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Optical Multi-Wavelength Source for Single Feeder Fiber Using Suppressed Carrier in High Capacity LR-WDM-PON

SIBGHAT ULLAH[1], RAHAT ULLAH[2], ADIL KHAN[3], HAFIZ AHMAD KHALID[1], QI ZHANG[1], QINGHUA TIAN[1], FAHEEM KHAN[4], AND XIANGJUN XIN[1]

[1]State key Laboratory of Information Photonics and Optical Communications, School of Electronics Engineering, Beijing University of Posts and Telecommunications, Beijing 100876, China
[2]Institute of Optoelectronics, Nanjing University of Information Science and Technology, Nanjing 210044, China
[3]School of Electronics Engineering, Beijing University of Posts and Telecommunications, Beijing 100876, China
[4]Department of Computer Science, Bacha Khan University, Charsadda 24420, Pakistan

Corresponding author: Rahat Ullah (r.rahatullah@gmail.com)

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ABSTRACT In this paper, a novel cost-effective optical multi-wavelength generation scheme based on a pulsed laser and a single Mach–Zehnder modulator (MZM) is proposed. Over 50 wavelengths has been achieved with the proposed cost-effective scheme among which 37 wavelengths were selected for transmission because of their small amplitude excursions between the wavelengths and high tone-to-noise-ratio of over 40dB. Frequency spacing is kept at 12.5 GHz, where 10-Gb/s data-based differential phase shift keying (DPSK) modulation technique is utilized for downlink (DL) transmission across each wavelength in single feeder fiber (SFF) wavelength-division multiplexed-passive optical network (WDM-PON), and the results are examined for 25 and 50-km SFF. In SFF, uplink (UL) transmission can be impaired by Raleigh backscattering (RBS) noise. In this scheme, the RBS noise is alleviated at ONU side with the help of carrier suppression by utilizing non-return-to-zero (NRZ) dual port (DP) dual drive (DD) MZM modulation technique, where both the DL and UL transmissions are merged by using optical circulators without using a dispersion compensating fiber. At the receiver side, the signals are identified with the help of optical filters and divided in two halves using 1×2 forks, half of which is received and demodulated using DPSK receiver, whereas the other half of the transmitted signal is re-modulated with the help of a single 10-Gb/s NRZ-DP-DD-MZM modulation technique for UL transmission. Overall, 740-Gb/s data has been transmitted across 25 and 50-km bidirectional optical fiber for DL and UL transmission. The proposed scheme is analyzed in terms of bit error rate of $10e^{-9}$, power penalties (PP), and eye diagrams (ED). It is found that the observed PPs are negligible, and wide openings of the EDs satisfies that the proposed scheme is worth consideration for deployment in long reach WDM-PON.

INDEX TERMS Differential phase shift keying-transmitter/receiver (DPSK-Tx/Rx), long reach- wavelength division multiplexed- passive optical network (LR-WDM-PON), optical multi-wavelength generation (OMWG).

I. INTRODUCTION

Optical multi-carriers or optical multi-wavelengths (OMW) also known as optical frequency comb is a succession of comb lines formed by evenly spaced distinct comb lines [1]. In recent years, OMW based wide-range applications have been realized because of its unrivaled advantages including precisely locked frequencies of the wavelengths, large quantity of sub-wavelengths, excessively small duration of the pulses, and stable spectral characteristics [2], [3]. With the advancements in the technique of OMW generation (OMWG) having multiple bands, flexible tenability, and identical frequency spacing, its applications has been prolonged to many aspects, for instance, generation of ultra-short pulses [4], dense wavelength division multiplexing [5], [6], and generation of arbitrary wave-from [7]. For OMWG, numerous approaches have been suggested in the recent years including mode locked lasers [8]–[10], noise free optical multi-carriers based on Phase modulator [11], cascaded modulators [12]–[15], optoelectronic oscillator [16], [17], re-circulating frequency shifter [18]–[20], wave mixing in non-linear medium [21], exploiting modulation based on fiber loops [22], and generation of OMW based on pulsed laser (PL) [23]. However, they lake certain features, such as [15] undergoes poor stability issues. The OMWG based on mode locked lasers is one way of generating flat and stable wavelengths, and yet, they are excessively expensive, and their recurrence proportions are hard to be made high [8], and has complex structures [9]. Likewise, [11] has demonstrated a cost effective scheme with a single phase modulator but only 4 wavelengths are generated, which, compared to the proposed scheme, are about 9 times lesser than the generated OMWs by the proposed scheme.

Recent studies reveal several approaches towards mitigation of Raleigh backscattering (RBS) noise. Various modulation and re-modulation schemes have been offered to produce efficient results in WDM-PON system [24]. For instance, RBS noise mitigation in access networks was attained with the help of an optical suppressed sub-carrier, and phase re-modulation technique [25]–[27], and [28] demonstrates another technique for RBS noise mitigation in SFF (BDOF) which is based on phase re-modulation. It is revealed in [29] that by merging the downlink (DL) and uplink (UL) transmission via optical circulators (OCs) may reduce the RBS where typical IM-OOK is used for uplink transmission. Novel campaigns for mitigation of in-band RBS cross talk in PON network are proposed such as pulse broadening, multi-wavelength source, and seeding schemes (shared) [30]–[32]. Many other systems has also been proposed for RBS noise mitigation containing various techniques, such as dual drive (DD) MZM technique, orthogonal coding, line coding, detuning of wavelengths, electrical filtering, ring based WDM-PONs, and noise equalization prediction [33]–[37]. It is also investigated that RBS noise can be alleviated by producing certain shift in wavelength during the UL transmission with regards to the DL transmission [38]. Another technique suggests that in dense WDM-PON RBS noise can be minimized by carrier suppression with the help of cascaded configuration of semiconductor optical amplifier (SOA) at the ONU side [39], and WDM-PON based on tunable laser is also presented for RBS noise mitigation [40]. Alternatively, single sideband suppressed carriers (SSBSC) results in RBS noise reduction [41], [42], and shrinks the spectral overlap among the suppressed wavelengths and UL transmission. But the referenced work either needs additional circuits or optical devices [39], [40], [30]–[32] at the network side, or followed by complex modulation schemes [28], [38] to reduce RBS noise in UL transmission using SFF. Moreover, these practices have the deficiency of operating power budgeting minimization, and reducing operating high voltage values. Likewise, some approaches have used loop-back configurations which experiences interferometric noise that is generated by the carrier, and carrier redistribution. In addition to the given problems, the proposed models have also faced wavelength redistribution.

