to different effects, such as self-phase modulation (SPM), cross-phase modulation (XPM), and four-wave mixing (FWM) [6,8]. FWM is a type of optical Kerr effect and occurs when light of two or more different wavelengths is launched into a fiber. Generally speaking, FWM occurs when light of three different wavelengths is launched into fiber, giving rise to a new wave (known as an 'idler'), the wavelength of which does not coincide with any of the others. FWM is a kind of optical parametric oscillation. Figure 1 below is a schematic diagram that shows FWM in the frequency domain. As can be seen, the light that was there from before launching, sandwiching the two pumping waves in the frequency domain, is called the probe light (or signal light). The idler frequency, Fidler may then be determined by the equation:

$$F_{idler} = f_{p1} + f_{p2} - f_{probe}$$

Where fp1 and fp2 are the pumping light frequencies, and fprobe is the frequency of the probe light [7]. This condition is called the frequency phase – matching condition. FWM can have important deleterious effects in optical fiber communications, particularly in the context of wavelength division multiplexing (WDM) where it can cause cross-talk between different wavelength channels, and/or an imbalance of channel powers [5].

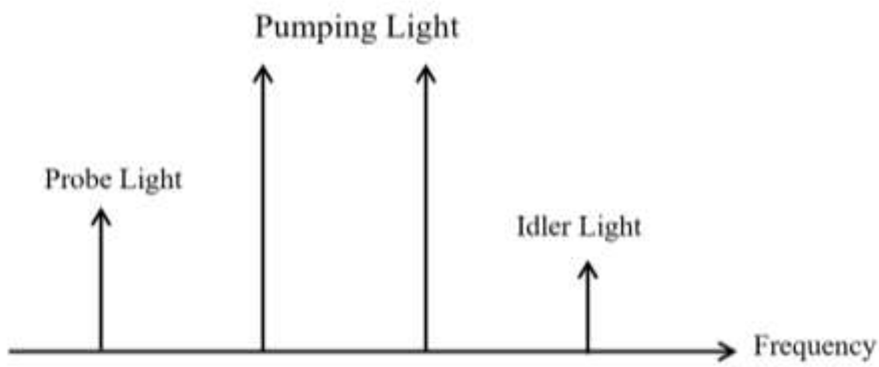

Figure 1. Two channel pump wave

FWM can transfer data to a different wavelength. A continuous wave pump beam is launched into the fiber together with the signal channel. Its wavelength is chosen half-way from the desired shift. FWM transfers the data from signal to the idler beam at the new wavelength [4,9].

II. RELATED WORK

Lei Xu et al (2022) designed a silicon membrane metasurface consisting of dimer airy holes, as a

versatile platform for generating four-wave mixing (FWM). They showed that such a metasurface exhibits a multi-resonant feature, including a quasi bound state in the continuum (BIC) generated by the collective toroidal dipole mode excited in the designed subdiffractive periodic system. They demonstrated that via employing the BIC mode in the short-wave infrared (SWIR), together with other resonant enhanced electric near fields in the near-infrared (NIR) region, simultaneously, one can convert invisible SWIR light to visible light radiation with high efficiency, via FWM. They experimentally demonstrated a significant FWM emission enhancement from their metasurface, which leads to a conversion efficiency of 0.76×10^{-6} using pump and signal beam peak intensities as low as 0.33 GW cm^{-2} and 0.17 GW cm^{-2}, respectively. Obtained results open new routes for enhancing nonlinear efficiencies for up-conversion processes. They have demonstrated highly-efficient FWM from a silicon dimer-hole membrane metasurface with double resonances. The proposed membrane metasurfaces support a strong quasi-BIC TD mode around at the signal beam wavelength, and simultaneously it enables strong electric near-field enhancement due to the multipolar responses from MD, EQ, and EO at the pump beam wavelength. Such a multipolar resonant metasurface can significantly boost the nonlinear FWM process.

