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PHOTONIC MMW GENERATION USING PM-DPMZM FOR FULL DUPLEX 32×10 GBPS ROF-WDM SYSTEM

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This paper presents a study of a 32×10 Gbps Radio over Fiber and Wavelength Division Multiplexing (RoF-WDM) full-duplex system that uses Phase Modulators and a Dual-Port Mach-Zehnder Modulator (PMs-DPMZM) for bidirectional data transfer. The system employs Millimeter-Wave (MMW) signaling over optical fiber and focuses on selecting a technology that provides high transmission capacity per wavelength, improved spectral efficiency, and resistance against optical transmission impairments. The proposed method was validated using simulation results to confirm the efficiency of the proposed system in generating a 40 GHz signal and efficiently detecting and modulating the RF signals. The results demonstrate that the system exhibits strong resistance against dispersion, non-linear effects, and noise, delivering satisfactory performance for distances of up to 220 km. By analyzing the input power, the paper establishes a relationship between input power and signal quality, revealing that an optimal power of 0 dBm leads to an improved Quality Factor (QF) and reduced transmission errors. Furthermore, the evaluation of received optical power indicates the power level required to maintain an acceptable error rate, approximately -20.9690 dBm for downstream data transfer and -20.7245 dBm for upstream data transfer at the BER limit. The simulation performance also demonstrates the transmission efficiency achieved through a high Polarization Mode Dispersion (PMD) coefficient of up to 0.8. The analytical calculations conducted in this work provide valuable insights for optimizing and enhancing the performance of RoF-WDM networks.

Keywords: Radio over fiber, wavelength division multiplexing, millimeter-wave, phase modulator, dual-port mach-zehnder modulator

1. Introduction

The enormous growth of multimedia applications and the widespread use of sensors in most products have created a demand for high data transfer speed, high energy efficiency, and increased mobility. Consumers expect more interactive real-time multimedia experience with faster data transmission and minimal latency from their Mobile Station, as these devices are designed to meet increasingly higher demands. (Kavitha *et al.,* 2021). Due to the high density present in the RF frequency spectrum; it has become necessary to operate at high frequencies. As a result, advancements have been assisted in recent years in optical communication systems utilizing radio frequencies within the THz range. Interest in optical systems has been increasing over time, which offers dependable communication over long distances and high data transfer rates. These systems work by transmitting digital signals from the information source to the receiver through fiber optic channels and optical waveguides. To achieve this, the digital signals are first modulated at the transmitter and then transported by an optical fiber channel (Mençik *et al.,* 2022).
Modern radio networks based on optical communication provide a novel solution that allows for the combination of the advantage of the radio and optical fiber transmission technologies to provide fast, reliable, and economical communication. This can be beneficial for creating an efficient and powerful infrastructure. On the other hand, optical communications have much lower latency than other communications systems by using optical technology for the core network and radio technology for the access network. This infrastructure reduces energy consumption to transmit signals over long distances of optical fiber. The RoF technique is an optical communication method that involves analog RF optical transmission with modulated RF signals. This technique allows for the connection between the Central Station (CS) and the Base Stations (BSs) for both UpLink (UL) and DownLink (DL) transmission which leads to providing a full-duplex connectivity for the Transmitter (Tx) and the Receiver (Rx) at the same

time. RoF system also provides extensive coverage for transmission to Mobile Units (MU) that are far from the CS, so it uses the Remote Node (RN) module located in the Optical Distribution Network (ODN) that allows effective transmission of radio signals to many BSs, Figure 1 shows the overall architecture of a RoF link. One of the primary advantages of RoF systems is their ability to support mobile communications and effectively meet the increasing demand for gigabit services in various broadband data access techniques (Ali *et al.*, 2019; Bhattacharjee *et al.*, 2022; Mandal *et al.*, 2021).

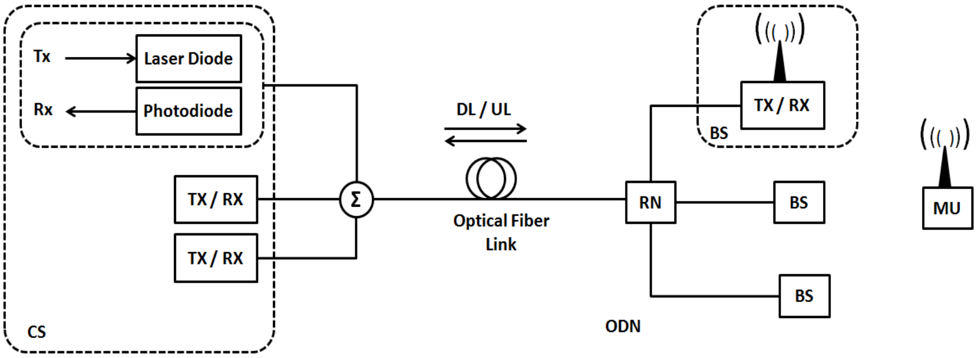


Figure 1. General RoF architecture. Tx / Rx: Transmitter / Receiver, DL / UL: DownLink / UpLink; CS: Central Station, ODN: Optical Distribution Network, RN: Remote Node, BS: Base Station, MU: Mobile Unit

The RoF system is being developed to support the growth of MMW photonics applications and to provide new ideas for mobile broadband technologies. These electromagnetic waves have a frequency range of 30 to 300 GHz, which is higher than the microwave frequencies currently employed in communication systems. MMW technology has several advantages over microwave frequencies, including the ability to transmit higher data rates and support more devices simultaneously, in which the optical MMW signal is distributed remotely over a low-loss fiber, from the central office to several base stations. Effectively eliminating the loss of signal propagation in both electrical and wireless transmission lines (Shi *et al.*, 2011). The WDM technique is an optical method that enables the multiplexing of multiple optical carriers. This approach permits the transmission of optical signals produced by different lasers, with spacing between channels (Ali *et al.*, 2019). However, WDM systems are subjected to nonlinear effects, causing limitations in the performance of the received signals caused by the low spacing between the channels. The incorporation of RoF techniques into WDM systems significantly improves the coverage area and capacity of the existing and future optical networks. The use of the RoF-WDM system can simplify network design and installation by enabling signal demodulation without the need for separate networks. This integration results in a more efficient and cost-effective solution for delivering high-speed data to mobile devices and extending network coverage (Ali *et al.*, 2019).

