FWM suppression in radio over fiber systems using optical phase conjugation and band pass filter

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Radio over Fiber (RoF) systems supporting high frequency millimeter waves have emerged as a great choice for the Fifth generation (5G) broadband communication. In this research article, a RoF system has been proposed with the integration of Wavelength Division Multiplexing (WDM) over 100 km single mode fiber (SMF) with Four Wave Mixing (FWM) suppression. Optical phase conjugation (OPC) and Band pass optical filter (BPF) based technique has been employed to suppress the FWM idlers. The results of the proposed WDM-RoF system have been evaluated at different input parameters such as input power, WDM channel spacing and the number of channels in the terms of output power, FWM, Q factor and Bit error rate (BER). A detailed comparison of Dispersion compensation fiber (DCF)-BPF and the proposed OPC-BPF has been performed. The results reveal the mid-link spectrum inversion in OPC-BPF helps achieve improved performance with enhanced FWM suppression and support for high input powers in the proposed system.

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Keywords: Four wave Mixing, Optical Phase Conjugation, RoF, Band Pass filter(BPF)

1. Introduction

Nowadays, expeditious growth in the internet services such as online gaming, video conferencing, high definition video transmission, etc. has led to a prominent increase in high speed data demands [1-4]. Microcellular systems are getting attention due to ever-increasing data and capacity demands in wireless services. Utmost advantage of microcellular systems is the potential to support high speed because of the many small cells for frequency utilization [5]. However, aforementioned advantages come at the cost of huge investment for installing multiple Base stations (BSs). One the most expensive factor for the high cost is the complex channel control in the spectral delivery in BSs and the handoffs. In order to eradicate this limitation, operations performed at BSs should replace and be preferably done at the Control Station [6]. Optical fiber is a promising medium for the transmission of radio frequency (RF) signals due to the absence of electro-magnetic interferences (EMI), low attenuation, and ability to support high speed [7]. Transmission of RF waves over optical fiber is referred as Radio over Fiber (RoF) technology and it is perceived as a competent technique to cater high speed data [8-9] demands. A schematic diagram of basic RoF system is illustrated in Fig. 1. It has three major sections such as transmitter (also referred as CS) consisting of binary data generator, electrical pulse shaping, electrical to optical conversion using modulator and RF mixing at 1310/1550 nm, second section is transmission medium such as optical fiber and followed by third section i.e. receiver (BS) consisting of photodetector, noise removing filter and regenerator. Received radio signal at BS then transmitted using BS antenna in the air to Mobile Units (MU) [10]. RoF systems can be integrated with multiple wavelengths to increase capacity and termed as Wavelength Division Multiplexing (WDM). Integration of RoF systems with WDM offers transparency, flexibility, and high speed but at the same time also suffers from the nonlinear effects such as Four-Wave Mixing (FWM), Cross-Phase Modulation (CPM), and Self-Phase Modulation (SPM) [11-12].

These systems also face the scattering impairments such as Stimulated Brillouin Scattering (SBS) and Raman (SRS) [13]. Nonlinear and scattering effects are distance and performance limiting effects eventually leading to distortion in the form of spectrum broadening, pulse broadening and unintended signal modulation [14]. Nonlinear effect such as FWM is prevalent in WDM systems and perceived as prime performance limiting factor in WDM-RoF systems [15]. FWM generated wavelengths cause interference in the intended wavelengths. The detrimental effect of FWM and their power can be lowered by taking wide channel spacings, lower power levels, and optical fiber lower effective area [16]. FWM effects have been mitigated in [17] with the integration of noise compression technique using laser pump. Raman fiber amplifier (RFA) with backward pumping has been explored for the FWM reduction and it has been perceived that Raman constant of 0.18 reduces the FWM but up to 10 km only [18]. Dispersion tailored photonic crystal fibers have been deployed in [19] to enhance the efficiency of FWM. Different optical fibers too have been investigated in [20] and provide FWM power of 2.8 mW in dispersion shifted fiber, 0.125 mW in non-zero dispersion shifted fiber, and 5 W in single mode fiber. Massive reduction in FWM has been reported in [21] employing Corning large effective area fiber (LEAF). Pre-FWM compensation has mathematically investigated and reduced by 75% in [22]. FWM in [23] employed for assigning different wavelengths to different packets and termed as optical labeling at 2.5 Gbps and 350 km long distance was achieved in [24] by transmitting multiple binary signals in single quaternary signal.