Yang Qu et al (2021) theoretically investigated and optimized four-wave-mixing (FWM) in silicon Nitride (SIN) waveguides integrated with 2D layered Graphene oxide (GO) films, they performed detailed analysis on the influence of device parameters including waveguide geometry, GO film thickness, length and coating position, on the FWM conversion efficiency(CE) and Conversion Bandwidth (CB). The influence of dispersion and photo-thermal changes in the GO films ia also discussed. Owing to the strong mode overlap between the SIN waveguides and the highly nonlinear GO films, FWM in the hybrid waveguides can be significantly enhanced. They obtained good agreement with previous experimental results and show that by optimizing the device parameters to balance the trade-off between Kerr nonlinearity and loss, the FWM CE can be improved by as much as -20.7Db and the FWM CB can be increased by -4.4 folds, relative to the uncoated waveguides. These results highlight the significantly enhanced FWM performance that can be achieved in SIN waveguides by integrating 2D layered GO films.

D. Uzunidis et al (2019) In their work, derived closed-form expressions which incorporate the impact of modulation format on FWM generation, extending and improving the accuracy compared to existing closed-form FWM expressions. Moreover, the proposed method includes terms that make it applicable to systems with small span lengths (<30 km), which is the case in metro networks. The accuracy of the proposed formulas is benchmarked against a numerical method, where the signal transmission is modeled using the split step fourier method (SSFM), for a wide range of system configurations and parameters. They have derived and validated the accuracy of a closed-form formula which includes the impact of modulation format on FWM generation. This method can be used to estimate the optical performance for a wide range of system configurations and parameters spanning from metro applications to long-haul and submarine transmissions.

Pawel M. K. et al (2019) presented a comprehensive experimental and numerical investigation of the impact of system parameters on wavelength converters based on Four-wave-mixing (FWM) with focus on practical system implementations in addition to the interaction within the non-linear medium. The input signal power optimization is emphasized according to the trade-off between the linear and nonlinear impairments, and the origin of the limitations at the optimum is studied. The impact of the input signal quality on the converted idler is discussed, and depending on the dominant noise contribution a varying conversion penalty is demonstrated.

Surbhi Jain and Brintha Therese A. (2015) investigated The performance of wavelength division multiplexing (WDM) in radio over fiber (RoF) systems and found it to be strongly influenced by nonlinearity characteristics inside the fiber. In their work, they have studied the effect of four wave mixing (FWM) as one of the influential factors in the WDM for RoF using Optisystem Software. It was observed that due to decrease in power level of the signal source, the FWM effect becomes nominal. Also, when the spacing between channels and dispersion parameter is increased, FWM effect decreases. Hence, it could be concluded that results obtained from this study will provide useful information for recognizing the limit of the WDM systems capability and the effect of FWM nonlinearity effect can be further reduced in the WDM networks.

III. METHODOLOGY

The simulations are performed using Optisystem 13.0 simulation software with a two channel WDM system using externally modulated laser sources on an optical fiber link of length 25km at 1550nm central wavelength. The simulation model used in the analysis is shown in Fig.2 below.

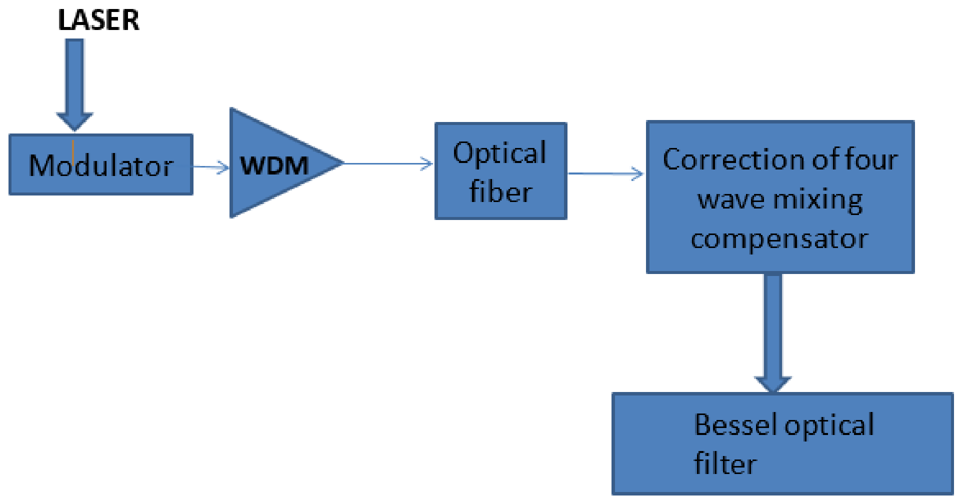

Figure 2. Simulation model.