Both linear and nonlinear effects affect the optical signal in the propagation of the fiber, which leads to modifying the transmitted light. The transferred signal over optical fiber may suffer attenuation, dispersion, and polarization as a result of linear effects in an optical network. In addition, nonlinearities in optical fiber can produce inter-channel crosstalk and distortions in the transmitted signals, such as Four Wave Mixing (FWM), Self-Phase Modulation (SPM), and Cross-Phase Modulation (XPM) (Irfan *et al.*, 2021). Additionally, the nonlinearities associated with the refractive index (RIrNL) can result in the generation of unwanted frequencies within the optical medium due to the mixing of transmitted optical signals with each other or with the carrier wavelength during their propagation (Habib *et al.*, 2017). The presence of these effects can limit the distance over which the signal can travel without significant degradation, the amount of data that can be transmitted through the fiber, and the quality of the received signal. Therefore, it is crucial to carefully design and optimize optical fiber systems to minimize the impact of these effects on the transmitted signal.

2. Related work

Recently, in (Patiño-Carrillo *et al.*, 2018) an overview of RoF architecture for the centralized bidirectional MMW transmission is presented, demonstrated experimentally, and simulated. The proposed method is based on the bidirectional transmission of a single-sideband optical subcarrier generated by an electro-optical Mach-Zehnder modulator (MZM). The downstream connection uses one of the single sideband subcarriers, whereas the upstream link utilizes the other subcarrier. Also, this method makes it possible to centralize the optical source, eliminating the need for optical sources at the base station. This process generates a downlink signal with a significantly higher penalty than its uplink counterpart.

In (Wang *et al.,* 2016) an optical source in the form of a distributed-feedback laser is employed, offering the capability to adjust its frequency by manipulating the bias current. To enable the modulation of mixed data with a Local Oscillator (LO) operating at 30 GHz, an electrical modulation is employed using an electrical multiplier. By utilizing a PM, the phase of the optical carrier signal is modulated. A new photonic mm-wave generation method has been proposed in a recent study (Al-Dabbagh *et al.,* 2017). This method aims to establish a full-duplex RoF link using an MMW signal. The researchers investigated the transmission performance of MMW generated by applying a PM technique while analyzing the characteristics of the Stimulated Back Scattering effect (SBS) in the optical fiber. To realize this RoF link, a single laser source is used in conjunction with a Fiber Bragg Grating (FBG) to enable wavelength reuse in the uplink connection. However, a powerful laser source with a wide laser linewidth is employed for this purpose. This approach offers several important advantages. Firstly, it increases the stability and quality of the MMW RoF link at a carrier frequency of 64 GHz. it also improves the quality of the MMW RoF link at the same carrier frequency.

The studied system in (Mençik *et al.,* 2022) consists of an active optical network that uses a bidirectional optical fiber to transmit an optical signal to the end users. Each user unit is equipped with a low-pass filter, which can be of the Chebyshev, Bessel, Butterworth or Gauss type. The impact of the filter type selection on the overall system efficiency was evaluated. It is proposed to integrate RoF technology into a WDM passive optical network with 10 km to enable two-way optical communication between a Central Office and a group of BSs. According to research presented by (Mazoor *et al.,* 2020) the use of polarization manipulation to reduce nonlinearities in dense WDM systems while maintaining the system's performance. Specifically, circular polarizers are used to alternate the polarization state of incoming pulses, which results in less power interacting in the same polarization state and reduces the effect of FWM.

Furthermore, in (Mahmood *et al.,* 2019) The Dispersion Compensation FBG in a RoF passive optical network architecture was suggested by using the Subcarrier Multiplexing/Amplitude Shift Keying (SCM/ASK) technique. The proposed system employs an FBG after a 10 km optical fiber length to compensate for the dispersion effect. Also in (Meena *et al.,* 2020) a new dispersion compensation model has been proposed for Long-Haul optical transmission systems. This model uses a Chirped FBG. Optimized CFBG parameters have been studied to minimize chromatic dispersion and compensate for undesirable dispersion effects in the system, but the system was designed using a high transmission power of 17 dBm and high amplifier gains of 40 dB and 10 dB with Erbium Doped Fiber Amplifier (EDFA) amplifiers. The authors (Okeke *et al.,* 2021) report a Bidirectional network functionality created by utilizing the WDM technique, which enables the simultaneous transmission of multiple signals over a single fiber. This approach increased the network's efficiency and capacity. Additionally, the bidirectional network enabled both upstream and downstream data to be transmitted through the same fiber. To reduce the effects of FWM and improve the efficiency of FWM in Dense WDM optical communication networks. In (Manzoor *et al.,* 2020), the PMD emulation technique is used to eliminate FWM products and improve FWM efficiency. It is observed that by applying PMD, the FWM efficiency can be improved. Simulation results show an improvement in FWM efficiency of 7 dB in downlink and 5 dB in uplink at a data rate of 5 Gbps in an eight-channel DWDM network.

In this paper introduces and investigates the efficacy of a proposed full duplex 32×10 Gbps ROF-WDM transmission system utilizing PMs-Dual-Port MZM modulation technique for both upstream and downstream data transfer, employing MMW signaling across the bidirectional optical fiber. The importance of this research lies in the selection of a technology that provides a high transmission capacity per wavelength, improved spectral efficiency, and high efficiency against the effects of optical transmission especially with interring PMD, SPM, and XPM in the optical fiber, and a stable upgrade path for future RoF networks to meet the evolving demands of customers.

The remaining sections of the paper are structured in the following manner: Section 3 outlines the design schematic and describes the system details. Section 4 provides details on the simulation setup, outcomes, and discussions on their significance. Lastly, the paper concludes in Section 5.

3. System description

The full-duplex system, including a single channel transceiver detail and optical fiber link is depicted in the overall block diagram presented in Figure 2.