The proposed setup utilizes intensity modulator for generation of OMW comprising of over 50 wavelengths. 12.5GHz frequency spacing is held amongst each channel in the OMW source. The scheme for OMWG consists of cascaded connection of PL and single Mach Zehnder modulator (MZM). MZM is driven by a sine wave having frequency of 12.5GHz. PL is designed by passing user defined bit sequence generator (UDBSG) across Optical Gaussian pulse generator (OGPG) having frequency 192.15THz (1560.2nm) and power of 5dBm. The generated comb lines have weak sidebands which are blocked with the help of rectangle optical filter (ROF) by defining its bandwidth value. This way, 37 healthy and stable comb lines, which is higher than the generated comb lines by cascaded configuration of modulators [43], with high tone-to-noise ratio (TNR) of over 40dB are passed through the ROF depending on their least amplitude differences (AD), and propelled through a 1×37 fork. Fork is an alternative to de-multiplexer (de-MUX). In order to utilize all the wavelengths, the wavelengths are required to be individually identified and separated from each other. Optical filters (OF) are used to separate wavelengths of specific frequencies, and pass it through 10Gbps differential phase shift keying (DPSK) modulator. Next to it, an ideal multiplexer (MUX) is used to syndicate all these signals and transmit it through the single feeder fiber (SFF). The SFF is a bi-directional optical fiber (BDOF) which has a temporary configuration of a standard single mode fiber (SSMF). In total, data transmission of around 740Gbps for DL and UL has been achieved with the proposed cost-effective scheme. The transmitted signal is detached using a 1×37 fork. Gaussian OFs (GOF) are used to identify these signals. All these GOFs are assigned specific frequencies to make sure only the particular wavelengths/frequencies can pass through it. The filtered signals are split in two halves with the help of 1×2 power splitter (PS). Half of the signal is received and de-modulated using 10Gbps DPSK based receiver, whereas the other half is re-modulated with the help of a single 10Gbps non-return-to-zero (NRZ) dual port (DP) DD-MZM. It is essential to mitigate RBS noise in UL transmission as it's a major factor that impairs the UL transmission. This can be alleviated by lessening the spectral overlap among the scattered wavelengths, and re-modulated wavelengths. Similarly it can also be controlled by merging the DL and UL transmission via OCs. RBS noise has been mitigated by utilizing OCs, and by deploying the NRZ-DP-DD-MZM modulation scheme for generation of SSBSC. The proposed system is analyzed in terms of power penalties (PPs), and bit error rate (BER) with their resulted eye diagrams (EDs) during the transmission. It is found that the system is deployable in long reach wavelength division multiplexed- passive optical network (WDM-PON) system for a fiber span of 25km, and 50km.

We have recently proposed an OMWG scheme based on a single MZM in WDM-PON system for 25km fiber [44]. This work addresses certain improvements by means of increase in the number of generated wavelengths, frequency spacing, and length of fiber; which is increased from 33 wavelengths to 37 wavelengths with an additional increment of 2.5GHz in the frequency spacing, and fiber length is increased from 25km to 50km. The model was based on a continuous wave laser and was designed for DL transmission. Whereas the proposed scheme is based on a PL for OMWG, and is designed for both DL and UL transmission. Colorless ONUs have been achieved for UL transmission and RBS noise is also alleviated with the help of OCs, and by deploying NRZ-DP-DD-MZM at ONU side.

We have performed four main contributions in this paper. First one is generation of OMW with a single MZM modulator; which comprises of 37 healthy spectral lines, and its deployment at the OLT side. Secondly, continuous wave laser source or conventional laser array has been replaced by PL source. The PL is based on unification of UDBSG and OGPG, and is designed to generate maximum number of wavelengths. Thirdly, a SFF based on BDOF having the specifications of a SSMF is used for the transmission which results in cost reduction as compared to a dual feeder fiber. Fourthly, colorless ONUs are achieved by replacing conventional IM-OOK [11, 15, 23, 29, 33] with NRZ-DP-DD-MZM that reduces RBS noise by means of SSBSC in UL transmission.

This paper is organized in four parts. The first one is the introduction where literature review, and an overview of the proposed scheme is presented. The second part of the paper is a detailed view of the OMWG scheme. In the third part, the implementation of the generated multi-wavelength source and detailed analysis of DL transmission is discussed. In the fourth part, UL transmission is discussed based on colorless ONUs and the proposed scheme based on NRZ-DP-DD-MZM modulation technique is demonstrated for mitigation of RBS noise. In the end, a conclusion of the proposed work is present.

II. DETAILED DISCUSSION OF OPTICAL MULTI-WAVELENGTH GENERATION SCHEME

In the proposed scheme of OMWG, an innovative method is used to generate spectrally flattened wavelengths by using only one MZM tailored by low powered RF signal. The proposed OMWG scheme is principled on a single RF source (sine wave), PL source, MZM, and ROF. The PL source is a combination of UDBSG and OGPG, designed to produce the maximum number of multiple wavelengths for the transmission. The sine wave is assigned a frequency of 12.5GHz, 12dBm power, and an amplitude of 1 a.u. The PL source is based on a UDBSG and OGPG. The UDBSG is assigned a user defined bit sequence, and OGPG is configured with a frequency of 192.15THz (1560.2nm), width of 0.1bit, and

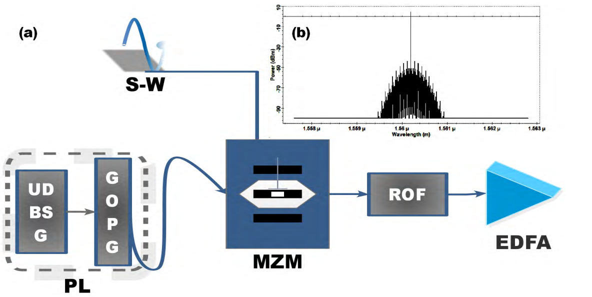

FIGURE 1. (a) Schematic representation of the suggested OMWG [UDBSG; user defined bit sequence generator, GOPG; Gaussian optical pulse generator, PL; pulsed laser, S-W; sine wave, MZM; Mach Zehnder modulator, ROF; rectangle optical filter, EDFA; erbium doped fiber amplifier] (b) output of PL.

5dBm power. The UDBSG is assigned a fixed number of bits value with a firm pattern of it prior to applying at the input port of OGPG. Sequence length of the UDBSG can be mathematically described as:

$$\mathrm{N} = \mathrm{T_w B_r} \quad (1)$$

where the global parameter of time window is denoted by T_w, and the bit rate is symbolized with B_r. Incase bit sequence is shorter than the value of N, the sequence will repeat itself until it is equal to the value of N. The OGPG takes a binary signal as an input, and generates Gaussian optical pulses as its output in accordance to the input bit sequences. The output signal form of the PL is shown in Fig. 1(b), and the output optical power for each bit can be described as:

$$p\left(t\right) = B.\left(A_p.e^{-\frac{1}{2}\left(\frac{t.k}{T_{FWHM}}\right)^{2N}} + A_{bias}\right) \quad (2)$$

where B represents the bit value (0, 1) and rely on the input bit sequence, peak to peak power is represented by A_p, biasing parameter is symbolized by A_{bias}. T_{FWHM} represents the width of the signal. The fitting coefficient is numerically determined for pulse generation based on the exact values of parameter width (T_{FWHM}), and is represented by k. The order of the Gaussian pulses (N = 1) is signified as N. The MZM has two inputs which takes electrical and optical signals as inputs, and gives the output in optical form. The RF source is connected to the electrical input arm of the MZM, and PL is connected to the optical input arm of the MZM.

The output of PL can be given as:

$$P.L_{(output)} = E_0 expo\left(j2\pi f_c t\right) \quad (3)$$

where E_0 and f_c shows the amplitude and frequency of central frequency. Similarly, the RF signal coming to MZM can be presented mathematically as:

$$f\ (t) = Acos\left(\omega t\right); w = 2\pi f \quad (4)$$

A and ω shows the amplitude and frequency of RF signal. Therefore, the output of MZM can be given as:

$$MZM_{o-p} = E_0 \exp(j2\pi f_c(t).A_1 \cos(j \cos 2\pi f(t)) \quad (5)$$

where E_0 shows the amplitude of optical signal. The above equation can be expanded with the help of Jacobi-anger expression [45], [46].

$$MZM_{o-p}(t) = \frac{E_0}{\sqrt{2}} \sum_{n=-\infty}^{\infty} \cdot \begin{bmatrix} J_n\left(-\frac{\pi A}{V_\pi}\right) . \exp\left(j\frac{\pi V_b}{V_\pi}\right) + \\ J_n\left(\frac{\pi A}{V_\pi}\right) \end{bmatrix} . \times \cos[2\pi(f_c + nf)t] \quad (6)$$