The Optisystem simulation setup for the proposed BOF system is as shown in Fig. 3 below.

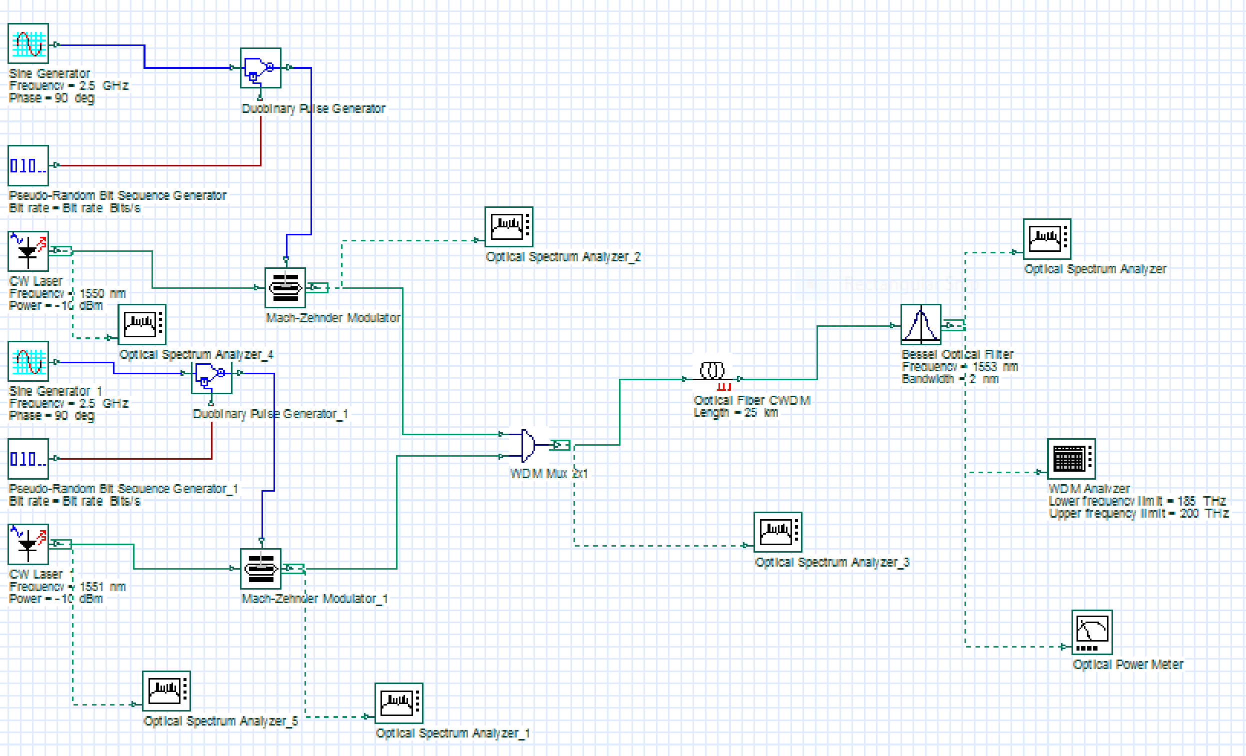

Figure 3. Optisystem simulation setup

The transmitter section consists of a pseudorandom bit sequence generator (PRBS) which generates a stream of 0's and 1's at a rate of 2.5Gbps which are directed to the input of duobinary pulse generator. The duobinary pulse generator converts these 0's and 1's in form of electric pulses having duobinary format. These electrical pulses from output of duobinary pulse generator are directed to input of mach-zender modulator which modulates information signal with a continuous wave (CW) laser. The mach-zender modulator also function for the balancing of optical paths i.e. optical power output of light produced by the CW laser. The CW laser produces the light. The transmitter section consists of two such channels separated at some frequency interval. In this investigative study, two WDM channels have been considered which are separated from each other at some frequency interval. These two channels are multiplexed and directed into an optical fiber coarse wavelength division multiplexing (optical fiber CWDM) of length 25km. The optical signal from the output of the optical