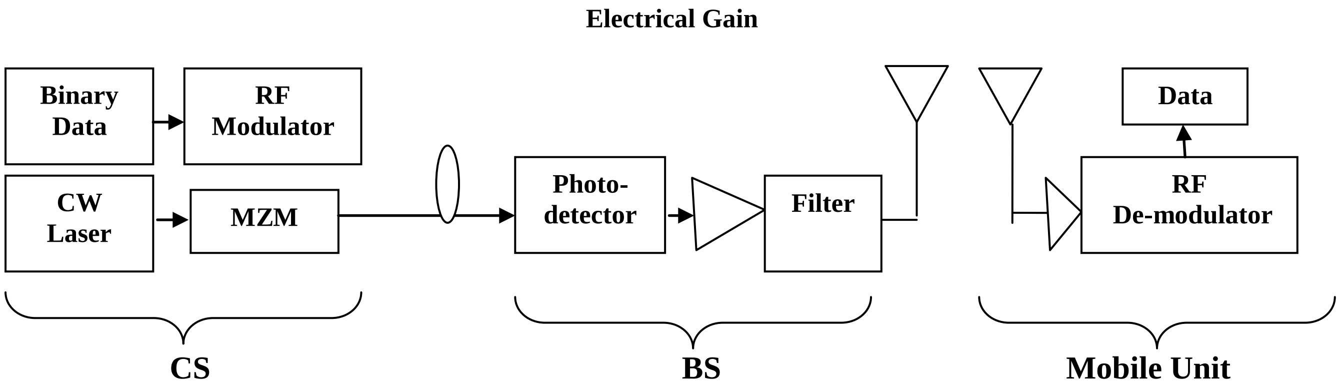


Fig. 1. General block diagram of RoF system

A low launched power based system using assign shortest path first (ASPF) algorithm to reduce the FWM has investigated in [25-26]. Dense WDM (DWDM) system exhibit higher FWM as compared to the WDM systems. Three channel coding was proposed in [27] in DWDM systems to mitigate FWM. OPC too has competence to reverse the phase of the input signal and used in the middle of the link to suppress FWM [28]. Use of OPC for FWM compensation has been demonstrated in a 30 Gbps WDM system employing orthogonal frequency division multiplexing (OFDM) [29]. Optimum Placement of OPC in ultra DWDM has been reported in [30] for decreasing the maintenance issues of FWM compensation. To reduce the FWM, different modulation techniques and optical filters were used in [31] and maximum 25 dB reductions were observed with Duo-binary return to zero. In [32], Polarization Mode Dispersion (PMD) emulator at input of the transmitter for FWM suppression has been investigated. Optical back-propagation for nonlinear compensation with OPC and Raman pumping has been shown to increase the distance reach in [33]. Though numerous studies have been reported to suppress the effects of FWM [34-49] however, the optimal technique to mitigate the FWM power is still being explored.

In this work, a FWM suppressed WDM system has been presented for RoF application using hybrid combination of OPC and Bessel filter at 4 Gbps. As per author's best knowledge, no similar work has been reported where combined effects of OPC and Bessel filter are studied on FWM suppression. Different input parameters have been investigated such as input power, channel spacings, and channels to validate their effects in FWM.

Proposed research paper is organized as follows: Section 2 covers the principle of FWM and its control, system setup is covered in Section 3. Investigation at different input parameters and results are discussed in Section 4. Concluding remarks are given in Section 5.

2. Principle of FWM and its control

Optical fiber can carry multiple wavelengths at same time but power accumulation of all channels modulates the refractive index of the fiber. Change in refractive index further leads to the change in speed of signals and thus change the phase of the signal. Phase change is the primary reason for the nonlinear effects and in WDM systems, FWM is the most dominant. FWM sidebands products (M) are expressed as [11]:

$$M = \frac{N^3 - N^2}{2} \quad (1)$$

where N are the number of channels and for two channels having wavelengths $\lambda_1$and λ_2, FWM generated sidebands are at $\lambda_3$and λ_4. Where λ_3=2λ_1-λ_2 and λ_4=2λ_2-λ_1

Let's assume three wavelengths having power P_1, P_2, P_3 at λ_1, λ_2,λ_3 and their output at the end of optical fiber is [13]

$$P_{FWM} = \eta D_c^2 P_1 P_2 P_3 e^{-\alpha L} L_{eff}^2 \quad (2)$$

where,$L_{eff} = \frac{(1-\exp(-\alpha L))}{\alpha}, \gamma = \frac{2\pi\eta}{\lambda Aeff},$

$$\eta = \frac{\alpha^2}{\alpha^2 + (\Delta\beta)^2}[1 + \frac{4\exp(-\alpha L)\sin^2\frac{(\Delta\beta L)}{2}}{(1-\exp(-\alpha L)^2},$$

$$\beta = \frac{-\lambda^4\pi}{c}\frac{dD_c}{d\lambda}[(f_1 - f_0) + (f_1 - f_0)]((f_1 - f_3)(f_2 - f_3)$$

Attenuation constant is α, effective core area of fiber Aeff, nonlinear coefficient γ, length of fiber Leff, FWM efficiency η, phase matching factor is Δβ, dispersion is Dc. Here, f_0 and f_1 are the zero dispersion frequency and 1st dispersion frequencyrespectively, andf$_2$, f_3 are 2nd and

3^{rd} dispersion frequencies. It is observed that 9 new FWM idlers are obtained as given in equation (1). More the number of WDM channels, more are the FWM idlers. Power of FWM is expressed as [3]

$$\frac{P_{FWM}}{P_0} = (D_C \gamma L_{eff})^2 P_i^2 (mW) \quad (3)$$

Higher power generates more FWM power as shown in equation (3).

Extensive literature studies revealed that FWM reduction is accomplished by using different modulation formats, low input power, wide channel spacings, OPC, dispersion compensation fiber [50] with optical filter etc. However, high suppression of FWM has been explored for WDM systems.

3. Proposed 8/32 WDM ROF system using OPC-BPF

Fig. 2 represents the proposed WDM-RoF system at 4Gbps using OPC-BPF for FWM suppression. In central office, binary data in the form of ones and zeros is generated from pseudo random data generator and followed by electrical pulse shaper such as Non Return to Zero (NRZ). This line coding has advantage of simple pulse generation and power efficient modulation format. RF signal at 40 GHz is superimposed on the NRZ data pulse and further electrical to optical conversion is performed with high carrier laser at conventional band (C-Band) and Machzendar modulator (MZM). Eight wavelengths starting from 193.1 THz to 193.8 THz at -10 dBm to 20 dBm input power with 25 GHz to 100 GHz channel spacing is deployed. Simulation parameters of the proposed system have been presented in Table 1.

