

A performance enhanced bidirectional three-band lightwave transmission system for RoF and RoFSO link using serial and parallel modulators

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A bidirectional three-band lightwave system is proposed for Radio over Fiber (RoF) and Radio over Free Space Optics (RoFSO) platforms which can be used for simultaneous transmission of 1.25 Gbps Baseband upstream and 1.25 Gbps Baseband downstream, 1.25 Gbps/20 GHz Microwave (MW), 1.25 Gbps/ 40 GHz Millimetre-wave (MMW) downstream signals. For RoF link, performance is evaluated using a serial modulator and a chromatic dispersion compensated parallel modulator along with Erbium Doped Fiber Amplifier (EDFA) of appropriate length. An enhanced link performance with sufficiently high Quality (Q)-factor is achieved for a length of 35 km and 58 km with serial and parallel modulators respectively. The system is simple and economical as it eliminates the use of multiple transmitters, additional Reflective Semiconductor Optical Amplifier (RSOA), Delay Interferometer and uses direct detection at the receiver. Using a serial modulator and amplifier, the bidirectional three-band lightwave system is also investigated for establishing a RoFSO link up to a distance of 1km. This RoFSO link can be used in remote and disaster prone areas. The proposed schematic can be used for both wired and wireless users in various broadband and multimedia applications.

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1. Introduction

In modern times, the demand for the high speed broadband services has increased tremendously. In the near future, it is expected that the networks would be capable of providing sufficiently high data rates which can satisfy the hunger of the users. The conjunction of wireless and wired networks has been receiving vast attention for building a pervasive network which can be used for real-time multimedia applications [1-3]. It is also desired to employ an effective system that can simultaneously transmit BaseBand (BB), Microwave (MW) and MilliMeter Wave (MMW) signals over the same platform. Radio-over-Fiber (RoF) and Radio over Free Space Optics (RoFSO) are the evolving technologies that can be used for such applications. RoF technology consists of a Central Station (CS) and a Base Station (BS) which are connected with each other through an optical fiber. The optical signal generated at the CS is modulated with a high frequency RF carrier and then transmitted over the fiber to the BS from where the wireless delivery of the signals take place [4]. RoF systems offers various advantages like high capacity, centralization of equipments, low attenuation, excellent mobility, low cost etc [5]. However, the installation of fiber between CS and BS in remote or disaster prone areas, fiber dispersion, non-linearities, etc limit the usage of RoF. These problems can be resolved by RoFSO which is a combination of RoF and FSO technology that uses free space as a channel instead of optical fiber. It is a Line of Sight (LOS) communication, resistant to intersystem

interference, prevents eavesdropping, offers license free spectrum and has a small terminal size [6]. However, it is highly vulnerable to attenuation caused due to weather conditions like rain, fog, snow etc, which impacts its transmission distance making it suitable for short distance communications only [7].

Previously work has been done to generate BB, MW, MMW signals using Wavelength Division Multiplexing (WDM), however, such a system require many Laser Diodes (LDs), high frequency Local Oscillators (LOs) and mixers to down convert the RF signal into BB at the receiving site [8]. Using Light Emitting Diodes (LEDs), the output power of the LED was inadequate to accumulate several channels [9]. Amplified Spontaneous Emission (ASE) was a solution to this problem but it required costly Erbium doped fiber and Pumping LDs [8]. J. Li et al. [10] used Four-Wave-Mixing (FWM) in semiconductor optical amplifier to generate these signals and then distribute them to the BS but due to FWM, its polarization state and transmitter became complicated with a high degree of chirp due to directly modulated laser which confines the transmission distance to a small value [11]. In most of the schemes, the main focus was on the transmission of MW/BB or MMW/BB and not on BB/MW/MMW signals simultaneously. C.Y. Li *et al.*, 2012 [12] proposed a hybrid bidirectional BB/MW/MMW system by cascading a phase modulator (PM) and a Mach-Zehnder modulator (MZM) using Optical Signal to Noise Ratio (OSNR) enhancement circuit in which the achieved length was limited to only 20 km for a data rate of

1.25 Gbps. The OSNR enhancement circuit was composed of Delay Interferometer (DI) and Reflective Semiconductor Optical Amplifier (RSOA) which further increased the complexity of the circuit and reduced the system performance by introducing their own losses. DI produced a desired delay in the two beams generated which intensified the problem of chromatic dispersion whereas RSOA has an amplified spontaneous emission (ASE) associated with it. In this work, a bidirectional three-band lightwave system for triple play service is proposed where in a 1.25 Gbps BB upstream, 1.25Gbps/20GHz MW, 1.25 Gbps/40 GHz MMW and 1.25 Gbps BB downstream signals have been transmitted over a link length of 35km using serial modulator without dispersion compensation and 58 km using parallel modulator by compensating dispersion for RoF platform. For the OSNR enhancement, Erbium Doped Fiber Amplifier (EDFA) of suitable length and optical amplifiers have been used. These signals were generated using Optical Circulator (OC) and Fiber Bragg Grating (FBG) thus making the system simple and cost effective. This can serve as an attractive candidate for broadband, telecommunication, multimedia and real-time applications. RoF scheme can be used for both wireline and wireless users whereas RoFSO scheme can be used in remote or disaster prone areas. Moreover keeping in view the eye safety standards and power requirements, FSO transmission is done in the 1550 nm window.

Section 2, describes the system set-up for RoF and RoFSO schemes using the serial and parallel modulator along with the optical spectrum of the generated three-band signals. Section 3, compares the performance of proposed schemes for transmission of three-band lightwave system in RoF and RoFSO link. Finally, section 4 concludes the work done.