In equation (6), $J_n(.)$ shows the Bessel function, V_π represents the half wave voltage of MZM, and V_b is the biasing voltage of the MZM. Therefore, the resultant spectrum (optical) for equation (6) can be given as:

$$MZM_{o-p}(t) = \sum_{n=-\infty}^{\infty} |An(A, V_b)|^2 .\delta.[f - (f_c + nf)t] \quad (7)$$

It demonstrates that amplitude and biasing voltage of the RF source enables MZM to generate flattened comb lines by using appropriate amplitude and biasing voltage. As we have some weak sidebands as well in the generated OMW, we can eliminate them by using ROF, and mathematically can be eliminated by using the given equation obtained by least square method [39]:

$$An(A, V) = \begin{Bmatrix} n(n \neq 0) & n = -18 \; to \; 18 \\ 0 & otherwise \end{Bmatrix} \quad (8)$$

With the help of the proposed setup, over 50 wavelengths were generated successfully but there were weak sidebands at both sides. In order to suppress the weak signals and filter out the healthy and stable wavelengths; an ROF is used having the same laser frequency, a bandwidth of 462.5GHz, and noise threshold value of −100dB, whereas the value of dynamic noise is 3dB. The bandwidth for ROF is the product of frequency spacing, and the number of wavelengths desired. The generated wavelengths are amplified by a 5m erbium doped fiber amplifier (EDFA). The schematic illustration of the proposed OMWG is shown in Figure 1(a).

A clear demonstration of the suggested OMWG is projected in the schematic illustration shown in Fig. 1(a). The flow and connectivity is clear and easy to understand. Unlike some other models, we have make no use of any phase shifter or electrical/optical biasing in the OMWG scheme. The conventional laser array has been replaced by PL source. The extinction ratio of the MZM is preserved at 30dB. The output spectrum of MZM and ROF is shown in Fig. 2(a) and Fig. 2(b) respectively.

It can be observed clearly in the illustration of generated OMW spectra that output of the MZM, as shown in Fig. 2(a), consists of some weak channels at both sides having low TNR and high AD and hence suppressed with the help of the ROF: following the condition specified in equation (8). In Fig. 2(b), the OMW spectrum have least excursions in wavelengths, frequency spacing of 12.5GHz, and high TNR of over 40 dB which is highly suitable for data transmission. Amongst the right and left four lines, the AD is observed to be around

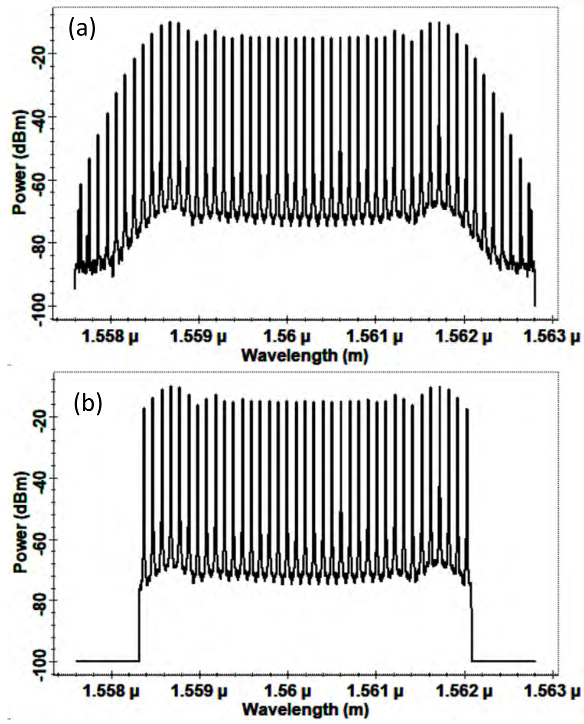

FIGURE 2. Graphical illustration of the generated OMW channels. (a) MZM, (b) ROF.

2.2 dB while in the rest of the comb lines the difference becomes ∼0.2db-0.5dB.

III. DETAILED ANALYSIS AND EXPLANATION OF DL TRANSMISSION

After generating the OMW, an EDFA is used to amplify the wavelengths. The generated wavelengths are filtered out with 37 filters to separate each wavelength/frequency. Each wavelength modulates 10Gbps data using DPSK modulation scheme. The DPSK modulator is based on a single LiNb-MZM with a data rate of 10Gbps. Then, the overall data of 370Gbps is multiplexed and transmitted across bidirectional fiber. The length of fiber used in the simulation is 25km, and 50km SFF. The SFF is a BDOF which has the arbitrary configuration of a SSMF. BDOF parameters, and its configuration values are given in Table 1.

The data is successfully carried across the BDOF with acceptable loss. Fig. 3(a, b, c) shows the channel prior to transmission, after transmission over 25km BDOF, and transmission across 50km BDOF, respectively. On the receiver side, the OMW source is detached by a 1 × 37 fork and connected to a 1 × 2 power splitter. With the help of Gaussian optical filter, all the wavelengths are identified and separated before receiving the wavelengths directly by the DPSK receiver.

It can be seen in Figure 3 that the wavelengths are almost identical and the losses are negligible. This loss is occurred because of channel attenuation which is around 5dB for 25km length, and around 10 dB for 50km length of the fiber.

TABLE 1. BDOF parameters [BDOF; bidirectional optical fiber].

BDOF parameters	Values
Length	25km/50km
Reference wavelength	192.15THz (1560.2nm)
Attenuation	0.2dB
Attenuation data type	Constant
Dispersion	16.75ps/nm/km
Dispersion slope	0.075 ps/nm^2/k
Effective area	80um^2
RB scattering	50e-006/km

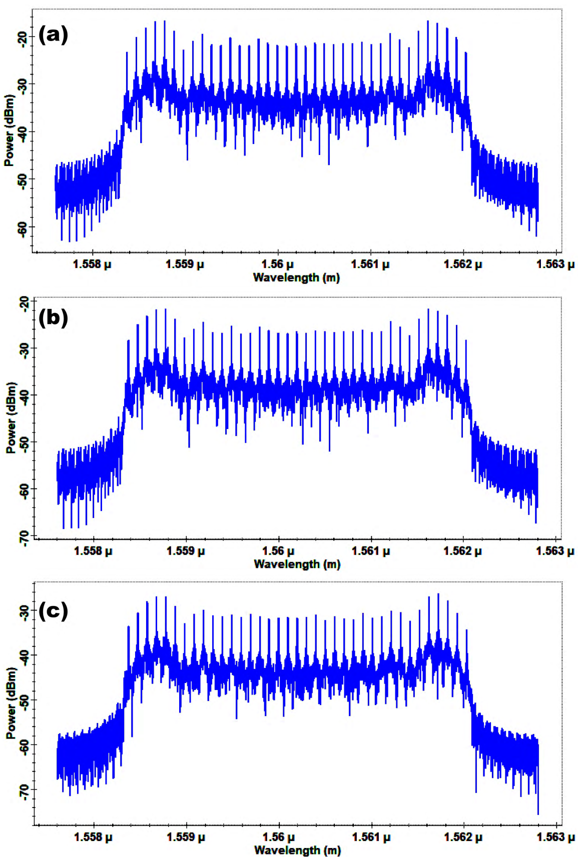

FIGURE 3. Representation of the comb signals at different intervals during the transmission: (a) 0km (before transmission), (b) after 25km, (c) after 50km.

Variable optical attenuators are used at the receiver side to adjust the BER at specific value. The first half of the received signal is acknowledged and demodulated by DPSK receiver. The detailed architecture of the proposed scheme is demonstrated in Figure 4 along with the demonstration of DPSK transmitter and receiver. DPSK receiver is based on a single Mach Zehnder interferometer (MZI), and a balanced pair of PIN photo diodes with low pass Bessel filter, as shown in (DPSK-Rx) Fig. 4. DPSK transmitter is principled on a single Lithium Niobate (LiNb) MZM, OMW carrier signal, and a combination of PRBS based NRZ pulse generator with bit rate of 10Gbps. The RF source is connected to both electrical input arms of the LiNb-MZM as shown in (DPSK Tx) Fig. 4. The results are analyzed in terms of BER, EDs, & losses in power. The other half of the wavelength is re-modulated using NRZ-DP-DD-MZM modulator for UL transmission, subsequently colorless transmission has been achieved, as shown in Fig. 4. The DL transmission is performed at 25km fiber length as well as 50km, and the achieved results expresses that the proposed scheme is deployable in long reach WDM-PON system.