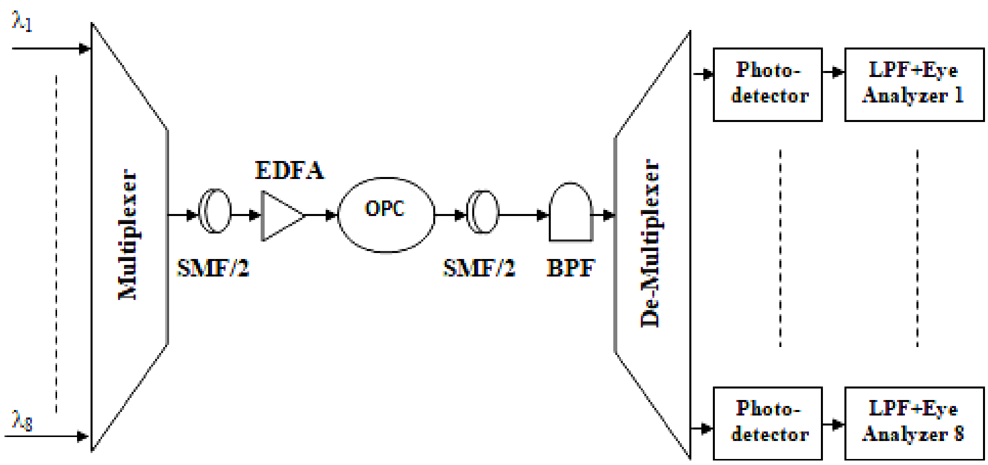


Fig. 2. Block diagram of proposed WDM-RoF system with the integration of OPC-BPF

Table 1. Simulation parameters of proposed WDM-RoF system

Parameters	Values [50]
Data Rate	4 Gbps
Sequence length	256 bits
Samples per bit	128
Number of samples	32768
WDM Channels	2, 4, 8
Input Power	-10 to 20 dBm
Channel Spacing	25 to 100 GHz
CW laser linewidth	10 MHz
MZM extinction ratio	30 dB
SMF Length	100 km
Attenuation and dispersion	0.2 dB and 16.75 ps/nm/km
Effective area	$80 \mu m^2$
EDFA Gain and Noise Figure	20 dB and 2 dB
PIN responsivity	1 A/W
Thermal noise	10-21 W/Hz
Dark current	10 nA
Low Pass Bessel Filter	0.75× Bit Rate Hz

Further, WDM channels are multiplexed and signal is fed to the transmission medium having single mode fiber (SMF) of 100 km. In the proposed system, the total length of the fiber is divided into two halves because of the deployment of OPC (encoded in Matlab) in the middle of the link and therefore 50 km SMF and an EDFA is followed by an OPC and then followed by EDFA. Gain of EDFA is 20 dB and noise Fig.2 dB for both the amplifiers and it utmost of amplifiers is to mitigate the power losses introduced by attenuation and nonlinear effects. OPC suppress the FWM idlers power due to phase reversal properties and therefore nonlinearity generated in the first half of the SMF are compensated by OPC and then in the second half, zero phase change obtained. Bessel optical filter is placed after transmission due to further reduction in FWM. Flat group delay, wave shaping and slow overshoot and cut-off are prominent advantages of band pass filter. FWM suppressed signals are isolated using de-multiplexer and each filtered wavelength passed through photo detector, low pass Bessel filter and BER analyser in BS.

4. Results and discussions

Investigation of the proposed WDM-RoF system at different input parameters has been performed in the terms of Q-factor, FWM power and BER for an 8 channel system. Channel spacing between 8 WDM channels has been varied as shown in Table 2 and power received, Q factor, and BER output values have been listed. Effects on received power with and without BPF are for DCF [50] and OPC are also compared. There is reduction in the output power in DCF and OPC when BPF is used, and this is because of the filtration of data pulse trains and also filter blocks some unnecessary part of desired signal.

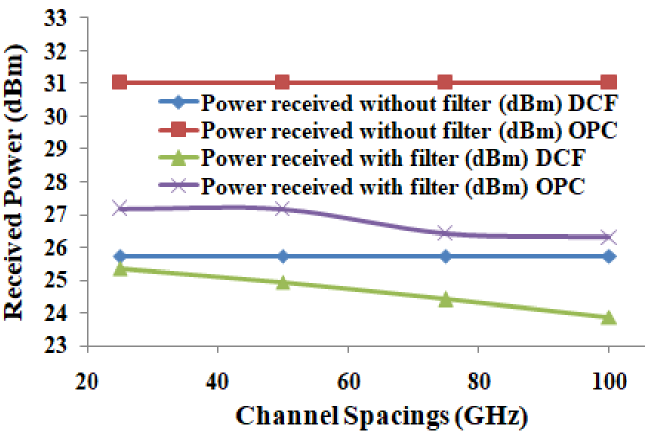
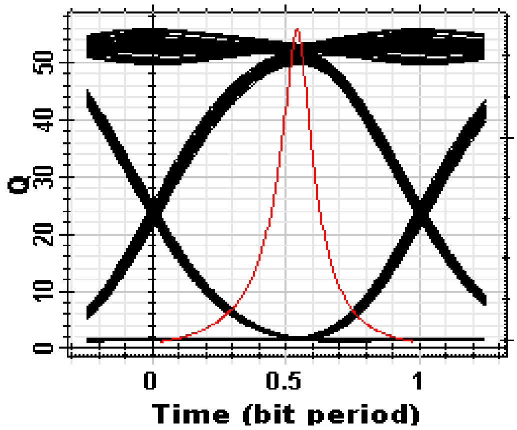


Fig. 3. (a) Received optical power before and after DCF/OPC-BPF at different channel spacings (color online)



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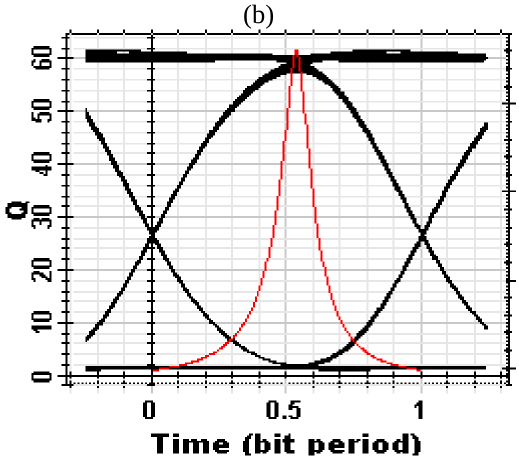

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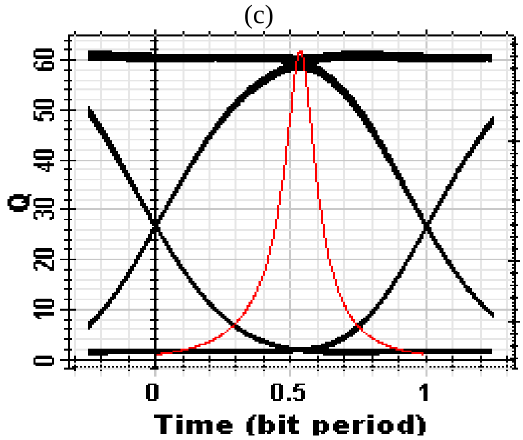