2. System set-up

2.1. RoF scheme using serial modulator

The system set-up for the proposed bidirectional three-band lightwave transmission system for RoF link

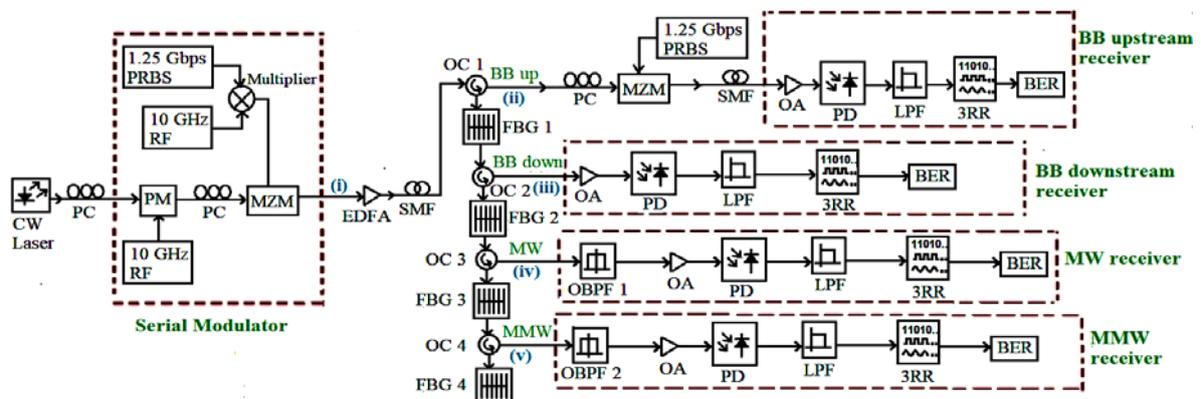


Fig. 1. Set-up of bidirectional three-band lightwave transmission system for RoF link using serial modulator

A SMF is used for upstream data transmission, fiber parameters are listed in Table 1. At the receiver an Optical Amplifier (OA) of gain 10 dB is used to boost-up the signal. A PIN Photodiode is used and the desired signal is

using serial modulator is shown in Fig. 1. It consists of a Continuous Wave (CW) Laser of 1 MHz Linewidth, centred at 1550.07 nm wavelength and 10 dBm power. The output of CW laser is given to a Polarization Controller (PC) which provides 45 degree azimuth polarization. A serial modulator is used (as in Fig. 1) which consists of a Phase Modulator (PM) and Lithium Niobate (LiNbO_3) Mach Zehnder Modulator (MZM). The PM is driven by a 10 GHz RF carrier whereas the LiNbO_3 MZM is provided a 1.25 Gbps /10 GHz RF carrier. Switching bias, switching RF voltage of 4V is set in the LiNbO_3 MZM to produce several optical carriers of fixed channel spacing as shown in Fig. 2(i). An Erbium Doped Fiber Amplifier (EDFA) of length 3 m is used and the signal is then transmitted over a SMF. The resultant signal has various modes. Mode 0 is used for BB upstream transmission. Modes +1 and -1 are used for MW, Modes +2 and -2 are used for MMW and Mode +3 is used for BB downstream signal. After SMF the signal is passed to Optical Circulator (OC 1) having an insertion loss of 0.54 dB for routing the signal into the FBG 1. FBG has the functionality that it reflects back a particular wavelength and passes all other wavelengths. According to the modes of the received signal, the bandwidth of the FBGs are set. FBG 1 is set to 0.05666 nm such that it reflects back mode 0 and passes all other modes. The reflected mode 0 signal is the desired BB signal which can be used for upstream transmission. This BB upstream signal is given to PC to control its state of polarization and is externally modulated by 1.25 Gbps PRBS data sequence by using a MZM.

Table 1. Fiber parameters for RoF scheme

Parameters	Value
Attenuation	0.2 dB/km
Dispersion	16.75 ps/nm/km
Dispersion slope	0.075 ps/nm ² /km
DGD	0.2 ps/km

filtered out by using a rectangular LPF. The remaining signal from FBG 1 is given to the OC 2 which routes the signal into FBG 2 tuned to 0.0433 nm. FBG 2 reflects back mode +3 to generate 1.25 Gbps BB downstream

signal. Here, the same SMF can be used for both the upstream and downstream transmission however in such a case there will be a problem of crosstalk and jitter due to phase error of these signals. To eliminate this problem, two SMFs are used for upstream and downstream transmission [12]. The remaining signal from FBG 2 is then given to FBG 3 (tuned to 0.05 nm) using OC 3 which reflects back mode +1 and -1 to generate 1.25 Gbps/ 20 GHz MW signal for downstream transmission. FBG 4 is tuned to 0.16 nm so that it reflects back mode +2 and -2 to generate 1.25 Gbps/ 40 GHz MMW signal for downstream transmission. Optical band pass filter (OBPF1) and OBPF2 are used to band limit the 20 GHz MW and 40 GHz MMW signals respectively and reject other higher sidebands. The optical spectra at various points of Fig. 1 are shown in Fig. 2. In this scheme, the link length is limited to 35 km only and hence the problem of dispersion is not addressed. However, as the transmission distance is increased, the effect of chromatic dispersion (CD) starts to creep in the system resulting in different phase shifts

between the carrier and sidebands due to which the resulting phase of the RF beat signal changes. As a result, power of the composite RF signal degrades and becomes null if the phase difference is 180° [13]. The RF power, P_{RF} is estimated as [14]

$$P_{RF} \propto \cos [\pi LD/c \lambda^2 f_{RF}^2] \quad (1)$$

where D is dispersion parameter, λ is carrier wavelength and the cosine term indicates that for a fixed RF complete power cancellation happens for a SMF of length L (as in eq. 2), which may degrade the system performance.

$$L = Nc / 2D\lambda^2 f_{RF}^2 \quad \text{for } N=1, 3, 5 \quad (2)$$

A new scheme to generate bidirectional three-band lightwave transmission system for triple play service has been proposed for RoF link using parallel modulator which combats the chromatic dispersion [15].