fiber is directed to bessel optical filter (BOF) which eliminates all the high frequency noise present in the received electrical signal. The BOF can automatically distinguish between the active wavelength and the newly generated wavelength by the algorithm programmed inside the filter which leads to a dramatic reduction in FWM. The BOF also drops multiple undesired frequencies that appear with the optical channels. At the last stage, the received signal is analyzed using optical spectrum analyzer and WDM analyzer.

IV. RESULT AND DISCUSSION

The spectrums in figures 4, 5 and 6 show the four wave mixing (FWM) sidebands. The channel spacing was set at 1nm with input powers of 0dBm, -4dBm and -8dBm respectively. The performance at 0dBm shows maximum FWM sideband of -84dBm. The reason for this performance is because of the incorporation of bessel optical filter (BOF) in this work.

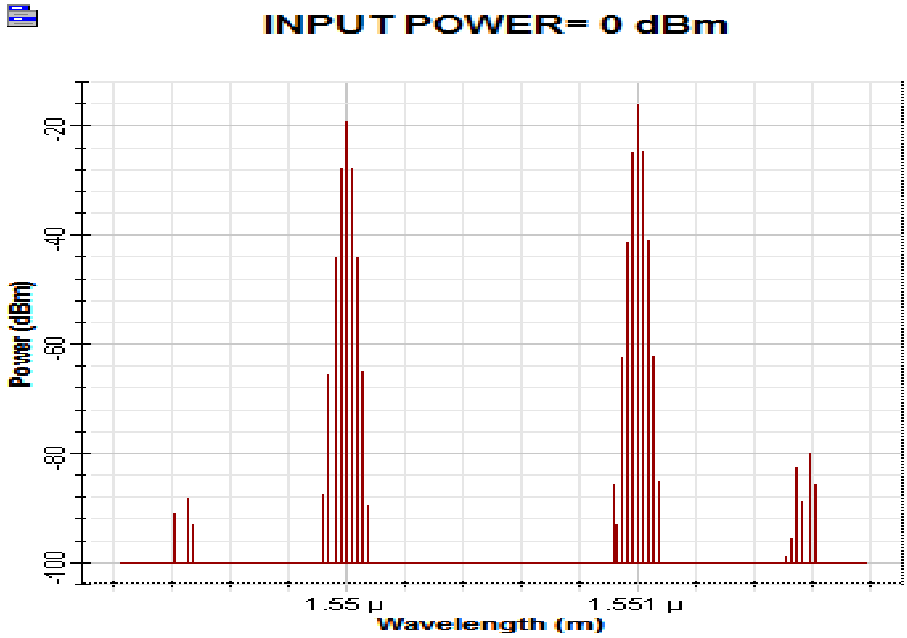

Figure 4: The optical spectrums at the output when the two wavelengths are transmitted at 0dBm.

This is due to the fact that the BOF is an optical filter with a Bessel frequency transfer function and also due to the self-healing property of the bessel beam, the extended depth and tight focusing features of the bessel beam.