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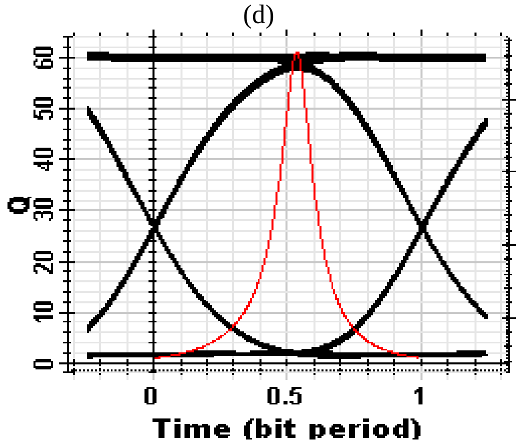


(e)

Fig. 3. Eye diagram at (b) 25 GHz (c) 50 GHz (d) 75 GHz (e) 100 GHz (color online)

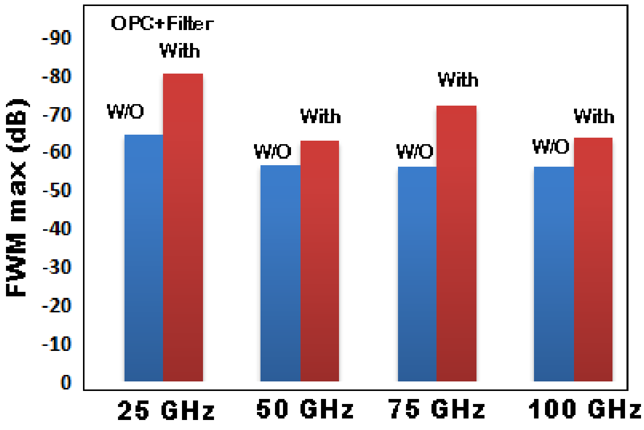


Fig. 3. (f) Effects on FWM power at different channel spacings with and without OPC-BPF (color online)

Received power in DCF/OPC-BPF systems has been compared at different channel spacings. Results revealed that received power is more in OPC-BPF i.e. 31.02 dB with filter at 25 GHz and reduces to 27.19 dB when BPF has been incorporated as shown if Fig. 3(a). Q factor at 25 GHz is 55.81 for OPC and 43.17 in case of DCF. Mid-link spectrum inversion with BPF is more competent to reduce FWM and therefore able to provide better Q factor and BER. Eye diagram at 25 GHz for OPC-BPF is presented in Fig. 3(b). Further, eye diagrams are also taken at 50 GHz, 75 GHz and 100 GHz and shown in (c), (d) and (e). Effects on FWM power at different channel spacings with and without OPC-BPF is depicted in Fig. 3(f) and it is observed that maximum FWM suppression is seen at 25 GHz using OPC-BPF.

Table 2. Impact of channel frequency on mitigating FWM effect

Channel Spacings (GHz)	Power received without filter (dBm)		Power received with filter (dBm)		Q factor		BER	
	DCF	OPC	DCF	OPC	DCF	OPC	DCF	OPC
25	25.72	31.02	25.37	27.19	43.17	55.81	0	0
50	25.72	31.02	24.93	27.18	47.05	61.44	0	0
75	25.72	31.02	24.40	26.41	53.15	61.73	0	0
100	25.72	31.02	23.86	26.30	46.83	60.91	0	0

Further effects of varied input powers have been evaluated in the proposed WDM-RoF system with OPC-BPF in terms of FWM power, Q factor, and BER. Table 3 shows the values of system with and without BPF and comparison has been done for DCF and OPC. Higher output powers are obtained at higher input powers and using OPC-BPF as compared to DCF-BPF as shown in Fig. 4(a).

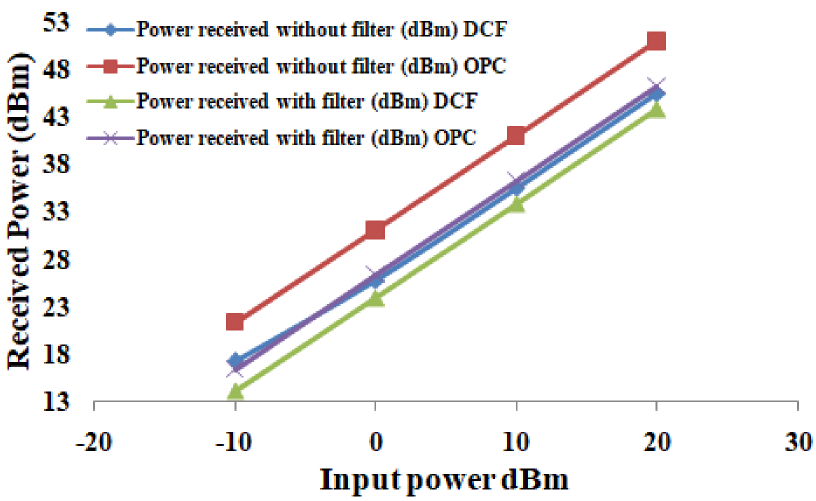
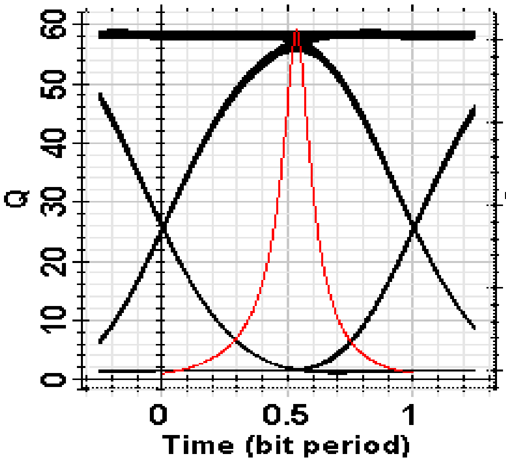