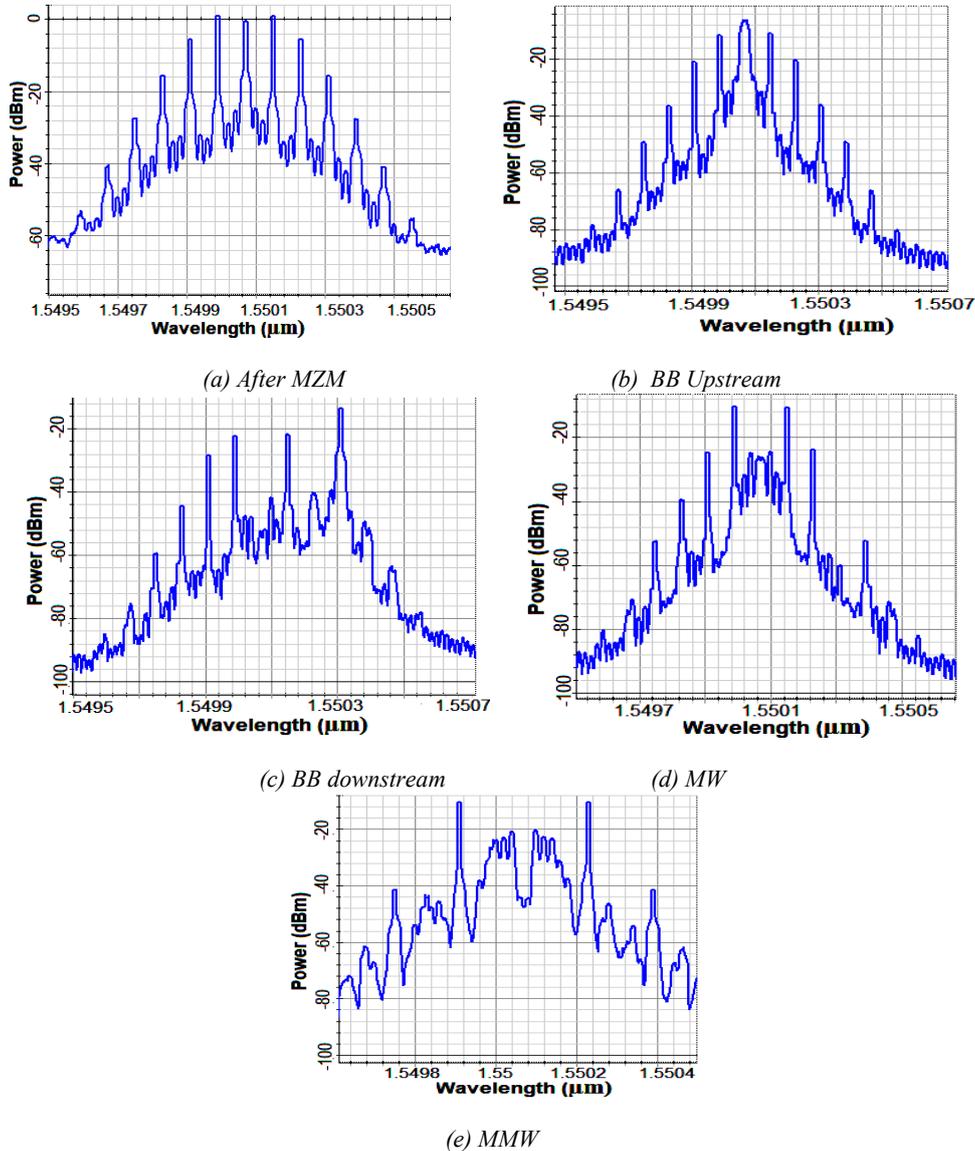


Fig. 2. Optical spectra at points (i)-(v) of Fig. 1

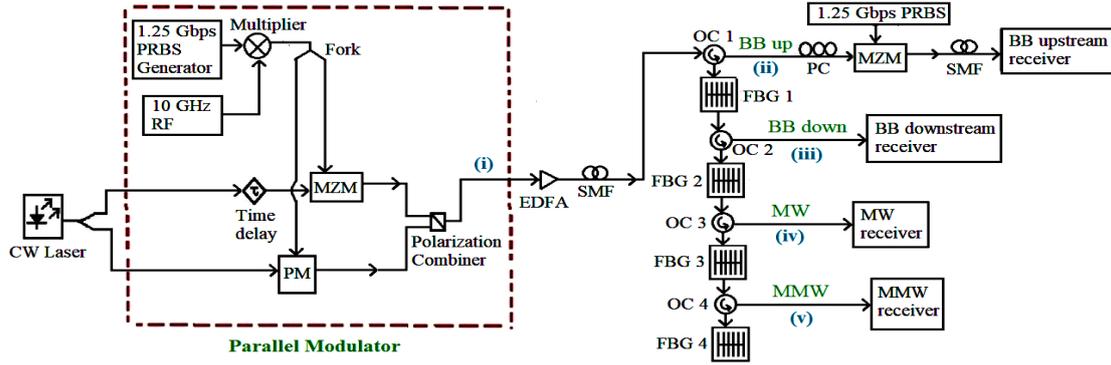


Fig. 3. Set-up of bidirectional three-band lightwave transmission system for RoF link using parallel modulator

2.2. RoF scheme using parallel modulator

With increase in transmission distance, the effect of dispersion becomes quite prominent in RoF link thus to improve the system performance over long distance the effect of dispersion need to be addressed properly [16].