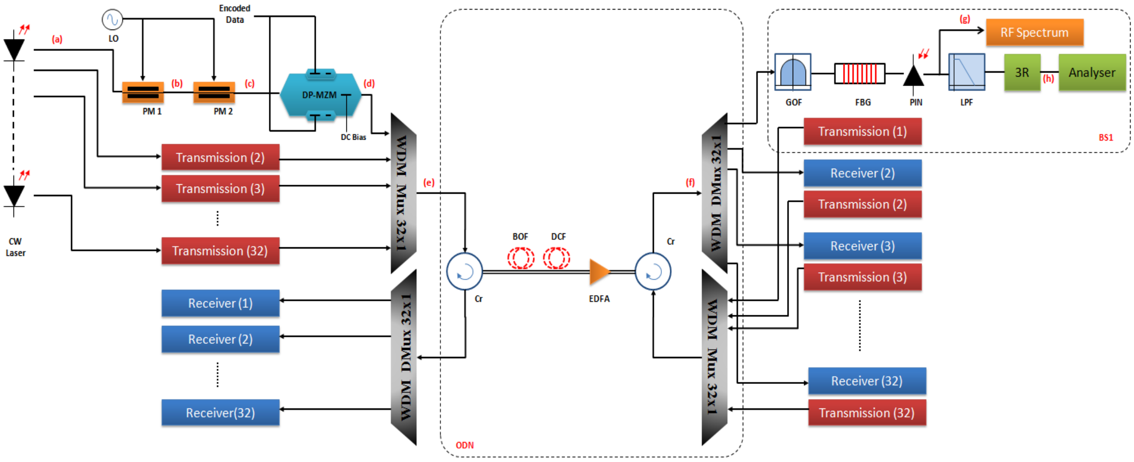


Figure 2. Schematic diagram of a full-duplex RoF-WDM structure with MMW. CW: Continuous Wave, LO: Local Oscillator, PM: Phase Modulator, DP-MZM: Dual-Port Mach-Zehnder Modulator, DC: Direct Current, Cr: Circulator, BOF: Bidirectional Optical Fiber, DCF: Dispersion Compensating Fiber, EDFA, Erbium Doped Fiber Amplifier, GOF: Gaussian Optical Filter, FBG: Fiber Bragg Grating, PIN: Positive Intrinsic Negative Photodiode, LPF: Low Pass Filter, 3R: 3R Regenerator

An aggregate data rate of 640 Gbps is provided for 32 channels, where each channel is modulated with a 10 Gbps data rate signal in the uplink and the downlink. The system is referred to consists of two stages of modulation to generate a filterless optical MMW signal. Initially, an optical PM is used for RF transmission, the frequency signal from the LO is divided into two separate paths and applied to the two PMs. In contrast to other modulation methods, the ROF system uses a PM to provide a greater degree of flexibility in adjusting the signal margin, this modulation is an Optical Double SideBand ODSB generation driven by an appropriate radio frequency signal. After that, the coded data is modulated using a DPMZM. This modulator works by modulating a carrier wave produced by a laser source with an information stream. By applying two electrical signals into the polarization division multiplexing MZM, the relative phase between the arms can be changed, thereby altering the output polarization state of the modulator, producing an optical output signal that carries the encoded data. ODSB is characterized by symmetrical upper and lower sidebands carrying identical information. In certain situations, it is possible to use only one of the sidebands to transmit the entire information, without the need to transmit both sidebands (Yang *et al.*, 2021). The optical output signals of PM1 and PM2 are given by eqs (1) and (2). The output of the DPMZM is given by eq (3).

$$E_{PM1} = E_{in}(t).e^{(j\Delta\Phi.M(t))}, \tag{1}$$

$$E_{PM2} = E_{in}(t).e^{(j2\Delta\Phi.M(t))}, \tag{2}$$

where $E_{in}(t)$ is the light signal emitted by the CW laser, $\Delta\Phi$ is the phase deviation, and $M(t)$ is the electrical signal.

$$E_{out}(t) = \frac{E(t)}{10^{(IL/20)}}.[\gamma.e^{(j\pi v_2(t)/V_{\pi RF} + j\pi v_{bias2}/V_{\pi DC})}$$

$$+(1-\gamma).e^{(j\pi v_1(t)/V_{\pi RF} + j\pi v_{bias1}/V_{\pi DC})}], \tag{3}$$

where $E(t)$ is the input signal, γ is the power splitting ratio of the DPMZM IL the parameter insertion loss, $v_1(t)$ and $v_2(t)$ are the input electrical voltage for modulator arms, v_{bias1} and v_{bias2} are the settings for bias voltage 1 and bias voltage 2, $V_{\pi RF}$ is switching modulation voltage, and $V_{\pi DC}$ is switching bias voltage

The optical field at the output of the optical modulation is determined by eq (4).

$$E_{out}(t) = \frac{E_{in}(t)}{10^{(IL/20)}}.[\gamma.e^{(j\pi v_2(t)/V_{\pi RF} + j\pi v_{bias2}/V_{\pi DC} + j2\Delta\Phi.M(t))}$$

$$+(1-\gamma).e^{(j\pi v_1(t)/V_{\pi RF} + j\pi v_{bias1}/V_{\pi DC} + j2\Delta\Phi.M(t))}], \tag{4}$$

After modulating each channel, the system utilizes a WDM structure with full duplex transmission for both downstream and upstream directions at 193.1 THz and 197 THz respectively. The signals are subsequently combined through a wavelength division multiplexer, which operates with a channel spacing of 150 GHz. The resulting optical signals are transmitted over a bi-directional optical fiber. By connecting a Dispersion Compensating Fiber (DCF) section in the transmission link to compensate the dispersion in the fiber, which limits the effects of nonlinear inter-channel interference RIrNLs and thus can improve the overall performance of the WDM system. After optical transfer, an amplifier is added to amplify the optical signal and compensate for the linear dispersion and attenuation that occur during transmission. The use of EDFA enables the amplification of the signal without significant distortion, which helps to maintain the quality of the signal and improve the overall performance of the communication system. The amplified signal is provided to a demultiplexer which separates the received signal into distinct wavelengths corresponding to each channel.

To improve the receiver quality of a selective optical signal and to remove nonlinear components from the signal such as FWM, an optical Gaussian filter is integrated into the system. The filtered output signal is subsequently linked to the FBG component which also helps to eliminate some portion of the Amplified Spontaneous Emission (ASE) due to the filtering operation (Manzoor *et al.*, 2020).

The receiver units contain a PIN photodetector that converts the optical signal into the RF signals transmitted in the RoF system. Once a signal is detected, the antenna sends the MMW radio signal to the user terminal. In the uplink direction, the signal is processed by the user's terminal and then modulated onto an optical carrier. Then the modified signal is sent via an ODN pass-through back to the central system. Table 1 presents the various design parameters, these specifications are necessary to ensure the obtained transmission.