Fig. 4. (a)Received optical power before and after DCF/OPC-BPF at different input powers (color online)



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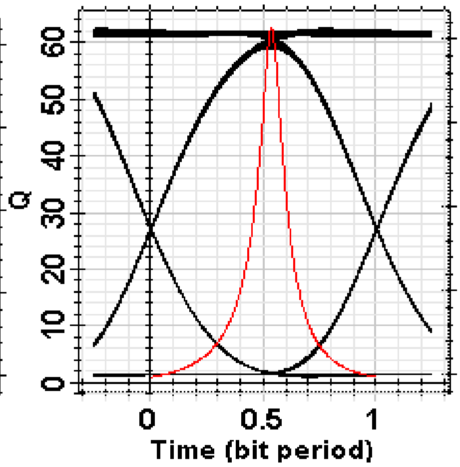

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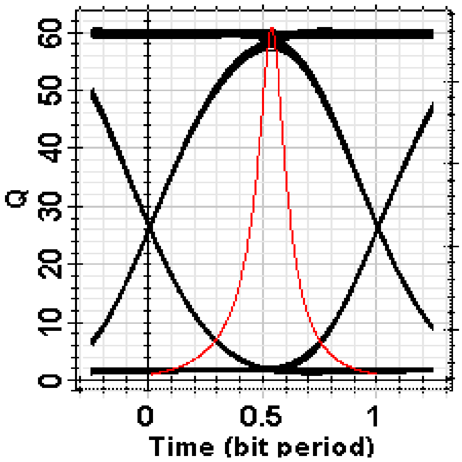

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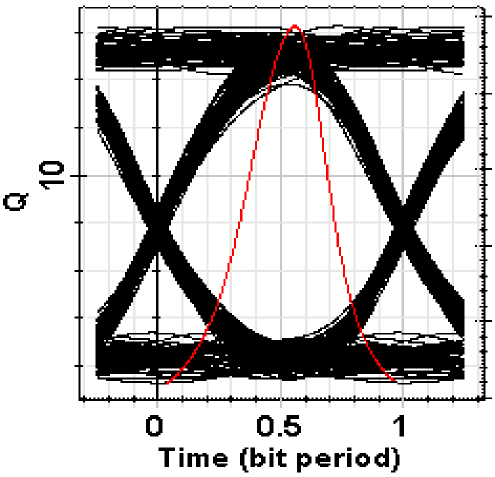


(e)

Fig. 4. Eye diagrams at (b) 20 dBm (c) 10 dBm (d) 0 dBm and (e) -10 dBm for OPC-BPF (color online)

Eye diagrams at using OPC-BPF for 20 dB, 10 dB, 0 dB and -10 dB input powers are represented in Fig. 4(b), (c), (d) and (e). Lowest FWM is obtained at -10 dB input power and maximum for 20 dB but these values are lower than DCF+BPF as shown in Fig. 4(f). Advantage of OPC-BPF is that it has potential to mitigate the effects of FWM even at 20 dB which is not true for DCF-BPF. Maximum suppression is done by OPC-BPF at -10 dBm input power and suppression slightly reduced without BPF.

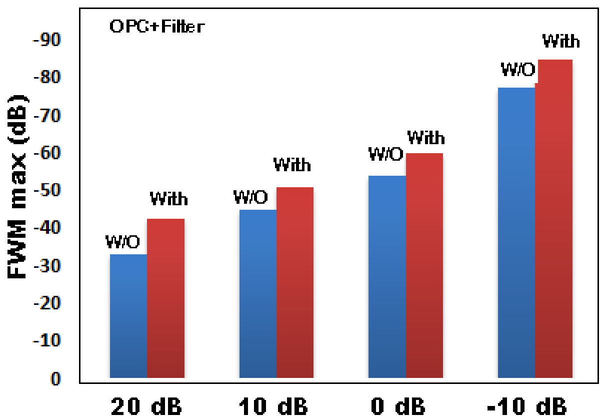


Fig. 4. (f) Effects of input powers at FWM and compensation with and without BPF in OPC (color online)

Table 3. Impact of input power on mitigating FWM effect

Input power (dBm)	Power received without filter (dBm)		Power received with filter (dBm)		Q factor		BER	
	DCF	OPC	DCF	OPC	DCF	OPC	DCF	OPC
20	45.52	50.99	43.83	46.30	3.21	59.08	0.0034	0
10	35.54	40.99	33.83	36.30	15.43	62.36	3.08e-45	0
0	25.72	31.02	23.86	26.30	46.83	60.63	0	0
-10	17.17	21.28	14.16	16.32	35.95	16.26	1.54e-283	9.1e-60

Table 4. Impact of channels on mitigating FWM effect

WDM channels	Power received without filter (dBm)		Power received with filter (dBm)		Q factor		BER	
	DCF	OPC	DCF	OPC	DCF	OPC	DCF	OPC
2	25.09	25	19.51	23.73	61.44	63.74	0	0
4	22.89	28.30	22.06	25.96	51.95	63.43	0	0
8	25.72	31.02	23.86	26.30	46.83	60.91	0	0

Lastly, channels are varied in WDM system such as 2, 4 and 8 to analyse their effects on FWM. With the increase in WDM channels, lower Q factor and higher BER are obtained as shown in Table 4. Presence of BPF in OPC offers lesser FWM in all WDM channels and minimum FWM is obtained for 2 WDM channels.