Due to Chromatic Dispersion (CD) there is time delay between the two sub-signals having different wavelengths which reduces the performance of the system. The basic concept used in this scheme is that if the time delay between the two sub-signals is properly adjusted then the effect of CD can be combated [17].

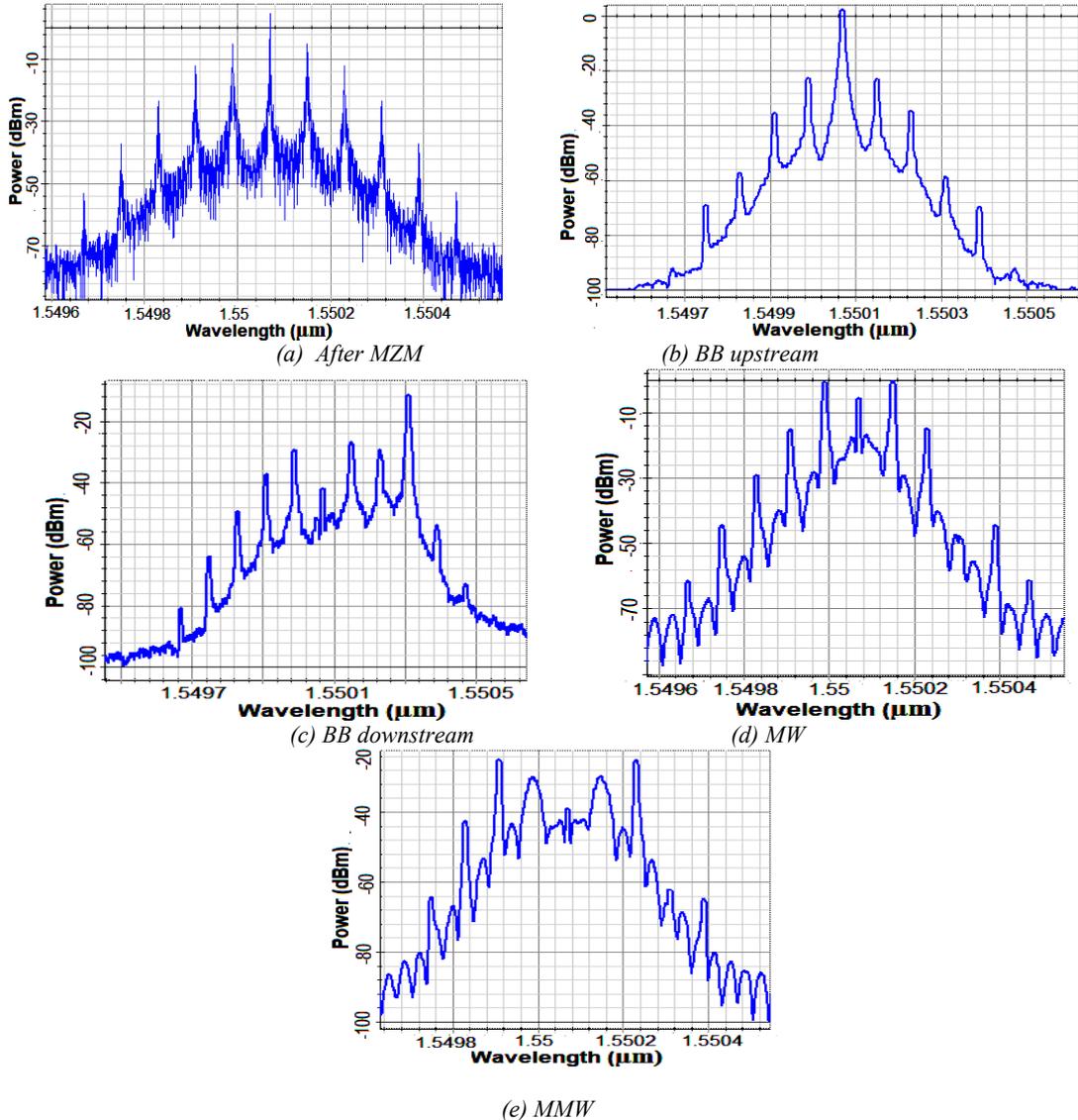


Fig. 4. Optical spectra diagrams at points (i)-(v) of Fig. 3

The system set-up for the proposed RoF scheme using parallel modulator is shown in Fig. 3 and the fiber parameters are the same as in Table 1. It consists of a CW Laser operated at 1550.07 nm wavelength, 10 dBm power and a Linewidth of 1 MHz. The output of this LD is divided into two parts by using a Tunable Optical Coupler (TOC). One part is given to the phase modulator (PM) while the other part is given to the Lithium Niobate MZM by providing a suitable time delay of 13ns to combat CD. The Lithium Niobate MZM and PM are fed by a 1.25 Gbps PRBS data multiplied by a 10 GHz RF carrier. The output signals from the two modulators are then combined by using a Polarization Combiner and the amplified signal is sent over the SMF. At the receiver, a combination of FBG tuned to respective wavelengths and circulators are used to separate out the BB upstream and BB/MW/MMW downstream signals same as described in serial modulator scheme. The optical spectra of these signals at various points of Fig. 3 are shown in Fig. 4. The parallel modulation scheme with optimized time delay between the two sub-signals is expected to improve the transmission distance but it cannot be used in remote or disaster prone areas where there is difficulty in laying out optical fiber between central station (CS) and base station (BS). For such areas, Radio over FSO is a novel solution which is proposed in the next section.