Table 1. The simulation parameters

Parameters	**Values**
Data rate	10 Gbps
The frequency of the first channel	193.1 THz
Linewidth	0.1 MHz
The channel spacing	150 GHz
Phase shift	90°
The extinction ratio of MZM	30 dB
SMF attenuation	0.2 dB/km
SMF Dispersion	16.75 ps/nm/km
Dispersion Slope	0.075 ps/ nm^2/km
Effective area	80 μm^2
DCF Length	10 km
DCF attenuation	0.3 dB/km
DCF Dispersion	-83.75 ps/nm/km
EDFA Gain	15
The noise figure	4 dB
Gaussian optical filter Bandwidth	30 GHz
PIN responsivity	1 A/W
PIN dark current	10 nA
Thermal power density	100e-24 W/Hz
The cutoff frequency of a filter	0.75* bit rate Hz
The filter order	4

4. Results and discussion

This section focuses on evaluating the performance of the proposed RoF-WDM system. As previously mentioned, we have transmitted a set of 64 wavelengths, each with a data rate of 10 Gbps, and with 150 GHz spacing between each channel. To understand how the Quality factor (QF) and bit error rate (BER) of the optical channels degrade as a function of different parameters, such as optical fiber length, input optical power, received optical power, and PMD coefficient.

4.1. Performances analysis of optical spectrums and eye diagrams of the system

In Figure 3, we present the simulation spectrum obtained at the end of each block, indicated from (a) to (j) in Figure 2, Figure 3(a) displays the optical spectrum of the carrier generated by a Continuous Wave (CW) laser. Figures 3(b) and (c) illustrate the spectral components of the output signal generated by the two PMs for MMW frequencies of 40, 80, and 120 GHz, with the first-order MMW frequency emerging as the primary components. It can be observed that an optical generator generates MMW signals by utilizing a sinusoidal electrical oscillator. The sidebands are symmetrically positioned around the optical carrier frequency, and their harmonics extend up to the third order. The sidebands appear symmetrically around the carrier frequency, the amplitude or power of each component is determined by the modulation depth and strength of the MMW signals. Figure 3(d) shows the downlink optical spectrum after the DPMZM modulation with MMW sideband generation for 10 Gbps data rate at 1552.5 nm wavelength. It can be observed that the optical carrier at the center of the spectrum with six optical sidebands at specific wavelengths: 1551.58 nm, 1551.88 nm, 1552.2 nm, 1552.844 nm, 1553.169 nm, and 1553.49 nm. The corresponding power levels for these sidebands are as follows: -35 dBm, -19 dBm, -16 dBm, -35 dBm, -19 dBm, and -16 dBm, respectively. The Figure 3(e) and Figure 3(f) analyze the optical spectrum of the full-duplex WDM channels before and after the optical distribution network.

The BS subsystem operates by using the principle of sideband detection in conjunction with the phase modulation of an optical fiber. This enables the reception of a high-quality 40 GHz mm carrier signal after the photodiode, as shown in Figure 3(g), The setup involves several components working together to achieve this outcome. According to the spectrum in the Figure 3(g), it can be seen that the received signal at a MMW frequency possesses an appropriate power level of approximately -7 dBm, this value can be amplified using an electrical amplifier. After filtering the signal with a Low-Pass Filter (LPF), the noise is reduced. The received data signal is shown in Figure 3(h).

Figure 4 depicts the eye diagrams illustrating the impact of different transmission distances on a WDM-RoF network with a data rate of 10 Gbps and a carrier frequency of 40 GHz. These diagrams represent the distortion of the baseband signal as the bidirectional fiber length increases in both the upstream and downstream directions. The diagrams show that as transmission distances increase the system performance degrades, particularly beyond 250 km. This deterioration occurs due to the presence of noise, which corrupts the eye height of the received signal as the fiber length increases. The degradation in signal quality is attributable to dispersion, amplitude distortion, and other transmission effects.

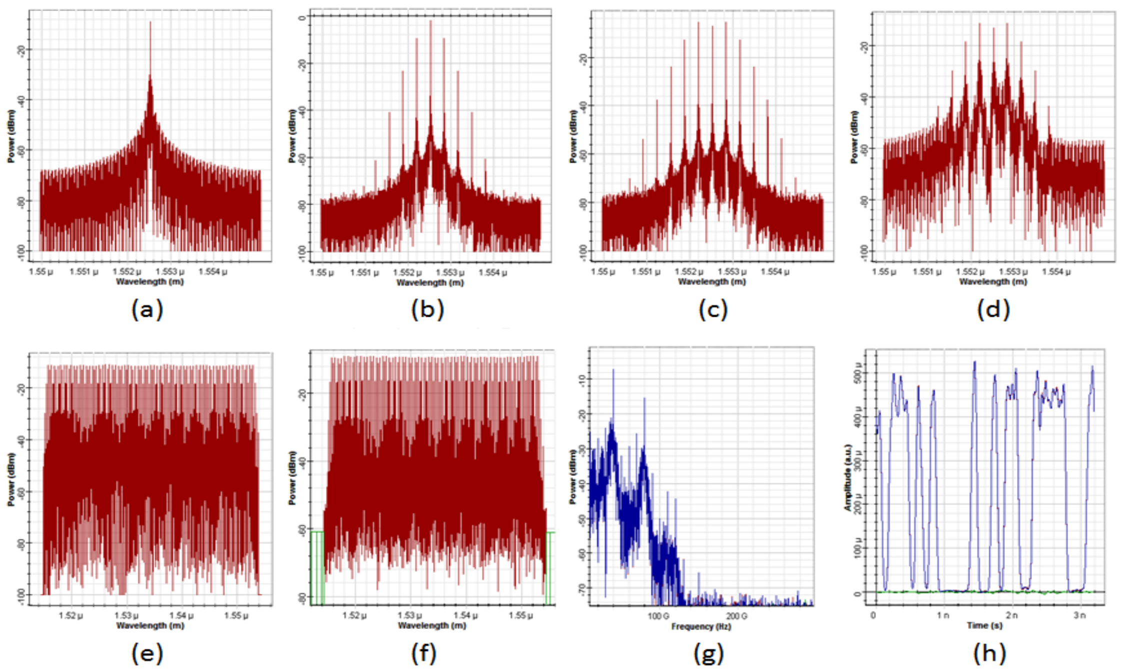


Figure 3. The analyzer results of the bidirectional RoF-WDM link shown in Figure 2. (a) CW signal spectrum, (b) optical signal spectrum after PM1 modulation, (c) optical signal spectrum after PM2 modulation, (d) optical signal spectrum after data modulation with DP-MZM, (e) WDM signal spectrum before transmission, (f) WDM signal spectrum after transmission, (g) RF signal spectrum, (h) received data signal