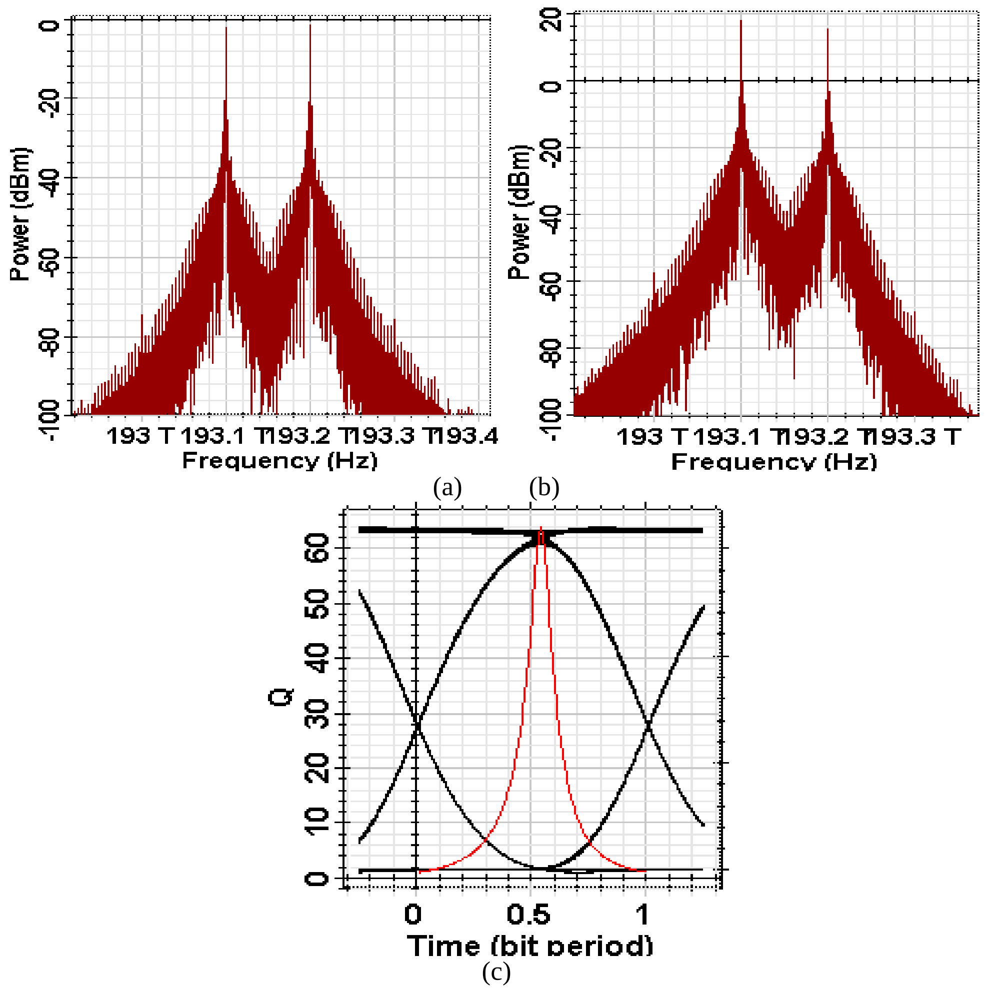
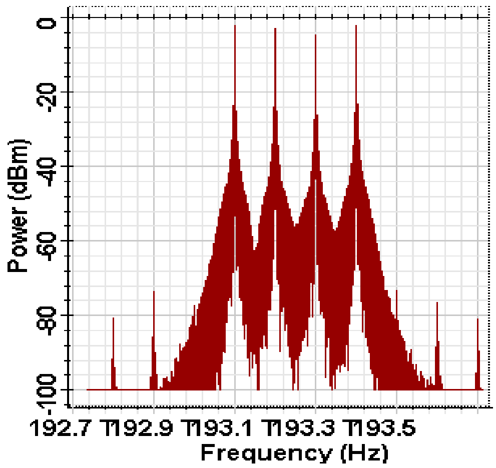
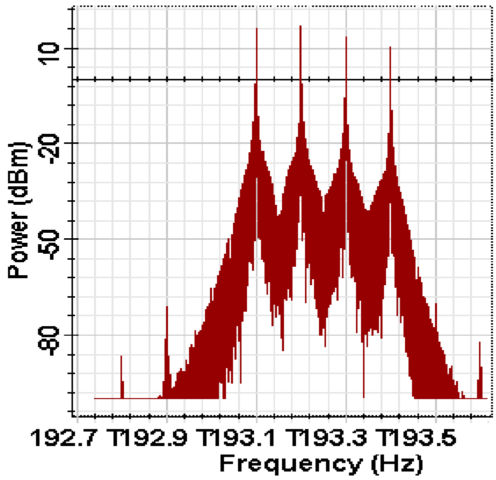


Fig. 5. Optical spectrums for 2 WDM channels (a) before OPC-Bessel filter (b) after OPC-Bessel filter (c) eye diagram (color online)



(a)



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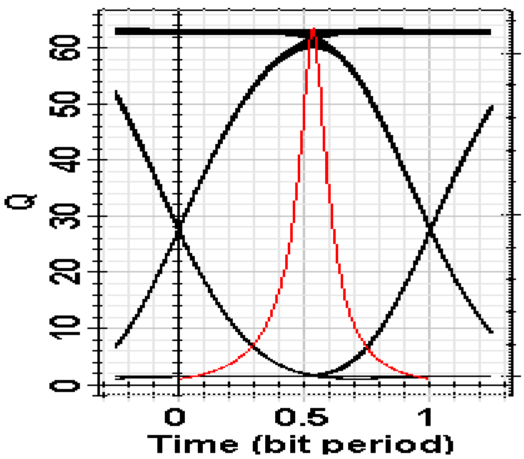
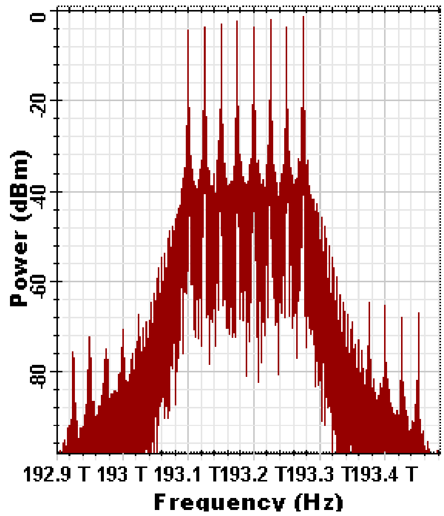