2.3. Radio over FSO scheme

The system set-up of the proposed scheme for RoFSO link is shown in Fig. 5. It consists of a CW Laser operated at 13 dBm power and 1550.07 nm wavelength. The 1550 nm transmission window is used for RoFSO link as it

meets the eye safety standards and provides better performance than other two transmission windows [7, 18]. The laser signal is passed through a serial modulator composed of PM and lithium Niobate MZM, driven by a 10 GHz RF carrier and 1.25 Gbps PRBS data sequence. This signal is then sent over the free space through suitable lens. The lens is used for beam shaping and focusing. Free space optics technology has the major drawback of high attenuation. This attenuation is due to the various atmospheric conditions like rain, fog, snow etc and other losses like geometric losses, transmitter losses, receiver losses etc. As RoFSO is a LOS communication, all these reasons make RoFSO suitable for transmission only up to a few kms. An attenuation of 15dB/km is taken in this case by considering the normal atmospheric conditions. In the proposed system, RoFSO was investigated first without using EDFA in which the transmission distance was limited to 300 m only. Later, an EDFA was employed after RoFSO channel to compensate the attenuation caused in the signal and boost-up the signal level which increased the transmission distance to 1 km. The receiver section is same as used above in the other two schemes. Optical spectra of three-band lightwave signals at various points in the system set-up (Fig. 5) are shown in Fig. 6 and the channel parameters are listed in Table 2. Generally, for the detection and down conversion of the MW and MMW signal, photodiodes (PDs) of high bandwidth, local oscillator (LO) and mixers are used which increase the overall cost of the system and make it more complex but in our schemes direct detection technique has been used [19-21]. The simulation results obtained for the proposed schemes are presented in the next section.

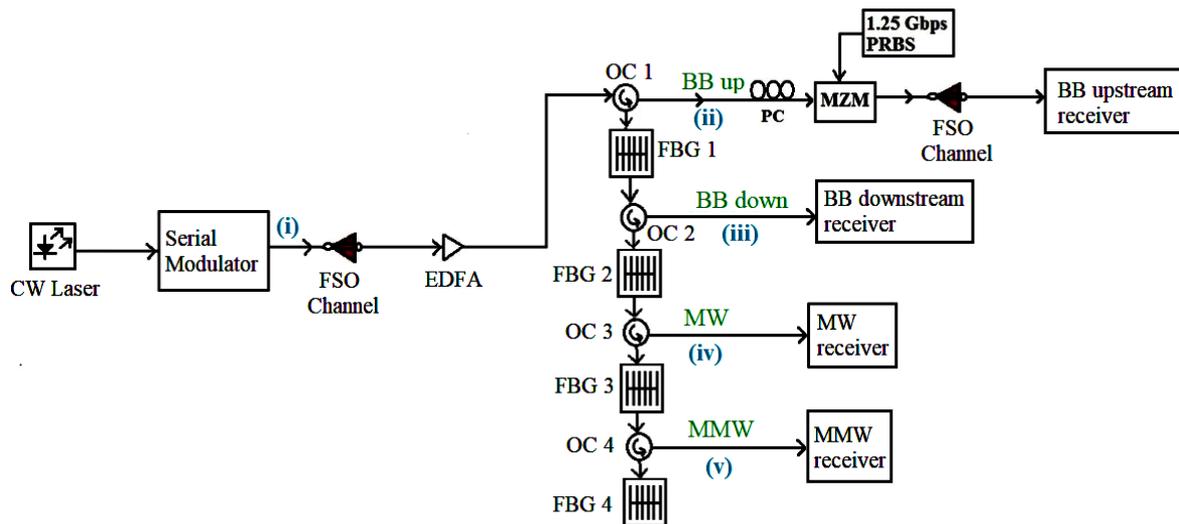


Fig. 5. Set-up of Bidirectional three-band lightwave transmission system for RoFSO link