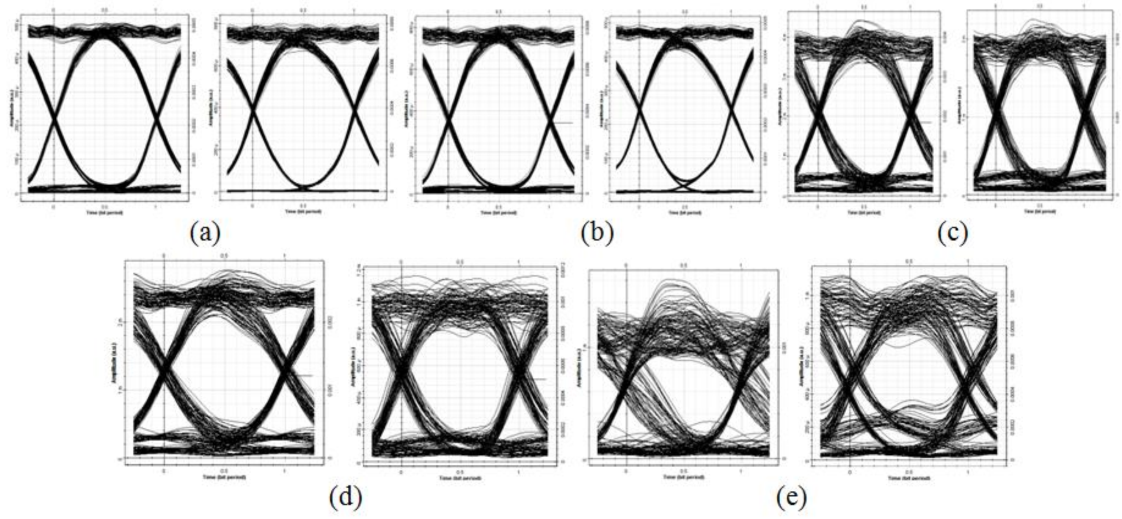


Figure 4. Eye diagrams for Downlink and Uplink transmission with different distances.
(a) 50 km, (b) 100 km, (c) 150 km, (d) 200 km, (e) 250 km

The obtained results demonstrate the efficiency of MMW signal generation from a sinusoidal local oscillator. They highlight the symmetry of the sidebands around the optical carrier frequency, as well as the modulation and detection of the RF signal, which is determined by the power of the transmitted component. This in-depth performance analysis provides a better understanding of the studied system and highlights the satisfactory performance of the different signal processing steps.

4.2. Performances analysis of QF and BER

To evaluate the performance of the proposed system, the designed optical transmission was simulated using OPTISYSTEM software (this tool used an Optical Spectrum Analyzer (OSA) to visualize the spectra shown in Figure 3). A detailed analysis has been performed on the RoF-WDM full duplex optical communication model is demonstrated in this section. In this study, the system simulation was performed using 32 channels and employing linear effects and non-linear effects such as PMD, CPM, and XPM. This analysis focused on the variation of several important parameters, including the optical fiber length, the input optical power, the received optical power, and the PMD coefficient. To evaluate the system, various performance measures are presented using QF and BER. The QF is an important metric of the transmitted signal quality, reflecting the efficiency of the transmitted signal. Besides, a low BER indicates the match between transmitted data and received data, while a high BER equal to or higher than 10E-9 indicates a deterioration of the signal quality which makes the received data unacceptable. The QF results are calculated with the using eqs (5). Assuming Gaussian noise with the standard deviations σ_1 and σ_0, the BER is calculated as (6) (Agrawal *et al.*, 2012).

$$Q = \frac{|\mu_1 - \mu_0|}{\sigma_1 + \sigma_0}, \quad (5)$$

where μ_1 and μ_0 are average values and standard deviations of the sampled values respectively.

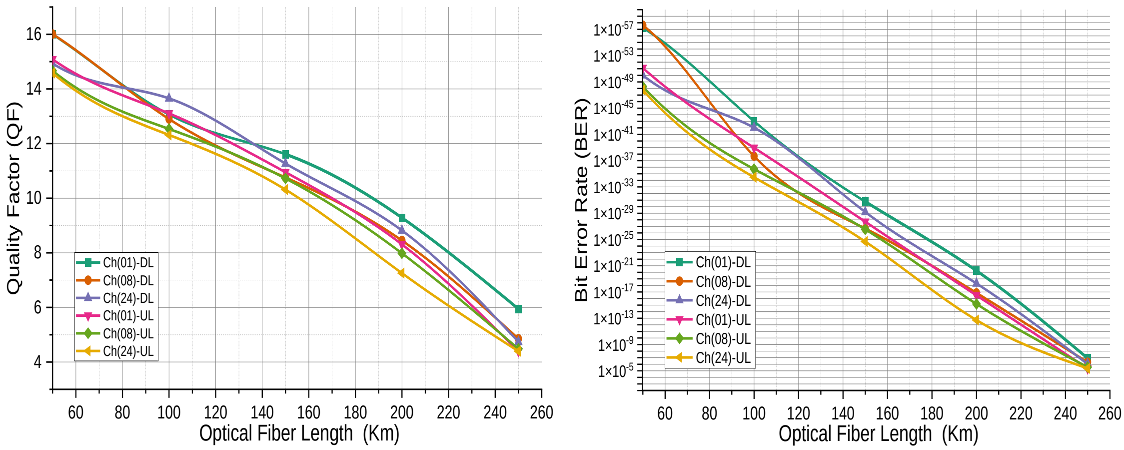
$$P_e = \frac{M}{N+M}.P_{e0} + \frac{N}{N+M}.P_{e1}, \quad (6)$$

$$P_{e0} = \frac{1}{2} erfc(\frac{S - \mu_0}{\sqrt{2}\sigma_0}),$$

$$P_{e1} = \frac{1}{2} erfc(\frac{\mu_1 - S}{\sqrt{2}\sigma_1}),$$

where P_{e0} and P_{e1} are the probabilities of the symbols, M is the number of samples for the logical 0 and N is the number of samples for the logical 1, and S is the threshold value, *erfc()* is the error function.