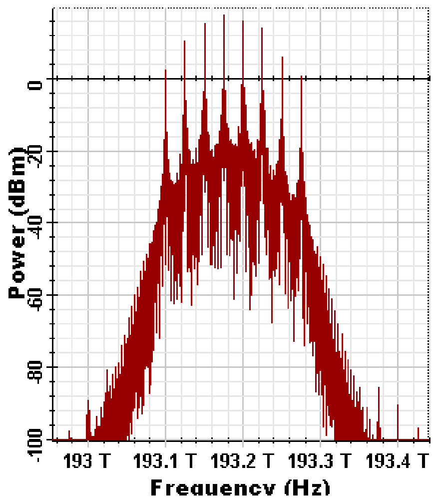
(c)

Fig. 6. Optical spectrums for 4 WDM channels (a) before OPC-Bessel filter (b) after OPC-Bessel filter (c) eye diagram (color online)

Optical carrier spectrums with and without BPF for 2, 4, and 8 WDM channels are represented in Fig. 5(a) and (b), Fig. 6(a) and (b), Fig. 7(a) and (b) respectively for OPC. Eye diagrams for aforementioned WDM channels are shown in Fig. 5(c), 6(c), and 7(c) respectively for OPC. Q factor of 63.74, 63.43, 60.91 are obtained with OPC-BPF and 61.44, 51.95, 46.83 with DCF-BPF for 2, 4 and 8 WDM channels.



(a)



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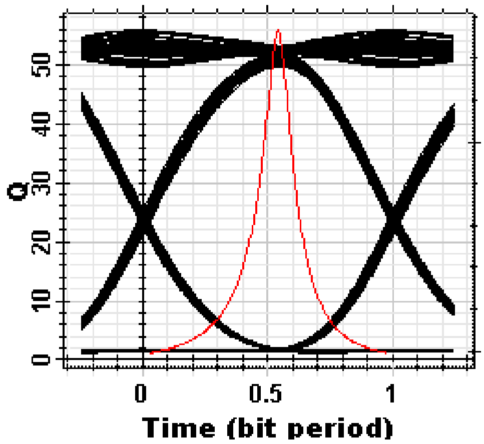

(c)

Fig. 7. Optical spectrums for 8 WDM channels (a) before OPC-Bessel filter (b) after OPC-Bessel filter (c) eye diagram (color online)

A detailed comparison of different reported studies and proposed work is performed in Table 5. Different reported studies are compared in terms of data rate, number of WDM channels, modulation used, FWM suppression technique, and maximum suppression offered. It is observed that proposed has less complexity, long reach and enhanced FWM suppression.

Table 5. Comparison of proposed work with reported studies

Author [Year] [Ref.]	Capacity and distance	Modulation	FWM Suppression Technique	Maximum Suppression
A. Nain [2017][21]	3×10 Gbps and 40 km	NRZ	single mode fiber, true wave (TW), true wave reduced slope (TW-RS), corning large effective area fiber (LEAF) and Alcatel Teralight	FWM reduced by 20 dB by Corning LEAF
M. Nehra [2018] [29]	3×10 Gbps and 100 km	OFDM	OPC	8 dB
H. U. Manzoor [2019] [31]	16×10 Gbps and 50 km	Duo-binary RZ (DRZ) and modified DRZ (MDRZ)	DRZ, MDRZ	MDRZ 25 dB
A. Chauhan [2020] [30]	2×10 Gbps and 25 km	OFDM	No OPC, Pre,Post, Mid, after transmitter and after laser	OPC after laser source 17.5 dB
H. U. Manzoor [2020] [32]	8×5 Gbps and 50 km	NRZ	Polarization Mode Dispersion (PMD)	7 dB in downstream
N. Kathpal [2020] [50]	8×4 Gbps and 100 km	NRZ	Bessel filter	5 dB (100 GHz)
Proposed work	8×4 Gbps and 100 km	NRZ	OPC-Bessel filter	7.8 dB (100 GHz)

5. Conclusion

In this work, a RoF system with the integration of WDM technology has been presented and effects of FWM are studied at different input parameters such as input power, WDM channel spacings and number of channels. The results have been evaluated in terms of output power, FWM, Q factor and BER. A detailed comparison of DCF-BPF and proposed OPC-BPF has been performed. OPC-BPF is the potential technique to mitigate the effects of FWM even at 20 dB which is not true for DCF-BPF. Maximum suppression is done by OPC-BPF at -10 dBm input power and suppression slightly reduced without BPF. Q factor at 25 GHz is 55.81 for OPC and 43.17 in case of DCF. Q factor of 63.74, 63.43, 60.91 are obtained with OPC-BPF and 61.44, 51.95, 46.83 with DCF-BPF for 2, 4 and 8 WDM channels. Due to mid-link spectrum inversion and joint effects of Bessel filter, proposed system provide lower FWM, greater Q factors and error free BER for 100 km.

References

[1] A. Sharma, S. Kaur, N. Nair, K. S. Bhatia, Optik **257**,168855 (2022).

[2] S. Kaur, M. Kumar, A. Verma, Journal of Optical Communications, ahead-of-print **43**(3), 379 (2022).

[3] S. Kaur, N. Tabassum, IETE Journal of Research (2021), published online.

[4] S. Kaur, R. K. Kapur, Journal of Optics **48**, 606 (2019).

[5] R. Llorente, M. Beltran, InTech, Book Chapter, Book: Frontiers in Guided Wave Optics and Optoelectronics pp 119-138 (2010).

[6] M. Bakaul, A. Nirmalathas, C. Lim, D. Novak, R. Waterhouse, IEEE Photon. Technol. Lett. **18**(21), 2311 (2006).

[7] V. A. Thomas, S. Ghafoor, M. El-Hajjar, L. Hanzo, IEEE Commun. Lett. **17**(2), 409 (2013).

[8] D. G. Lona, R. M. Assumpcao, O. C. Branquinho, M. L. Abbade, H. Hernandez-Figueroa, A. C. Sodre Jr., Microw. Opt. Technol. Lett. **54**(12), 2669 (2012).

[9] D. Wake, A. Nkansah, N. J. Gomes, J. Lightwave Technol. **28**(16), 2456 (2010).

[10] B. Patnaik, P. Sahu, Electronic System Design (ISED), 2010 Symposium on, IEEE, 119 (2010).