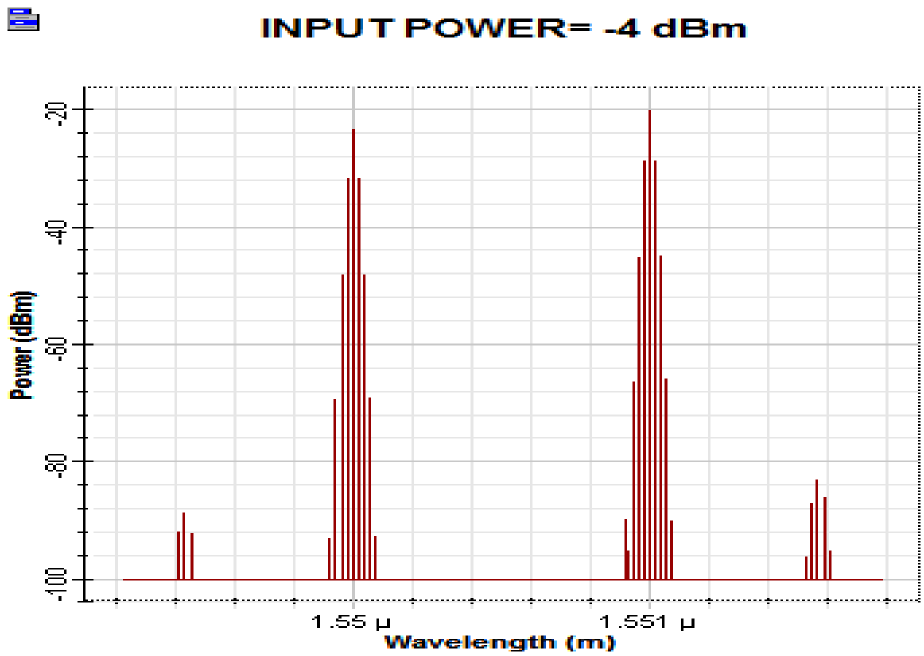

Figure 5: The optical spectrums at the output when the two wavelengths are transmitted at -4dBm.

Also, the bessel optical filter can automatically distinguish between the active wavelength and the newly generated wavelength by the algorithm programmed inside the filter which leads to a dramatic reduction in FWM. Also BOF drops multiple undesired frequencies that appear with the optical channels and BOF damp all FWM wavelengths in parallel that may appear with the main signals in the WDM system. When we decreased the power level from 29dBm to -10dBm, the input power level was compared with the noise power and the optical signal to noise ratio (OSNR) to find the threshold power level.

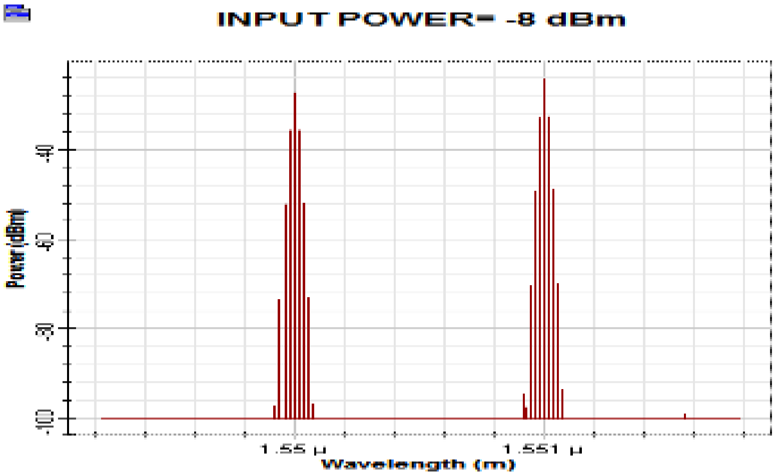

Fig.6: The optical spectrums at the output when the two wavelengths are transmitted at -8dBm.

Table 1 below shows the output of the WDM analyzer giving the value of the noise power and optical signal to noise ratio (OSNR) with respect to the input signal power. Figure 7 below shows the graph between the input power level with the noise power. Figure 8 below shows the graph between the input power level and optical signal to noise ratio (OSNR).

Table 1: Parameters for Different Input Power

Input power (in dBm)	Signal power (in dBm)	Noise power (in dBm)	OSNR (dB)
29	13.56	-30.77	44.33
27	11.74	-37.59	68.20
25	9.78	-44.69	68.20
20	4.80	-61.32	68.20
10	-5.20	-78.09	68.20
0	-15.20	-93.55	68.20
-4	-19.20	-100	68.20
-8	-23.20	-100	68.17
-10	-25.20	-100	68.17