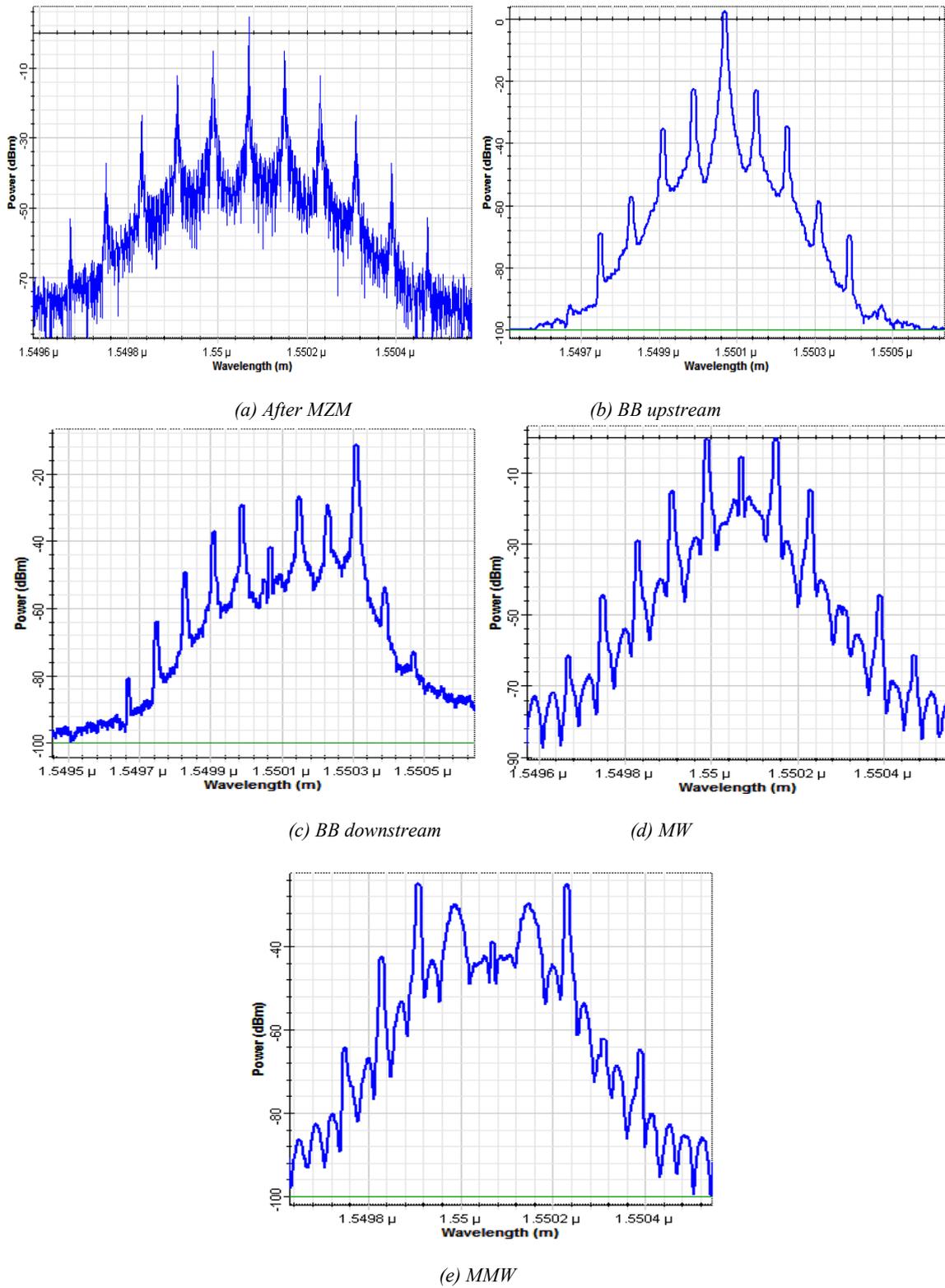


Fig. 6. Optical spectra at points (i)-(v) of simulation setup (Fig. 5)

Table 2. Parameters for FSO channel

Parameters	Value
Beam divergence	0.5 mrad
Attenuation	15 dB/km
Transmitter aperture diameter	5 cm
Receiver aperture diameter	20
Transmitter losses	2 dB
Receiver losses	2 dB

3. Results and discussion

The investigations has been performed using the commercially available Optisystem tool. The results have been gathered using the bit error rate (BER) analyzers and Q-factor performance has been used as the evaluation criteria for comparing various RoF schemes.