Figure 5 shows the variations of QF and BER as a function of link distance for three different channels and these are channels 1, 8, and 24. As shown in the QF curves in Figure 5(a) for each channel, we study how the QF changes with the variation in optical fiber length, the BER curves in figure 5(b) allow an evaluation of the bit error rate of the system with increasing optical fiber length. The analysis of the figure provides valuable information on the performance of the RoF system permitting the evaluation of the optical transmission in this system. From the graph, it can be observed that with an optical link of up to 50 km, the QF and BER values are 15.0845 and 7.6638E-52 respectively, indicating very low errors in this transmission. On the other hand, at longer distances up to 250 km, the QF and BER values decrease to 4.7384 and 9.5017E-7 respectively, indicating the presence of significant transmission errors. These performances from the results demonstrate that the system is capable of effectively managing the problems of dispersion, non-linear effects, and noise, while maintaining acceptable performance up to a distance of 220 km, with approximate QF results of 6.6036 and 6.0154, and BER results of 1.3805E-11 and 7.272E-10 for upstream and downstream respectively. The presentation of the calculated results demonstrates a valuable investment in enabling system optimization. So it clearly confirms the fiber length for transport signals in perfect functionality with high quality and meets the requirements of optical communication.

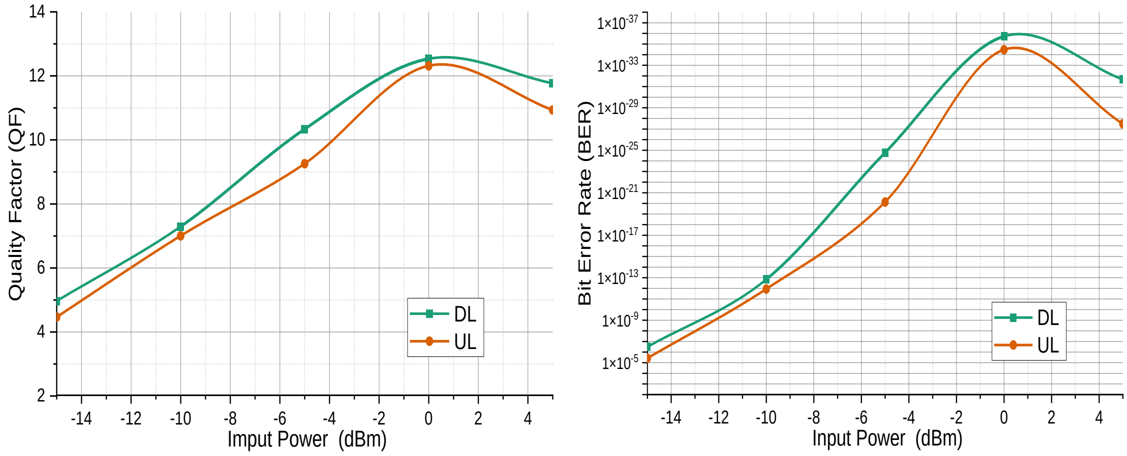


(a) (b)

Figure 5. (a) QF with respect to fiber length for DL and UL
(b) BER with respect to fiber length for DL and UL

Figure 6 shows the curves representing the QF and BER as corresponding with the input power variation of each channel for the transmission using a 100 km optical fiber link. It is important to note that the BER varies synchronously with the QF. From the results presented in this Figure, several important observations can be made regarding the QF and BER. They reveal that the optimal values are reached for transmitters with an input power of 0 dBm, where the BER is equal to 1.9003E-36 and the QF rises to 12.5326. On the other hand, the least favorable values are observed in the curves with an input power of -15 dBm with a lower QF and a higher BER. In addition, when looking at the range of input power variation from -15 to 5 dBm, an increase in QF is observed. It can be seen from the results of QF that the efficiency in the UL has improved from 4.4653 to 10.936 after applying an input power of -15 dBm to 5 dBm for each channel, as for the DL transmission it can be observed from the results of QF that the efficiency has improved from 4.9641 to 11.7696 after applying an input power of -15 dBm to 5 dBm for each channel. The investigation shows that the input power has an impact on signal quality in the transmission; this performance exhibits also an improvement of the QF for reducing transmission errors.

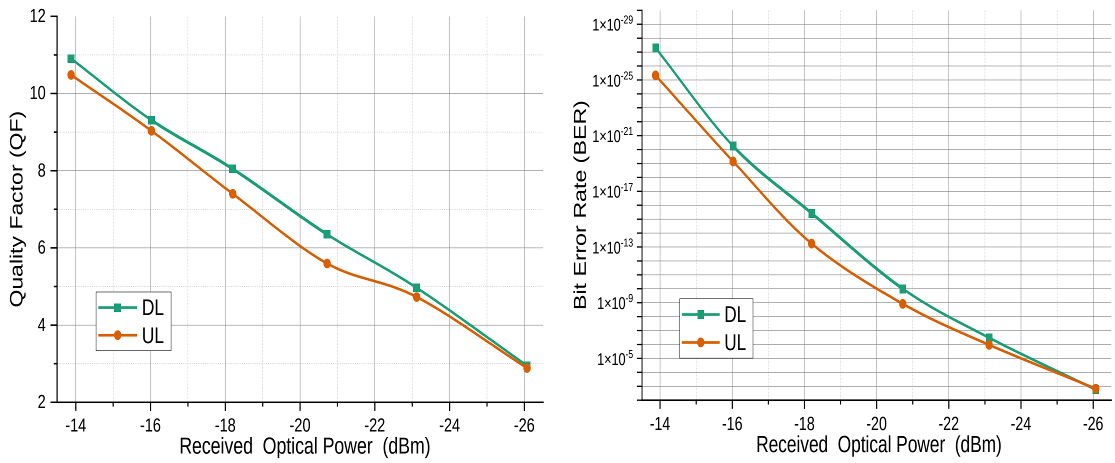
Simulation results show that when increasing the input signal power than 0 dB value, non-linear and dispersive effects such as FWM increase. This leads to the appearance of distortions in the signal, which reducing the QF and increasing the BER. As a result, the proposed RoF schemes show reduced performance of the WDM signals with using high input power. Furthermore, it has been observed that a decrease in input signal power leads to a reduction in QF and an increase in BER. This proves the importance of maintaining an optimum range of input power to ensure optimal communication system performance.