The system comprises of 37 healthy OMWs amongst which 3 consecutive signals were randomly utilized for both UL, and DL transmission to check its applicability in the targeted network system. The frequencies/wavelengths of the selected three channels are as follows: 192THz (1561.4191nm), 192.0125THz (1561.3174nm) and 192.025THz (1561.2158nm).

Fig. 5 shows the comparison between the transmitted and received optical signal for the three channels across 25km, and 50km fiber for DL transmission. It is noticeable that there is a slight loss of around 5dB in the signal across 25km fiber as shown in Fig. 5(a), and 10dB for transmitting the signal across 50km fiber, as shown in Fig. 5(b). Fig. 6 shows eye diagrams of the aforementioned three channels at the receiver side after covering the transmission distance of 25km, and 50km BDOF respectively. It is evidently noticeable that the eye openings for 25km channel, as shown in Fig. 6(a, b, c), are vividly open which depicts that the proposed system is near perfect for transmission in the said setup. However, with increase in the distance, losses are also increased due to the nonlinearity and dispersion of fiber. Yet, the results show that the proposed scheme is deployable at a length of 50km BDOF as well whose parametric values are already described in Table 1. The PPs are observed at BER of 10^{-9}. These values were calculated with 25km fiber, 50km fiber, and end-to-end formation. It is also noticeable that the PPs for these three channels, over a fiber span of 25km, are found to be negligible having values 2.35dB, 2.885dB, and 2.5dB respectively. The values are nearly doubled for 50km fiber length due to nonlinearity and dispersion losses of fiber. For 50km BDOF, the PPs are found to be slightly higher than the 25km distance but still tolerable. The PPs for the particular three channels are 5.25dB, 5.385dB, and 5.511dB, respectively. Fig. 7(a, & b) demonstrates graphical illustration of the observed power losses for the said three channels over the transmission media of 25km, and 50km fiber.

IV. UPLINK TRANSMISSION WITH DETAILED ANALYSIS OF RBS MITIGATION

As previously discussed, the DL signal is divided in two halves, amongst which, first is received by the DPSK receiver, and the other is re-modulated for UL transmission with the help of 10Gbps NRZ-DP-DD-MZM modulation technique.

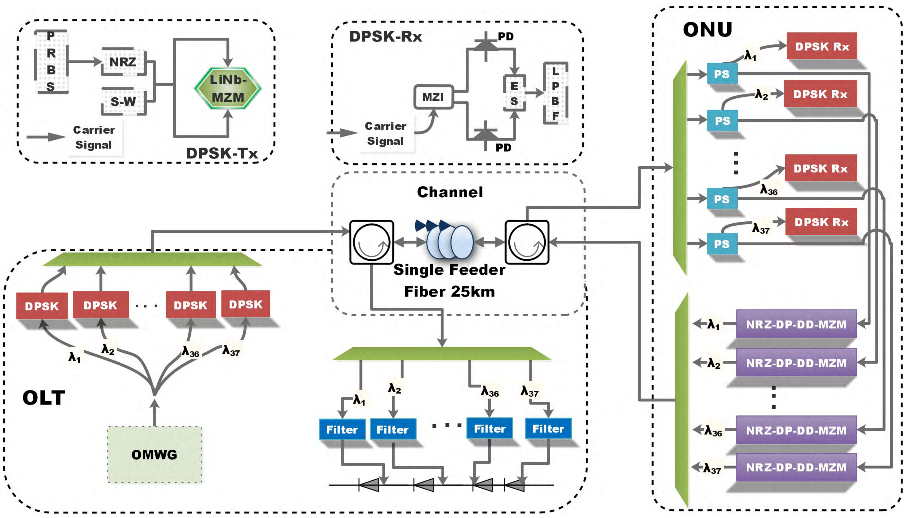

FIGURE 4. graphical illustration of the proposed OMWG based OLT, and NRZ-DP-DD-MZM based ONU [OLT; optical line terminal, ONU; optical network unit, OMWG; optical multi-wavelength generator, DPSK; differential phase shift keying, PS; power splitter, NRZ-DP-DD-MZ.

The signal experiences RBS noise in UL transmission with SFF which distorts the signal, and the UL transmission is disturbed. In the proposed system, a new NRZ-DP-DD-MZM based approach is preferred to overcome this issue. The NRZ-DP-DD-MZM reduces the noise by suppressing the signal, besides receiver sensitivity (at OLT) is also improved by decreasing ONUs cost. The RBS can be improved by lessening the spectral overlap between the disseminated wavelengths, and re-modulated wavelengths which has been mitigated by deploying NRZ-DP-DD-MZM.

Simulation results for UL transmission demonstrates that the transmission performance can be enhanced by utilizing NRZ-DP-DD-MZM at ONU side in terms of receiver sensitivity, and PPs. The results also indicates that the proposed 25km SFF can be extended to twice the length with acceptable BER. OCs are also used in assistance with the NRZ-DP-DD-MZM scheme to mitigate RBS noise.

A. RBS NOISE MITIGATION WITH SSBSC

The re-modulated splitted part of the DL signal helps achieve colorless transmission, and is used for generation of SSBSC using NRZ-DP-DD-MZM modulation scheme at the ONU side, as it was proposed that its performance is more enhanced than dual MZMs [47]. A PRBS with a bit rate of 10Gbps is used to help modulate the desired amount of data. The structure of the proposed NRZ-DP-DD-MZM modulation scheme is presented in Fig. 8.

As shown in Fig. 8, an NRZ pulse is generated from the PRBS, and combined with S-W which is further divided in two halves to produce phase shift in one of them, and connected with the DP-DD-MZM. Electric field at the upper arm of the DP-DD-MZM can be given as [33], [47]:

$$E_{Mod(Arm_1)}(t) = \frac{1}{\sqrt{2}}A_0\cos(\omega_0 t + \Delta\varphi(t)) = \frac{1}{\sqrt{2}}A_0\left\{\cos\omega_0 t\cos\Delta\varphi(t) - \sin\omega_0 t\sin\Delta\varphi(t)\right\} \quad (9)$$

In the above equation, the angular frequency is presented by ω_0, and amplitude by A_0, where $\Delta\varphi(t)$ is equal to $\Delta\varphi(t) = m\cos(\omega_{RF}t)$, the index of modulation is given by m, and ω_{RF} denotes the angular frequency of the driving signal. By substituting the value $\Delta\varphi(t)$ in the above equation, the equation can be re-written as

$$E_{Mod(Arm_1)}(t) = \frac{1}{\sqrt{2}}A_o(\cos\omega_0 t\cos\left[m\cos(\omega_{RF}t)\right] - \sin\omega_0 t\sin\left[m\cos(\omega_{RF}t)\right]) \quad (10)$$

After simplifying the upper arm of the DP-DD-MZM, equation 9 can be solved with the help of Bessel function, and can be written as:

$$E_{Mod(Arm_1)}(t) \cong \frac{1}{\sqrt{2}}A_0 \cdot \left\{\begin{array}{l} J_0(m)\cos\omega_0 t + J_1(m)\begin{bmatrix}\sin(\omega_0 t + \omega_{RF}t)+\\ \sin(\omega_0 t - \omega_{RF}t)\end{bmatrix} \\ -J_2(m)\left[\cos(\omega_0 t + 2\omega_{RF}t) + \cos(\omega_0 t - 2\omega_{RF}t)\right] \\ -J_3(m)\left[\sin(\omega_0 t + 3\omega_{RF}t) + \sin(\omega_0 t - 3\omega_{RF}t)\right]\end{array}\right\} \quad (11)$$