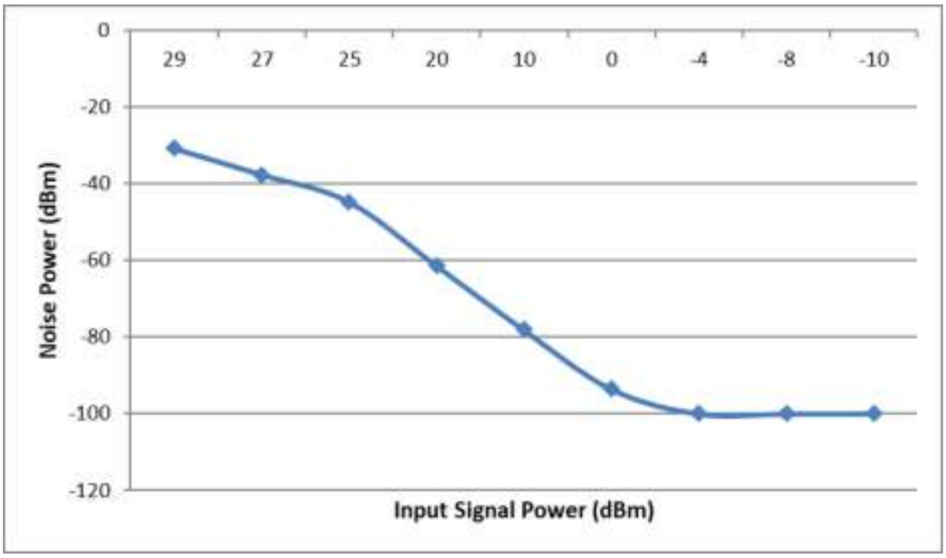

Figure 7. Graph between Input Signal Power and Noise Power

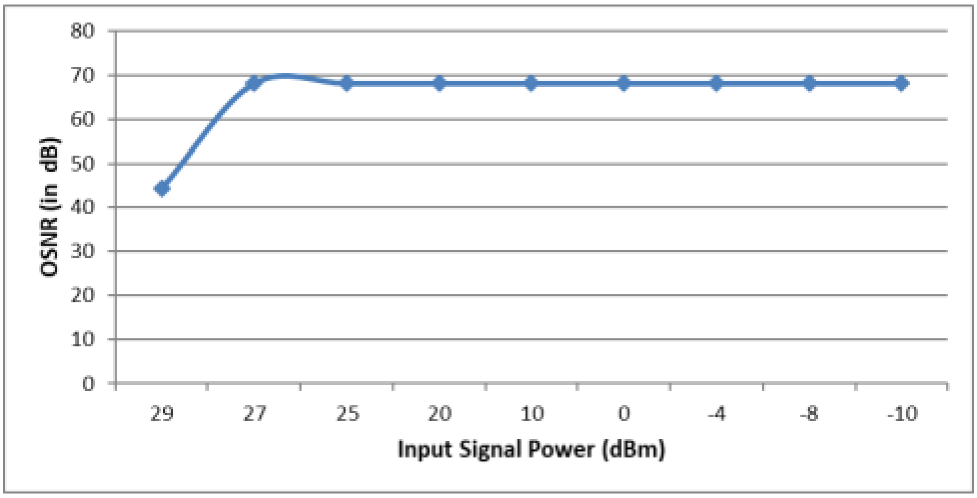

Figure 8. Graph between Input Signal Power and OSNR

Further increase in power level from 10dBm to 29dBm, the sideband of FWM is increasing due to the pronounced effect of the signal degradation of FWM as a result of high noise in the channel. This is clearly shown in figure 7. The effect of the input power on OSNR, signal power and noise power is compared and comprehensively shown in table 1, figure 7 and figure 8 respectively. The threshold value of input power is found to be 27dBm below which the optical signal to noise ratio (OSNR) is constant.