(a) (b)

Figure 6. (a) QF with respect to input power for DL and UL (b) BER with respect to input power for DL and UL

Figure 7 illustrates the evaluation of the QF and BER curves for the bidirectional transmission of DL and UL signals in a RoF-WDM link using a 100 km long fiber. This evaluation is performed according to the variations of the received optical power. For DL transmission, the receiver sensitivity is -13.8746 dBm with a QF of 10.9014. For UL transmission, on the other hand the receiver sensitivity is also -14.0236 dBm, and the QF is 10.479. For UL and DL, the QF reaches values of 2.8848 and 2.9471 respectively for received optical powers of -26.2927dBm and -26.0723 dBm. It is interesting to note that the QF decreases as the received optical power decreases. Figure 7(b) shows the BER curves for the DL and UL signals as a function of received optical power in the bidirectional fiber link. The receiver sensitivity is -20.9690 dBm at the BER limit for DL transmission, indicating the power level required to maintain an acceptable error rate. Similarly, for UL transmission, the receiver sensitivity is -20.7245 dBm at the BER limit. The outcomes illustrate the significance of the received optical power in the quality and reliability of signal transmission in the proposed RoF system, which helps determine the appropriate power ranges to ensure efficient transmission and reduce transmission errors.



(a) (b)

Figure 7. (a) QF with respect to received optical power for DL and UL
(b) BER with respect to received optical power for DL and UL

In Figure 8, the corresponding PMD coefficient curves are plotted for the DL and UL transmission modes. The PMD coefficient varies from 0.2 to 0.8 with an interval of 0.2 between each value. After analyzing the graphs, it is evident that the performance of BER and QF deteriorates as the PMD increases from 0.2 to 0.8. Conversely, at lower PMD values such as 0.2 and 0.4, the QF and BER exhibit better performance. In the DL, when considering PMD values of 0.2 and 0.4, the estimated QF values are approximately 12.1121 and 10.8743, respectively. Correspondingly, the associated BER values are approximately 3.1775E-34 and 6.0818E-28. On the other hand, in the context of the UL, when examining PMD values of 0.2 and 0.4, the estimated QF values are approximately 11.757 and 9.8369, respectively.

The corresponding BER values are approximately 2.0759E-32 and 2.7383E-23. These results indicate a relatively high QF and low BER, suggesting good transmission performance.

However, at 0.8 PMD coefficient, both DL and UL channels experience significant distortions. In the DL, the QF drops to 7.8605, and the BER increases to 1.4258E-15. Similarly, in the UL for PMD 0.8 the QF and BER reach values of 6.8248 and 3.7698E-12 respectively. These findings clearly demonstrate that at 0.8 PMD coefficient, the channels suffer from increased distortions, resulting in higher BER and decreased QF.

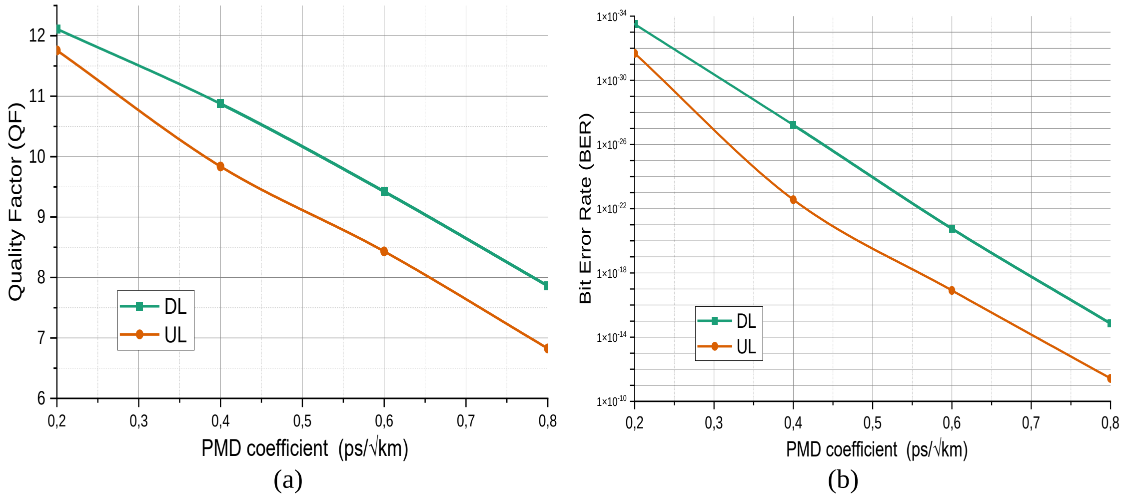


Figure 8. (a) QF with respect to PMD coefficient for DL and UL (b) BER with respect to PMD coefficient for DL and UL

In addition, the simulated system design in terms of overall performance of the results is in perfect providing successful high-capacity, long distance transmission of MMW signals over full-duplex optical fiber. This confirms the validity and applicability of the proposed system for practical use. In addition, all the specifications of the system components used are summarized in the parameters of Table 1. The Enhancing performance of the DCF-FBG combination for dispersion compensation at optical receivers effectively mitigates the adverse effects of higher-order dispersion harmonics. Furthermore, the comparative performance of our work demonstrates a significant improvement over recent works. For example, in recent studies, researchers have achieved high capacities of 6 × 2.5 Gbps (Liu *et al.*, 2020), 16 × 10 Gbps (Kumar *et al.*, 2021), 8 × 12 Gbps (Garg *et al.*, 2022), and 32 × 8 Gbps (Bhattacharjee *et al.*, 2022) over fiber distances of 40 km, 50 km, 100 km, and 120 km respectively. The analysis of the results provides a superior performance compared to previous works, this system also demonstrates an efficient high data transmission for a large number of channels with using MMW signals over long haul optical fiber under linear and non-linear fiber effects. Moreover, the proposed model proves a successful full duplex RoF transfer with minimizing the complexity of the system. The evaluation of the performance from the simulation indicates that our work provides a promising solution for supporting future RoF systems.