The higher order figures/terms are not incorporated because their coefficients are small. The driving signal at another arm of the modulator is out of phase (90°), where $-V\pi/2$ is the driving signal for the second arm. For this,

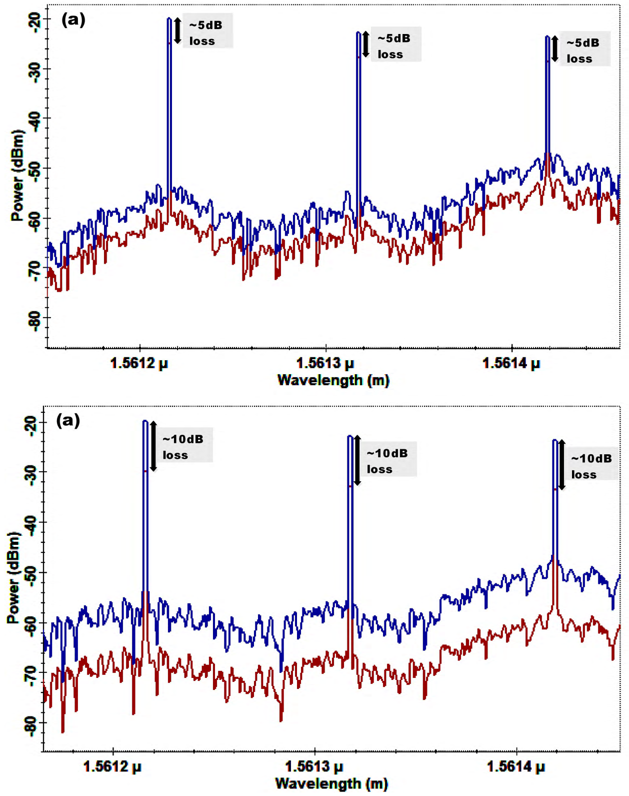

FIGURE 5. Signal representation of the DL signal after covering the respected distances in comparison with prior to transmission. (a) after covering 25km. (b) after covering 50km.

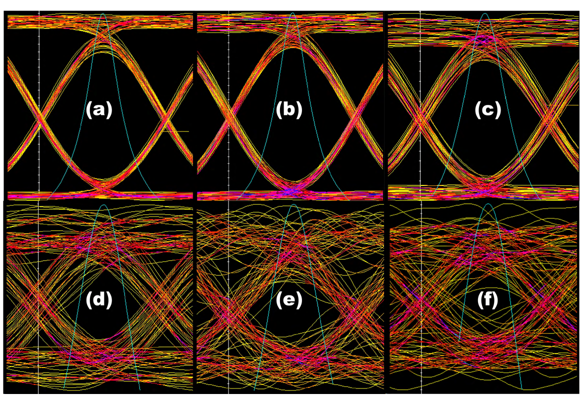

FIGURE 6. Eye diagrams of mentioned three frequencies over transmission length of (a, b, c) 25km, (d, e, f) 50km BDOF.

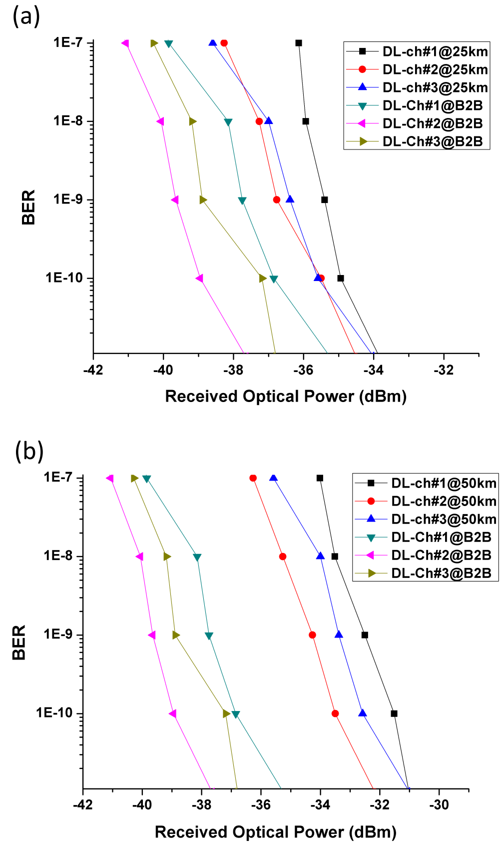

FIGURE 7. graphical illustration of the observed power penalties during (a) 25km fiber transmission, & (b) 50km fiber transmission.

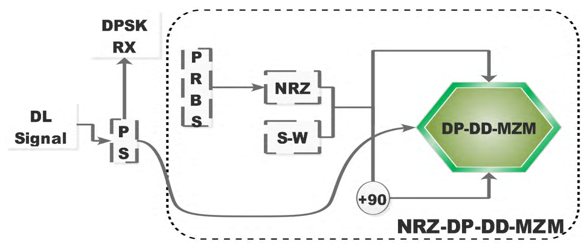

FIGURE 8. Schematic representation of NRZ-DP-DD-MZM [DL; downlink, PS; power splitter, DPSK Rx; differential phase shift keying receiver, PRBS; pseudo random bit sequence generator, NRZ; non-return-to-zero pulse generator, S-W; sine wave, DP-DD-MZM; dual port-dual drive Mach Zehnder modulator].

the $\Delta\varphi(t)$ can be defined as: $\Delta\varphi(t) = m\cos(\omega_{RF}t + \pi/2)$. Therefore, equation (9) can be explained as, which is than solved with the help of Bessel function:

$$E_{Mod(Arm_2)}(t) = \frac{1}{\sqrt{2}}A_o \left\{ \begin{matrix} \cos\omega_o t\cos\left[-m\sin(\omega_{RF}t)\right] \\ +\sin\omega_o t\sin\left[m\sin(\omega_{RF}t)\right] \end{matrix} \right\} \quad (12)$$

by ignoring the higher order terms in equation (12), the equation for the second arm of modulator can be given as:

$$E_{Mod(Arm_2)}(t)$$

$$\cong \frac{1}{\sqrt{2}}A_0 \cdot \left\{ \begin{matrix} J_0\cos\omega_0 t - J_2(m)\begin{bmatrix}\cos(\omega_0 t + 2\omega_{RF}t)+ \\ \cos(\omega_0 t - 2\omega_{RF}t)\end{bmatrix} \\ -J_1(m)\begin{bmatrix}\cos(\omega_0 t + \omega_{RF}t)- \\ \cos(\omega_0 t - \omega_{RF}t)\end{bmatrix} \\ -J_3(m)\begin{bmatrix}\cos(\omega_0 t + 3\omega_{RF}t)- \\ \cos(\omega_0 t - 3\omega_{RF}t)\end{bmatrix} \end{matrix} \right\} \quad (13)$$

Where m shows the modulation depth, and it suppressed the central electrical component, and generate the SSBCS signal [33], [47].

The same 10Gbps NRZ-DP-DD-MZM modulation technique is used for all uplink signals. All these signals are multiplexed, and sent through the SFF with the help of OCs. The length of fiber used for uplink transmission is 25km, and 50km BDOF which has a temporal configuration of SSMF. The RBS noise in upstream signals are mitigated by utilizing NRZ-DP-DD-MZM, and OCs. Cost is also improved with this proposed technique as colorless ONUs are utilized and we haven't used a dual feeder fiber for the transmission. The proposed scheme is analyzed in terms of PPs, BER, and EDs. For ease we've only examined the selected three channels having frequencies/wavelengths of 192THz (1561.4191nm), 192.0125THz (1561.3174nm) and 192.025THz (1561.2158nm).