Bessel Optical Filter (BOF)

In the BOF, output shown in fig. 9, the graphs of input signal power and noise power shows how large amount of noise was minimized employing the system in this work, from -61dBm to -100dBm compared previously to, -18dBm to -88dBm since FWM generates additional noise and

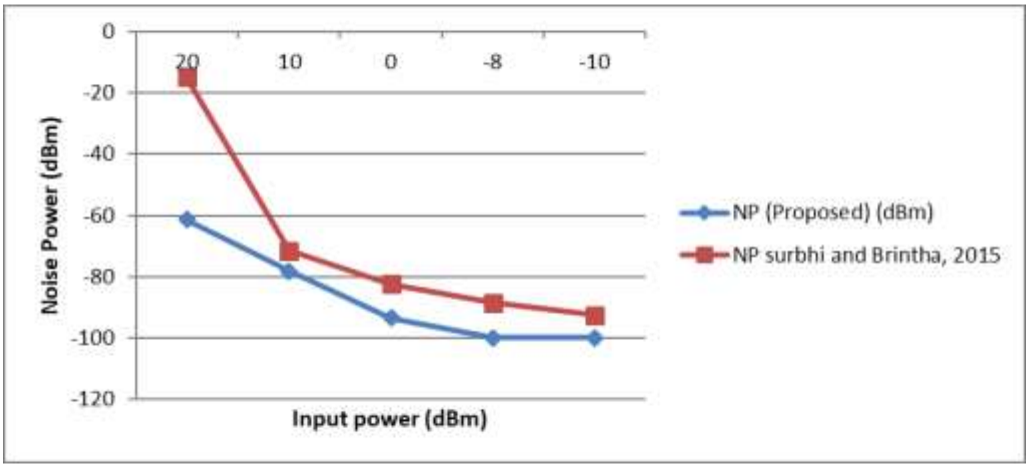

Figure 9. Graphs of Input Signal Power and Noise power

degrades system performance. In fig. 10, the graphs of input signal power and OSNR is obtained. The optical signal to noise ratio for Jain and Therese [2] (72dB) is slightly higher than that of the proposed work (68.20dB).

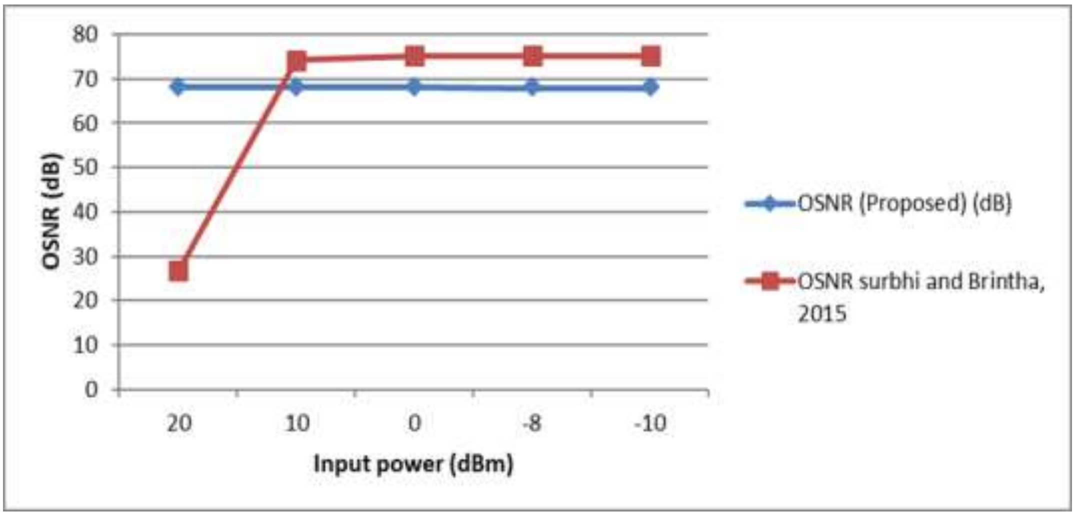

Figure 10. Graphs of Input Signal Power and OSNR

V. CONCLUSION

The transmission of signals in WDM has been investigated. The degradation due to FWM has been reduced by guaranteeing that there is more channel spacing and dispersion parameter with lesser power level. The performance of WDM network has been analyzed for reduction of FWM nonlinearity effect by the use of bessel optical filter (BOF) which was found to effectively reduce the FWM effect. As the input signal power decreases, the noise power also decreases and hence the FWM effect decreases.

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