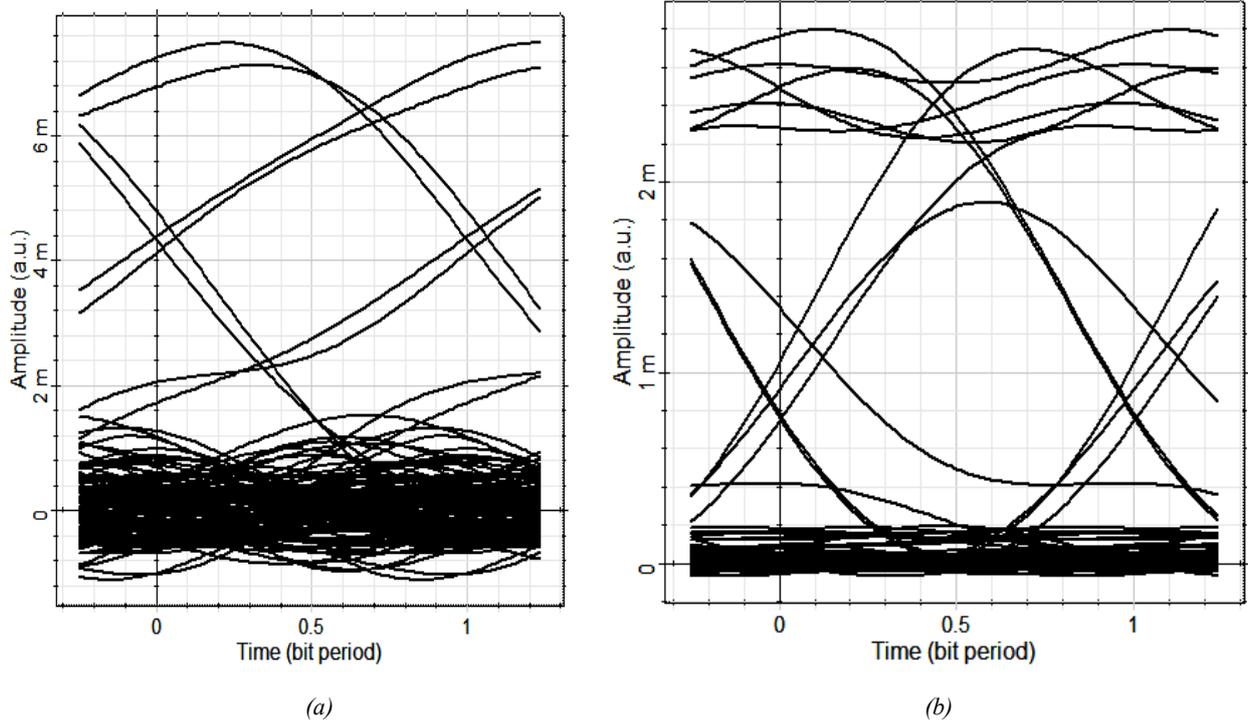


Fig. 7. Received eye patterns with RoF link for the BB upstream signals after a transmission distance of (a) 35 km using serial modulator scheme and (b) 58 km using parallel modulator scheme

3.1. Comparison of RoF scheme using serial and parallel modulator

Eye patterns with RoF link (in Fig. 7) show wide eye opening using parallel modulator scheme compared to the serial modulator scheme as the parallel modulator suppresses the effect of dispersion thus facilitating a higher transmission distance.

The Q-factor performance of RoF scheme with serial and parallel modulator has been compared for the BB upstream and BB, MW, MMW downstream signals over different link lengths (Fig.8 (i)-(iv)). Performance of serial modulator is affected due to CD. It is observed that the parallel modulator performs better with high Q-factor performance for all the signals and provides length improvement.

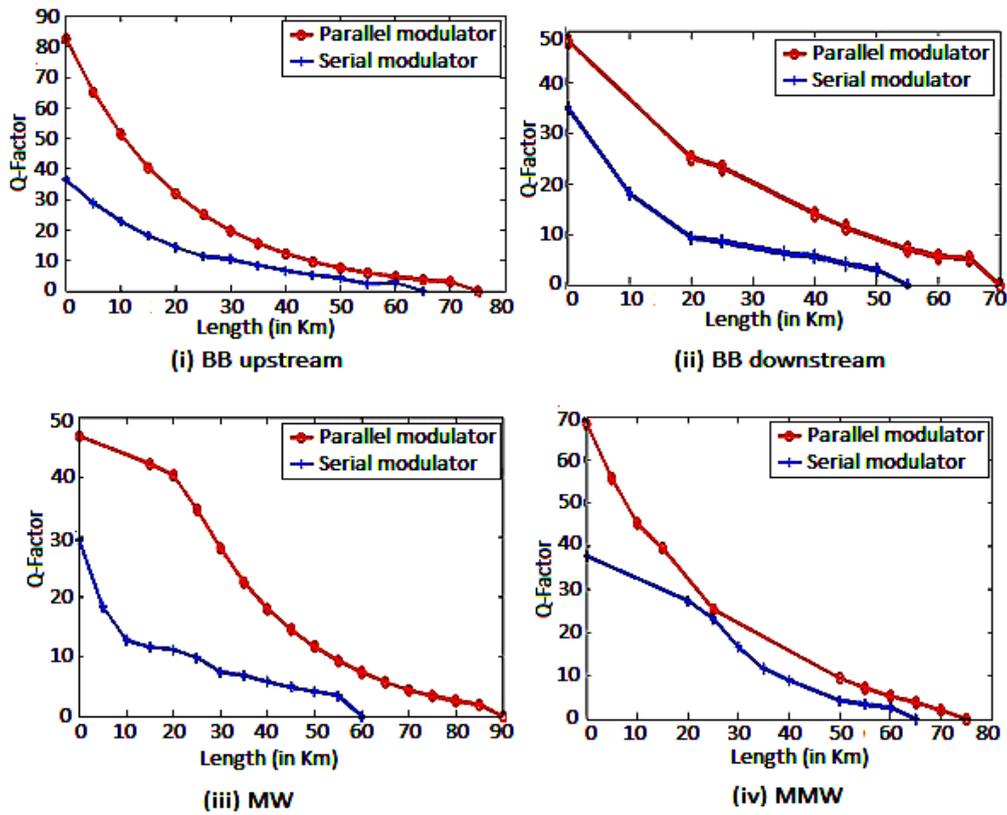


Fig. 8(i)-(iv) Plot of Q-Factor vs. Length graphs for RoF link using serial and parallel modulator

3.2. Comparison of RoFSO scheme with and without EDFA

By comparing the graphs and taking an optimum length over which all the four signals can be transmitted simultaneously over the SMF, we conclude that serial modulator can be used only up to a length of 35 km and parallel modulator can be used up to a length of 58 km after which the Q-Factor becomes < 6 and the BER is $> 10^{-9}$. This proves that parallel modulator provides better performance as compared to serial modulator by combating CD induced in the link.

The proposed RoFSO link was first evaluated without using an EDFA but attenuation limited the transmission length to some meters. An EDFA was used after FSO channel to compensate the high amount of attenuation caused in the link. Q-factor performance for RoFSO scheme for different signals has been compared for maximum transmission reach with and without using EDFA (Fig. 9). The results obtained from these investigations are summarized in Table 3. From the graphs

(Fig. 9) it can be concluded that the achieved transmission length was only 300 m through which all the signals can be transmitted simultaneously without EDFA and it increased to 1000 m after using EDFA. This shows that using an EDFA in FSO link improved the system performance.