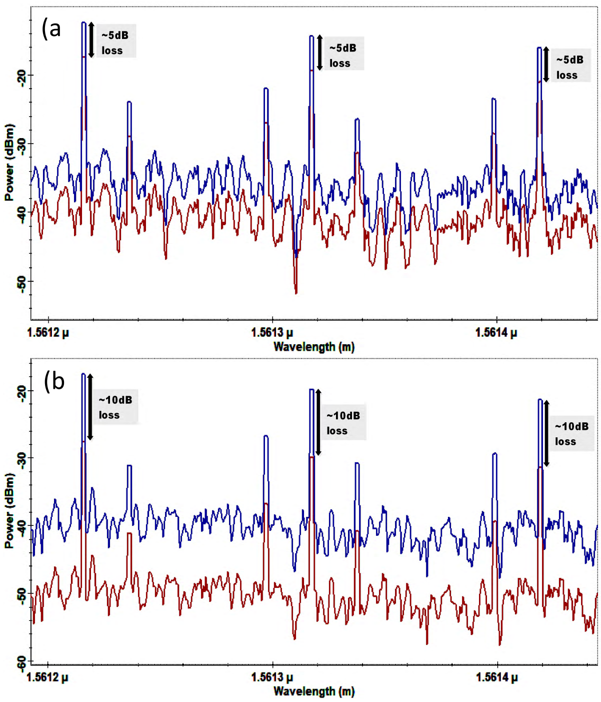

FIGURE 9. Signal representation of UL transmission prior to, and after covering the fiber span of (a) 25km, & (b) 50km.

Fig. 9 shows the comparisons between the transmitted, and received optical signal for three channels across 25km and 50km fiber for UL transmission. A slight loss of around 5dB is noticeable for transmission of over 25km fiber, as shown in Fig. 9(a), whereas the loss is around 10dB for 50km fiber, as shown in Fig. 9(b).

The EDs of these channels are shown in Fig. 10, and it can be observed from the figure that the BER, and eye openings are extremely good, making it a convenient suggestion for long reach WDM-PON system. The PPs for 25km fiber are found to be negligible having values 2.558dB, 2.974dB, and 2.044dB for the selected channels. However, for 50km BDOF, the PPs are found to be slightly higher than the 25km distance, having values 4.926dB, 5.272dB, and 5.518dB for the said three wavelengths, respectively. Fig. 11(a, & b) shows the observed PPs during the UL transmission having fiber length of 25 km as well as 50km.

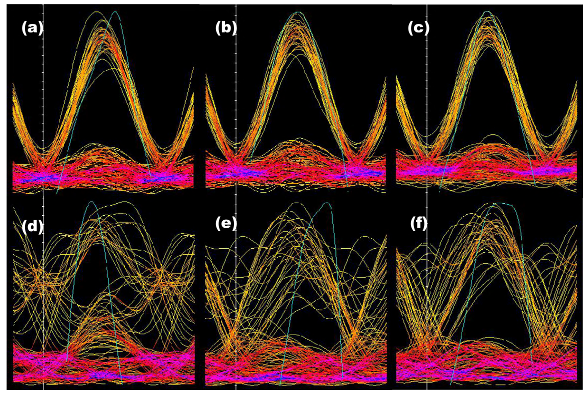

FIGURE 10. Eye diagrams of the said channels for UL transmission over different spans of fiber, (a, b, c) over 25km BDOF, (d, e, f) over 50km BDOF.

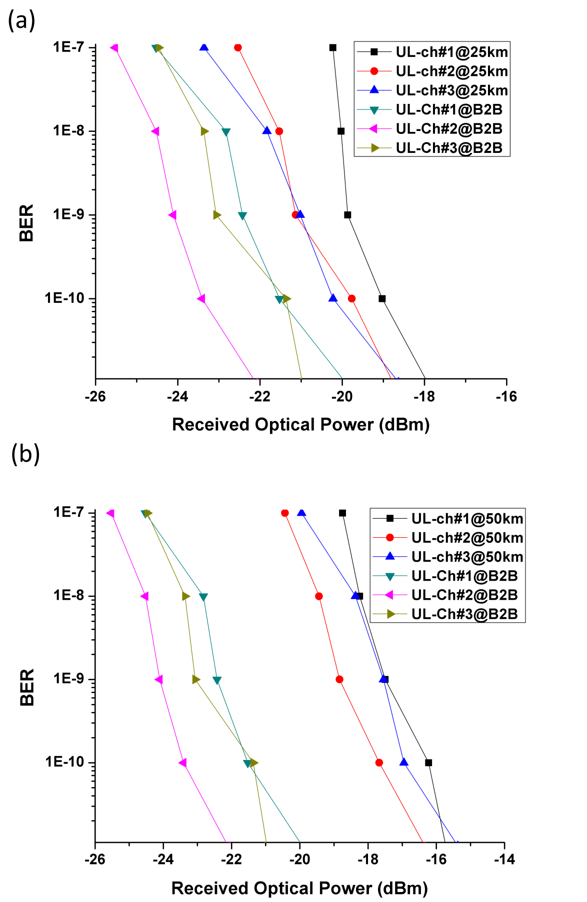

FIGURE 11. Graphical illustration of observed power penalties during UL transmission over (a) 25km fiber, & (b) 50km fiber.

In Fig. 10, it can be witnessed that the system is near perfect for 25km transmission. However, due to increase in the length of fiber and RBS noise, the transmission quality is deteriorated but still acceptable, as can be seen in the figure.

V. CONCLUSION

An innovative approach is proposed for Optical multi-wavelength generation, and its applicability in long reach single feeder WDM-PON system is demonstrated. A cost effective OLT is achieved with OMWG comprising of 37 healthy channels which is used for both downlink and uplink transmission. The frequency spacing is maintained at 12.5GHz, and an overall data transmission of 740Gbps is achieved for both UL transmission, and DL transmission via a length of 25km, and 50km BDOF. In UL transmission, colorless ONUs and SFF is used to reduce the system cost. In SFF, RBS noise is a serious matter that distorts the signal, and results in poor UL transmission of the signal. We have replaced IM-OOK at ONU side with the deployed NRZ-DP-DD-MZM modulation scheme that alleviates the RBS noise in assistance with OCs. The results are analyzed in terms of BER, EDs, and PPs. The wide openings of eye diagrams in a WDM-PON system guarantees the superior performance of the system. The PPs found in B2B, 25km fiber span, and fiber span of 50km are negligible. Thus, the proposed cost-effective OMWG based OLT, and NRZ-DP-DD-MZM based colorless ONUs are found to be highly applicable for long reach WDM-PON system.