5. Conclusions

In this research paper, a RoF-WDM structure is considered a promising solution to provide a cost-effective full-duplex and high capacity optical communication. The proposed system provides a filterless technique-based DP-MZM and PMs modulation model for high frequency optical MMW generation. The presented RoF-WDM architecture efficiently distributes 40 GHz signal for full-duplex 32 channels while incorporating bidirectional optical fiber, DCF, and FBG in order to achieve long distance transmission and 10 Gbps data rate per channel. We analyzed the system by calculating QF and BER results which have shown that transmission quality is affected by various factors such as fiber length, input optical power, received optical power, and PMD coefficient, demonstrating the importance of maintaining optimal ranges for these parameters to assure reliable transmission. The simulation results demonstrate an improvement in terms of BER and QF and strong resistance against linear and nonlinear effects, including attenuation, dispersion, and PMD with satisfactory performance for a distance of up to 220 km, with approximate QF results of 6.6036 and 6.0154, and BER of 1.3805E-11 and 7.272E-10 for upstream and downstream respectively. In addition, the results confirm an efficient transmission with a high PMD coefficient of up to 0.8. The designed work in this paper can be explored as an effective solution to achieving high capacity and long distance transmission at MMW frequencies for enhancing the performance of RoF-WDM networks.

References

1. Agrawal, G. P. (2012) Fiber-optic communication systems. *John Wiley & Sons*.
2. Al-Dabbagh, R. K., and Al-Raweshidy, H. S. (2017) 64-GHz millimeter-wave photonic generation with a feasible radio over fiber system. *Optical Engineering*, 56(2), 026117-026117.
3. Ali, A. H., and Farhood, A. D. (2019) Design and performance analysis of the WDM schemes for radio over fiber system with different fiber propagation losses. *Fibers*, 7(3), 19.
4. Bhattacharjee, R., Dey, P., and Saha, A. (2022) Implementation of an enhanced 32 channel 256 gbps dwdm based radio over fiber optical system for constricted channel spacing employing fiber bragg grating. *Optik*, 253, 168598.
5. Garg, D., & Nain, A. (2022) An efficient 110× 8 GHz WDM RoF system design for 5G and advance wireless networks. *Optical and Quantum Electronics*, 54(6), 342.
6. Habib, U., Aighobahi, A. E., Nair, M., Zhu, H., Quinlan, T., Walker, S. D., and Gomes, N. J. (2017) Performance improvement for OFDM-RoF transported 60 GHz system using spatial diversity and multiplexing. In: *2017 IEEE International Conference on Communications Workshops (ICC Workshops)*, 211-216.
7. Irfan, M., Ali, F., Muhammad, F., Alwadie, A. S., Glowacz, A., Goldasz, I., and Khan, H. (2021) An optimal framework for WDM systems using analytical characterization of refractive index-related nonlinear impairments. *Electronics*, 10(3), 221.
8. Kavitha, C., Manimegalai, C. T., Kalimuthu, K., and Gauni, S. (2021) A novel bidirectional RoF link with compensated SBS and RB for 16-QAM OFDM based mm-wave downlink and uplink vector signal generation and transmission on a single fiber. *Optical Fiber Technology*, 66, 102671.
9. Kumar, S., Sharma, S., and Dahiya, S. (2021) Wdm-based 160 gbps radio over fiber system with the application of dispersion compensation fiber and fiber bragg grating. *Frontiers in Physics*, 9, 691387.
10. Liu, Y., Gao, H., Chen, Y., and Li, P. (2020) Full-duplex WDM-RoF system based on OFC with dual frequency microwave signal generation and wavelength reuse. *Optical Fiber Technology*, 58, 102252.
11. Mahmood, H. A., and Rumyantsev, K. Y. (2019) Effect of FBG compensated dispersion on SCM/ASK radio over fiber system. In: *2019 12th International Congress on Image and Signal Processing, BioMedical Engineering and Informatics (CISP-BMEI)*, 1-5.
12. Mandal, P., Mallick, K., Dutta, B., Kuiri, B., Santra, S., and Patra, A. S. (2021) Mitigation of Rayleigh backscattering in RoF-WDM-PON employing self-coherent detection and bi-directional cross wavelength technique. *Optical and Quantum Electronics*, 53, 1-13.
13. Manzoor, H. U., Zafar, M., Manzoor, S. U., Khan, T., Liu, S., Manzoor, T., and Ali, M. (2020) Improving FWM efficiency in bi-directional ultra DWDM-PON networking centered light source by using PMD emulator. *Results in Physics*, 16, 102922.
14. Mazoor, H. U., Rehman, M., Manzoor, S., Aslam, A., & Manzoor, T. (2020) Improved FWM efficiency for already deployed bidirectional fiber optic cable using polarization manipulation for underwater applications. In: *2020 17th International Bhurban Conference on Applied Sciences and Technology (IBCAST)*, 567-572.
15. Meena, D., and Meena, M. L. (2020) Design and analysis of novel dispersion compensating model with chirp fiber bragg grating for long-haul transmission system. In: *Optical and Wireless Technologies*: *Proceedings of OWT 2018, Springer Singapore*, 29-36.
16. Mençik, V., Aytekin, A., and Tür, M. R. (2022) The effect of filter selection on q factor in active optical networks. In: *International Informatics Congress (IIC2022)*, February 2022, Batman, Turkey.
17. Okeke, R. O., Idigo, V. E., Akemi, M. O., and Ogbuokebe, S. K. (2021) Passive optical network: a fibre to the 'X'Approach. *European Journal of Engineering and Technology Research*, 6(3), 66-74.
18. Patiño-Carrillo, A., Puerto-Leguizamón, G., and Suárez-Fajardo, C. (2018) Bidirectional single sideband transmission of millimeter waves over fiber for 5G mobile networks. *TecnoLógicas*, 21(43), 15-26.
19. Shi, J. W., Huang, C. B., and Pan, C. L. (2011) Millimeter-wave photonic wireless links for very high data rate communication. *NPG Asia Materials*, 3(4), 41-48.
20. Wang, X., Liu, Y., and Wang, W. T. (2016) A 60GHz RoF (radio-over-fiber) transmission system based on PM modulator. *Semiconductor Lasers and Applications VII*, 10017, 167-173.
21. Yang, L., Zhang, Q., Wang, Y., Luo, Y., and Zhang, W. (2021) hybrid optical and wireless system using RoF-PON based on OCS modulation. In: *2021 9th International Conference on Communications and Broadband Networking*, 239-243.