Table 3. Transmission length achieved in RoFSO scheme with and without EDFA

RoFSO Scheme	Length achieved (in metres)			
	BB upstream	BB Downstream	MW	MMW
Without EDFA	303 m	300 m	305 m	330 m
With EDFA	1020 m	1040 m	1030 m	1000 m

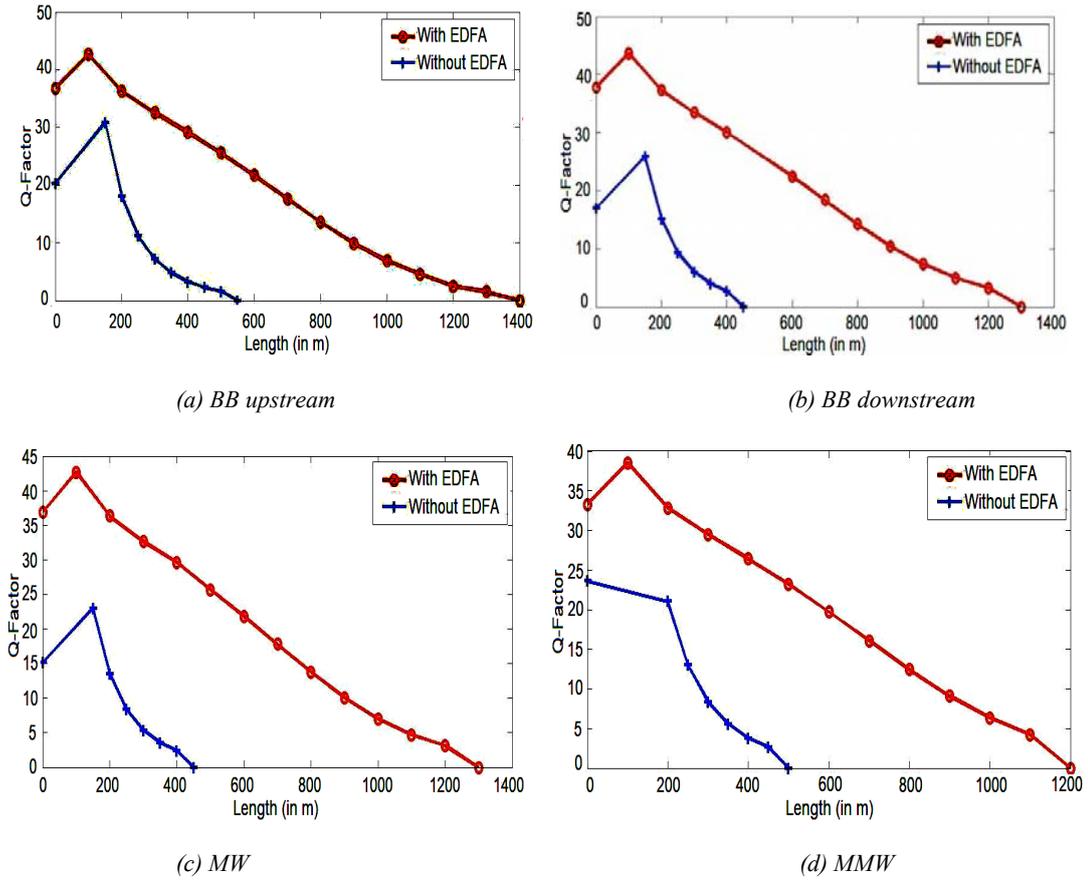


Fig. 9. (a)-(d) Plot of Q -Factor vs. Length graphs for RoFSO link with and without EDFA

Table 4. Summary of the proposed work

Parameter	RoF using serial modulator		RoF using parallel modulator	RoFSO	
	Li et al. (2012) [12]	Current Investigation		Without EDFA	With EDFA
Length achieved	20 km	35 km	58 km	300 m	1 km
Transmitted optical power	10 dBm		10 dBm	13 dBm	

Further, the proposed work is summarized and compared with the previous work 2012 [12] (Table 4), which showed the length achieved for RoF link was only 20 km by using serial modulator whereas in our proposed scheme the length achieved is 35 km using serial modulator and 58 km using parallel modulator. Since in FSO, dispersion is not a prominent phenomenon so serial modulator was used in FSO and the achieved length was 300 m without EDFA and 1 km with EDFA. Hence, an enhanced link performance using the parallel modulation scheme is achieved in terms of increased transmission distance for the same transmitted power.

4. Conclusions

A bidirectional three-band lightwave system for upstream and downstream data transmission is proposed and demonstrated for both the RoF and RoFSO platforms using the serial and parallel modulators. Simultaneous transmission of 1.25 Gbps BB upstream, 1.25 Gbps BB downstream, 1.25 Gbps/20 GHz MW and 1.25 Gbps/40 GHz MMW signals have been achieved for a distance of 35 km using the serial modulator without chromatic dispersion compensation. An impressive Q -factor performance for RoF link is attained at an increased transmission distance of 58 km for the same channel

power using the parallel modulator by compensating the chromatic dispersion. Hence, a 65.7 % improvement in length (from 35Km to 58 Km) has been achieved using the parallel modulator scheme. Furthermore, the proposed three band lightwave transmission system has been successfully demonstrated for RoFSO link using the serial modulator for a distance of 300m without amplifier and up to 1 km with amplifier. The system does not require Multiple LDs, RSOA, DI at transmitter or any high frequency LO, Mixers at receiver to down convert the signal making the system simple and convenient for implementation. The proposed system can be used by both wireline and wireless users and can be implemented in areas where fiber installation is not feasible.

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