REFERENCES

[1] J. Ye and S. T. Cundiff, Eds., *Femtosecond Optical Frequency Comb: Principle, Operation and Applications*. New York, NY, USA: Springer, 2005.
[2] A. A. Savchenkov, A. B. Matsko, V. S. Ilchenko, I. Solomatine, D. Seideland, and L. Maleki, "Tunable optical frequency comb with a crystalline whispering gallery mode resonator," *Phys. Rev. Lett.*, vol. 101, no. 9, p. 093902, 2008.
[3] S. A. Diddams, D. J. Jones, L.-S. Ma, S. T. Cundiff, and J. L. Hall, "Optical frequency measurement across a 104-THz gap with a femtosecond laser frequency comb," *Opt. Lett.*, vol. 25, no. 3, pp. 186–188, 2000.
[4] Z. Jiang, C.-B. Huang, D. E. Leaird, and A. M. Weiner, "Optical arbitrary waveform processing of more than 100 spectral comb lines," *Nature Photon.*, vol. 1, no. 8, pp. 463–467, Aug. 2007.
[5] F. Tian, X. Zhang, L. Xi, A. J. Stark, S. E. Ralph, and G.-K. Chang, "Experiment of 2.56-Tb/s, polarization division multiplexing return-to-zero 16-ary quadrature amplitude modulation, 25 GHz grid coherent optical wavelength division multiplexing, 800 km transmission based on optical comb in standard single-mode fiber," *Opt. Eng.*, vol. 52, no. 11, p. 116103, 2013.
[6] R. Ullah *et al.*, "Optical frequency comb generation for DWDM transmission over 25- to 50-km standard single-mode fiber," *Opt. Eng.*, vol. 57, no. 1, p. 010501, 2018.
[7] S. T. Cundiff and A. M. Weiner, "Optical arbitrary waveform generation," *Nature Photon.*, vol. 4, pp. 760–766, Oct. 2010.
[8] Z. Jiang *et al.*, "Spectral line-by-line pulse shaping on an optical frequency comb generator," *IEEE J. Quantum Electron.*, vol. 43, no. 12, pp. 1163–1174, Dec. 2007.
[9] S. Gee, F. Quinlan, S. Ozharar, and P. J. Delfyett, "Simultaneous optical comb frequency stabilization and super-mode noise suppression of harmonically mode-locked semiconductor ring laser using an intracavity etalon," *IEEE Photon. Technol. Lett.*, vol. 17, no. 1, pp. 199–201, Jan. 2005.
[10] F. Quinlan, S. Ozharar, S. Gee, and P. J. Delfyett, "Harmonically mode-locked semiconductor-based lasers as high repetition rate ultralow noise pulse train and optical frequency comb sources," *J. Opt. A, Pure Appl. Opt.*, vol. 11, no. 10, p. 103001, 2009.
[11] R. Ullah *et al.*, "Cost effective scheme for OLT in next generation passive optical access network based on noise free optical multi carrier," *China Commun.*, vol. 13, no. 6, pp. 76–87, Jun. 2016.
[12] J. Lancis and P. Andrés, "Lossless equalization of frequency combs," *Opt. Lett.*, vol. 33, no. 16, pp. 1822–1824, 2008.
[13] J. Yu, Z. Dong, and N. Chi, "1.96 Tb/s (21×100 Gb/s) OFDM optical signal generation and transmission over 3200-km Fiberr," *IEEE Photon. Lett.*, vol. 23, no. 15, pp. 1061–1063, Aug. 1, 2011.
[14] S. Zou, Y. Wang, Y. Shao, J. Zhang, J. Yu, and N. Chi, "Generation of coherent optical multi-carriers using concatenated, dual-drive Mach-Zehnder and phase modulators," *Chin. Opt. Lett.*, vol. 10, no. 7, p. 070605, 2012.
[15] R. Ullah *et al.*, "Optical frequency comb generation with high tone-to-noise ratio for large-capacity wavelength division multiplexed passive optical network," *Opt. Eng.*, vol. 54, no. 11, p. 116102, 2015.
[16] W. Li, W. T. Wang, W. H. Sun, L. X. Wang, J. G. Liu, and N. H. Zhu, "Generation of flat optical frequency comb using a single polarization modulator and a Brillouin-assisted power equalizer," *IEEE Photon. J.*, vol. 6, no. 2, pp. 1–8, Apr. 2014.
[17] M. Wang and J. Yao, "Tunable optical frequency comb generation based on an optoelectronic oscillator," *IEEE Photon. Technol. Lett.*, vol. 25, no. 21, pp. 2035–2038, Nov. 1, 2013.
[18] T. Kawanishi, T. Sakamoto, S. Shinada, and M. Izutsu, "Optical frequency comb generator using optical fiber loops with single-sideband modulation," *IEICE Electron. Express*, vol. 1, no. 8, pp. 217–221, 2004.
[19] J. Li, X. Zhang, F. Tian, and L. Xi, "Theoretical and experimental study on generation of stable and high-quality multi-carrier source based on re-circulating frequency shifter used for Tb/s optical transmission," *Opt. Express*, vol. 19, no. 2, pp. 848–860, 2011.
[20] H. Zhou, L. Xi, J. Li, X. Zhang, and N. Liu, "Theoretical analysis of polarization control for the stable output of multi-carrier source based on a re-circulating frequency shifter," *Chin. Opt. Lett.*, vol. 10, no. 10, p. 100602, 2012.
[21] V. R. Supradeepa and A. M. Weiner, "Bandwidth scaling and spectral flatness enhancement of optical frequency combs from phase-modulated continuous-wave lasers using cascaded four-wave mixing," *Opt. Lett.*, vol. 37, no. 15, pp. 3066–3068, 2012.
[22] M. Hirano and A. Morimoto, "Generation of flat optical frequency comb by fiber loop modulation," *Opt. Rev.*, vol. 18, no. 1, pp. 13–18, 2011.
[23] R. Ullah *et al.*, "Pulsed laser-based optical frequency comb generator for high capacity wavelength division multiplexed passive optical network supporting 1.2 Tbps," *Opt. Eng.*, vol. 55, no. 9, p. 096106, 2016.
[24] Z. Jia, J. Yu, G. Ellinas, and G.-K. Chang, "Key enabling technologies for optical–wireless networks: Optical millimeter-wave generation, wavelength reuse, and architecture," *J. Lightw. Technol.*, vol. 25, no. 11, pp. 3452–3471, Nov. 2007.
[25] P. J. Urban, A. M. J. Koonen, G. D. Khoe, and H. de Waardt, "Interferometric crosstalk reduction in an RSOA-based WDM passive optical network," *J. Lightw. Technol.*, vol. 27, no. 22, pp. 4943–4953, Nov. 15, 2009.
[26] X. Zhu and S. Kumar, "Effects of Rayleigh backscattering in single-source bidirectional fiber-optic systems using different modulation formats for downstream and upstream transmission," *Opt. Fiber Technol.*, vol. 14, no. 3, pp. 185–195.
[27] A. Chowdhury, H.-C. Chien, M.-F. Huang, J. Yu, and G.-K. Chang, "Rayleigh backscattering noise-eliminated 115-km long-reach bidirectional centralized WDM-PON with 10-Gb/s DPSK downstream and remodulated 2.5-Gb/s OCS-SCM upstream signal," *IEEE Photon. Technol. Lett.*, vol. 20, no. 24, pp. 2081–2083, Dec. 15, 2008.
[28] J. Xu, L.-K. Chen, and C.-K. Chan, "High extinction ratio phase re-modulation for 10-Gb/s WDM-PON with enhanced tolerance to Rayleigh noise," in *9th Int. Conf. Opt. Internet Dig.*, Jul. 2010, pp. 1–3, doi: 10.1109/COIN.2010.5546521.
[29] Y. Khan, X. Xin, I. Afridi, A. Husain, and A. Latif, "Single-feeder fiber colorless wavelength-division-multiplexing passive optical network using differential quadrature phase-shift keying downstream and intensity remodulated upstream signals," *Opt. Eng.*, vol. 52, no. 1, p. 015001, Jan. 2013.
[30] L. Banchi, R. Corsini, M. Presi, F. Cavaliere, and E. Ciaramella, "Enhanced reflection tolerance in WDM-PON by chirped RZ modulation," *Electron. Lett.*, vol. 46, no. 14, pp. 1009–1011, 2010.
[31] G. Berrettini *et al.*, "Colorless WDM-PON architecture for Rayleigh backscattering and path-loss degradation mitigation," *IEEE Photon. Technol. Lett.*, vol. 21, no. 7, pp. 453–455, Apr. 1, 2009.
[32] S.-C. Lin, S.-L. Lee, H.-H. Lin, G. Keiser, and R. J. Ram, "Cross-seeding schemes for WDM-based next-generation optical access networks," *J. Lightw. Technol.*, vol. 29, no. 24, pp. 3727–3736, Dec. 15, 2011.
[33] R. Ullah *et al.*, "Colorless WDM-PON using single side band carrier suppressed signals mitigating carrier Rayleigh backscattering," *China Commun.*, vol. 13, no. 12, pp. 150–161, Dec. 2016.