[11] S. P. Singh, N. Singh, Prog. Electromagn. Res. **73**, 249 (2007).

[12] N. Singh, M. Kumar, A. Verma, Journal of Optical Communications, ahead of printing, **43**(3), 303 (2022).

[13] F. S. Yang, J. Lightwave Technol. **18**(4), 512 (2000).

[14] S. Kumar, D. Yang, J. Lightwave Technol. **23**(6), 2073 (2005).

[15] F. Forghieri, R. Tkach, A. R. Chraplyvy, D. Marcuse, IEEE Photon. Technol. Lett. **6**(6), 754 (1994).
[16] S. Betti, M. Giaconi, M. Nardini, IEEE Photon. Technol. Lett. **15**(8), 1079 (2003).
[17] E. Ciaramella, F. Curti, S. Trillo, IEEE Photon. Technol. Lett. **13**(2), 142 (2001).
[18] A. Bindal, S. Singh, Photonic Netw. Commun. **28**(3), 214 (2014).
[19] S. Arismar Cerqueira Jr, J. C. Boggio, A. Rieznik, H. Hernandez-Figueroa, H. Fragnito, J. Knight, Optics Express **16**(4), 2816 (2008).
[20] A. Ramprasad, A. U. Mageswari, M. Meenakshi, M. Arumugam, Journal of Optic **35**(3), 144 (2006).
[21] A. Nain, S. Kumar, S. Singla, Journal of Optic **46**(4), 492 (2017).
[22] D. Yang, S. Kumar, J. Lightwave Technol. **27**(14), 2916 (2009).
[23] M. Abbade, E. Fagotto, R. Braga, I. Fonseca, E. Moschim, F. Barbosa, IEEE Photon. Technol. Lett. **17**(1), 151 (2005).
[24] M. Abbade, E. Fagotto, R. Braga, F. Barbosa, E. Moschim, I. Fonseca, IEEE Photon. Technol. Lett. **18**(2), 331 (2006).
[25] A. Chauhan, A. Vaish, A. Verma, IJMOT **13**(1), 98 (2017).
[26] T. S. Chin, Am. J. Appl. Sci. **5**(8), 1059 (2008).
[27] A. Bogoni, L. Poti, IEEE J. Sel. Top. Quant. Electron. **10**(2), 387 (2004).
[28] A. K. Garg, R. Kaler, Chin. Opt. Lett. **6**(11), 807 (2008).
[29] M. Nehra, D. Kedia, 2018 3rd IEEE International Conference on Recent Trends in Electronics, Information & Communication Technology (RTEICT), 1933 (2018).
[30] A. Chauhan, A. Vaish, A. Verma, Journal of Optical Communications **41**(4), 421 (2020).
[31] H. U. Manzoor, T. Manzoor,A. Hussain, M. H. Aly, S. Manzoor, Iran J. Sci. Technol Trans. Electr. Eng. **43**, 479 (2019).
[32] H. U. Manzoor, M. Zafar, S. U. Manzoor, T. Khan, S. Liu, T. Manzoor, S. Saleem, W. Y. Kim, M. Ali, Results in Physics **16**, 102922 (2020).
[33] A. Chauhan, I. Yadav, P. Dhawan, S. Kaur, A. Verma, Journal of Optical Communications, ahead of Printing, Article No 000010151520200282
[35] G. Kaur, Journal of Optical Communication **41**(1), 11-8 (2020).
[36] Gaganpreet Kaur, Gurmeet Kaur, Sanjay Sharma, Optoelectron. Adv. Mat. **12**(11-12), 678 (2018).
[37] C. Lim, A. Nirmalathas, Journal of Lightwave Technology **39**(4), 881 (2021).
[38] A. Kanno, 2018 IEEE Conference on Antenna Measurements & Applications (CAMA), 1-3 (2018).
[39] Y. Kase, S. Hori, N. Oshima, K. Kunihiro, 2020 50th European Microwave Conference (EuMC), 324 (2021).
[40] H. -Y. Kao, S. Ishimura, K. Tanaka, K. Nishimura, R. Inohara, IEEE Photonics Journal **13**(4), Art no. 7301106 (2021).
[41] I. S. Desher, 2020 2nd Annual International Conference on Information and Sciences (AiCIS), 81 (2020).
[42] A. Giovannini, J. Nanni, G. Paolini, F. Perini, E. Lenzi, A. Costanzo, J. Polleux, D. Masotti, J. Laheurte, G. Tartarini, 2020 International Topical Meeting on Microwave Photonics (MWP), 140 (2020).
[43] Y. A. Alkhlefat, A. Ragheb, M. A. Esmail, S. Alshebeili, 2018 21st Saudi Computer Society National Computer Conference (NCC), 1-5 (2018).
[44] A. Bahrami, Z. Ghassemlooy, M. M. Abadi, S. Zvanovec, 2020 12th International Symposium on Communication Systems, Networks and Digital Signal Processing (CSNDSP), 1-5 (2020).
[45] W. Zhai, A. Wen, D. Shan, IEEE Transactions on Microwave Theory and Techniques **69**(1), 210 (2021).
[46] S. C. Sree, M. Baskaran, 2016 International Conference on Communication and Signal Processing (ICCSP), 1864 (2016).
[47] D. Novak, R. B. Waterhouse, A. Nirmalathas, C. Lim, P. A. Gamage, T. R. Clark, M. L. Dennis, J. A. Nanzer, IEEE Journal of Quantum Electronics **52**(1), 1-11 (2016).
[48] M. Chen, B. Liu, X. Xin, X. Yin, Q. Zhang, Q. Tian, F. Tian, Y. Wang, L. Rao, D. Li, J. Zhao, R. Wang, 2016 15th International Conference on Optical Communications and Networks (ICOCN), 1-3 (2016).
[49] C. Wang, K. Wang, Y. Tan, F. Wang, B. Sang, W. Li, W. Zhou, J. Yu, IEEE Photonics Technology Letters **34**(11), 559 (2022).
[50] N. Kathpal, A. K. Garg, Digital Communications and Networks **6**(1), 115 (2020).

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