[34] C. W. Chow, G. Talli, and P. D. Townsend, "Rayleigh noise reduction in 10-Gb/s DWDM-PONs by wavelength detuning and phase-modulation-induced spectral broadening," *IEEE Photon. Technol. Lett.*, vol. 19, no. 6, pp. 423–425, Mar. 15, 2007.
[35] Q. Guo and A. V. Tran, "Reduction of backscattering noise in 2.5 and 10 Gbit/s RSOA-based WDM-PON," *Electron. Lett.*, vol. 47, no. 24, pp. 1333–1335, Nov. 2011.
[36] A. Chiuchiarelli *et al.*, "Enhancing resilience to Rayleigh crosstalk by means of line coding and electrical filtering," *IEEE Photon. Technol. Lett.*, vol. 22, no. 2, pp. 85–87, Jan. 2010.
[37] C. H. Yeh and C. W. Chow, "Signal remodulation ring WDM passive optical network with Rayleigh backscattering interferometric noise mitigation," *IEEE Commun. Lett.*, vol. 15, no. 10, pp. 1114–1116, Oct. 2011.
[38] C. W. Chow and C. H. Yeh, "Using downstream DPSK and upstream wavelength-shifted ASK for Rayleigh backscattering mitigation in TDM-PON to WDM-PON migration scheme," *IEEE Photon. J.*, vol. 5, no. 2, Apr. 2013, Art. no. 7900407.
[39] H. Feng, J. Ge, S. Xiao, and M. P. Fok, "Suppression of Rayleigh backscattering noise using cascaded-SOA and microwave photonic filter for 10 Gb/s loop-back WDM-PON," *Opt. Express*, vol. 22, no. 10, pp. 11770—11777, May 2014.
[40] Z. Zhang, J. Wang, X. Jiang, X. Chen, and L. Wang, "Channel-reuse bidirectional transmission at 10 Gb/s/λ in long-reach DWDM-PON employing self wavelength managed tunable laser," *Opt. Commun.*, vol. 343, pp. 107–114, May 2015.
[41] J. Prat, M. Omella, and V. Polo, "Wavelength shifting for colorless ONUs in single-fiber WDM-PONs," in *Proc. Opt. Fiber Commun. Conf. Expo.*, Oct. 2007, pp. 1–3.
[42] C. H. Wang, C. W. Chow, C. H. Yeh, C. L. Wu, S. Chi, and C. Lin, "Rayleigh noise mitigation using single-sideband modulation generated by a dual-parallel MZM for carrier distributed PON," *IEEE Photon. Technol. Lett.*, vol. 22, no. 11, pp. 820–822, Jun. 1, 2010.
[43] J. Li, J. Lin, X. Zhang, L. Xi, X. Tang, and Y. Qiao, "Scheme for generation of flat top and high signal-to-noise ratio optical frequency comb," *Chin. Opt. Lett.*, vol. 13, no. 1, p. 010605, 2015.
[44] S. Ullah *et al.*, "Generation of flattened multicarrier signals from a single laser source for 330 Gbps WDM-PON transmission over 25 km SSMF," *J. Opt. Commun.*, vol. 39, no. 1, pp. 129–135, 2017.
[45] X. Zhou, X. Zheng, H. Wen, H. Zhang, Y. Guo, and B. Zhou, "All optical arbitrary waveform generation by optical frequency comb based on cascading intensity modulation," *Opt. Commun.*, vol. 284, no. 15, pp. 3706–3710, 2011.
[46] A. A. M. Cuyt, V. Petersen, B. Verdonk, H. Waadeland, and W. B. Jones, *Handbook of Continued Fractions for Special Functions*. Dordrecht, The Netherlands: Springer, 2008.
[47] C. W. Chow, C. H. Wang, C. H. Yeh, and S. Chi, "Analysis of the carrier-suppressed single-sideband modulators used to mitigate Rayleigh backscattering in carrier-distributed PON," *Opt. Express*, vol. 19, no. 11, pp. 10973–10978, 2011.

SIBGHAT ULLAH received the B.S. (CS) degree from the University of Peshawar and the master's degree in electronics and communication engineering from the Beijing University of Posts and Telecommunications, Beijing, China, where he is currently pursuing the Ph.D. degree with the State key Laboratory of Information Photonics and Optical Communications. His research interests include coherent optical communications, multicarrier generation, wavelength-division multiplexed passive optical networks, and long reach PON.

RAHAT ULLAH received the M.Sc. degree in electronics from the University of Peshawar, Pakistan, in 2008, the M.S. (CS) degree in telecommunication and networking from Gandhara University, Peshawar, Pakistan, in 2012, and the Ph.D. degree in optical engineering from the Beijing University of Posts and Telecommunications and honored with the Outstanding Ph.D. Student Award of 2017. He was a Lecturer/Assistant Professor with Sarhad University, Peshawar, for six years. He is currently an Asscoaite Professor with the Institute of Optoelectronics, Nanjing University of Information Science and Technology, China. His research interests include optical communications, passive optical networks, optical multicarriers generation, and radio over fiber.

ADIL KHAN received the B.S. degree in telecommunications from Iqra National University, Peshawar, and the master's degree in electronics and communication engineering from the Beijing University of Posts and Telecommunications, Beijing, China, where he is currently pursuing the Ph.D. degree. His research interests include wireless communication, full duplex communication in 5G, and antenna design.

HAFIZ AHMAD KHALID received the B.S. degree in electronics engineering from the COMSATS Institute of Information Technology, Abbottabad, Pakistan, in 2010, and the M.S. degree in electrical engineering from the University of Engineering and Technology, Taxila, Pakistan, in 2015. He is currently pursuing the Ph.D. degree in electronics science and technology with the Beijing University of Posts and Telecommunications, Beijing, China. From 2013 to 2016, he was a Lecturer with the Wah Engineering College, University of Wah, Wah Cantt, Pakistan. His research interests include the wireless and optical MIMO communication.

QI ZHANG received the Ph.D. degree from the Beijing University of Posts and Telecommunications (BUPT), Beijing, China, in 2005. She is currently an Associate Professor with the School of Electric Engineering and a member of the State Key Laboratory of Information Photonics and Optical Communications, BUPT. Her main research interests focus on optical communication and satellite communication.

QINGHUA TIAN received the master's degree from the Beijing Institute of Technology in 2003 and the Ph.D. degree from the Beijing University of Posts and Telecommunications (BUPT) in 2013. She is currently with the School of Electronic Engineering, BUPT. Her main research interests focus on deep learning and optical communication.

FAHEEM KHAN received the Ph.D. degree in computer network and security from the University of Malakand, Pakistan. His areas of interest are computer networks, computer security sensor networks, and vehicular networks. He is currently an Assistant Professor at the Department of Computer Science, Bacha Khan University, Charsadda, Pakistan.

XIANGJUN XIN was born in Hebei, China, in 1969. He received the Ph.D. degree from the School of Electrical Engineering, Beijing University of Posts and Telecommunications (BUPT), Beijing, China, in 2004. He is currently a Professor with the School of Electric Engineering and a member of the State Key Laboratory of Information Photonics and Optical Communications, BUPT. His main research interests focus on broadband optical transmission technologies, optical sensor, and all-optical networks. Within this area, he has published over 60 SCI papers.