IEEE Access
Multidisciplinary : Rapid Review : Open Access Journal

Received November 29, 2017, accepted December 30, 2017, date of publication January 12, 2018, date of current version March 9, 2018.

Digital Object Identifier 10.1109/ACCESS.2018.2789863

Flattened Optical Multicarrier Generation Technique for Optical Line Terminal Side in Next Generation WDM-PON Supporting High Data Rate Transmission

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This work was supported in part by the National NSFC of China under Grant 61705107, Grant 61727817, Grant 61775098, Grant 61425022, Grant 61522501, Grant 61675004, Grant 61307086, Grant 61475024, Grant 61672290, Grant 61475094, and Grant 61605013, in part by the National High Technology 863 Program of China under Grant 2015AA015501, Grant 2015AA015502, Grant 2015AA015504, Grant 2015AA016904, and Grant 2015AA016901, in part by the Beijing Nova Program under Grant Z141101001814048, in part by the Fund of State Key Laboratory of IPOC, BUPT, and in part by NUIST under Grant 2107r27, Grant 2107r12, Grant 2107r028, and Grant 2107r29.

ABSTRACT A novel and cost effective optical multicarrier (OMC) generator is introduced in this article. OMC is generated by connecting three modulators in cascade with laser source, where laser is connected with one amplitude modulator and two Mach-Zehnder modulators (MZMs) in cascade. The amplitude modulator is used for the first time in cascade configurations for the generation of OMC signal. All the modulators are driven by RF signal of 30 GHz where specially tailored or fiber-Bragg gratings are not required. The generated OMC is very flat due to the proper DC biasing of MZMs and being related to the optimum ratio of DC bias and half wave voltage of MZMs. OMC offers 61 comb lines with minimum excursions in its comb lines, having tone-to-noise ratio greater than 40 dB, frequency spacing equal to 30 GHz, and high side mode suppression ratio over 35 dB. In this configuration, no optical phase shifter, amplifier, or attenuator is used. Second, optical line terminal (OLT) costs of conventional wavelength division multiplexed passive optical network (WDM-PON) system are reduced by introducing the proposed OMC source at OLT side of WDM-PON system for large capacity WDM-PON that supports numerous users. At OLT side, each out of 61 carriers is capable of supporting 10 Gb/s differential phase shift keying based data in downlink transmission. In the uplink transmission, half power splitters are deployed at optical network unit (ONU) side, where half power of the downlink signal is utilized for uplink transmission based on intensity-modulated on-offkeying resulting in colorless ONUs. The detailed power budget is discussed for the validity of results. Bit error rate (BER), eye patterns, and power penalties lie in the metrics encountered for the analysis in full duplex PON's transmission. Minimum power penalties at specific BERs of different channels show the applicability of the proposed model.

INDEX TERMS DPSK, high capacity WDM-PON, IM-OOK, optical multicarrier generator.

I. RELATED WORK AND CONTRIBUTIONS

In the recent years, due to the ever increasing demand for high data rate transmissions in optical communications, the generation of optical multi-carriers (OMC) remained the endeavor area of research throughout the industry. Due to the supportive property in high data rate transmissions, the OMC is deployed in different super channel systems by using various modulation techniques. The most well-known techniques are coherent optical dense wavelength division multiplexing (Co-DWDM) [1]–[3] and orthogonal frequency division multiplexing (Co-OFDM) [4]–[6]. OMC is a strong candidate for carrying high data rates in optical long distance communication system [7].

In OMC generators, mainly two configurations are used, 1) cascading of various modulators [3]–[10], [23]–[25], and 2) the re-circulating frequency shifting loop (RFS) using different modulators and filters [11]–[22], [28]–[31]. In these techniques, all the modulators are driven by high powered microwave signals incorporating amplifiers. Optical filters, phase shifter and some other circuitry have been also utilized in most of the above referenced techniques. OMC with high TNR is produced by deploying RFS loop using single-sideband (SSB) or multi-sideband (MSB) modulations in the loops that required high power electrical amplifier (EA). SSB modulators are more favorable as compared to MSB modulators due to the generation of additional multi-carriers with enhanced TNR [11], [12]. In SSB, the number of carriers is affected by amplitude spontaneous emission (ASE) noise [1], [14], which was suppressed by optical FIR filters in RFS loop [15] with costly setup. Similarly, cascaded modulators are used for OMC having different setups and configurations. Cascaded phase modulator with MZM, dual-drive MZM and with only phase modulator have already presented OMC signal generation. Dual parallel MZM is used with hybrid interferometer modulator for generating OMC. However, these techniques had the major issues of expensive components, high RF power amplifier, greater spectral power difference between comb lines and less number of comb lines. Whereas, the number of comb lines generated by phase modulator were limited due to its weak capabilities of power handling [3]–[12], [23]–[28]. Meanwhile, due to high bandwidth hungry applications, next generation optical access systems were highly desired [25], hence prodigious bandwidth could be provided by WDM-PON. Moreover, a tunable light source was required in WDM-PON system that could provide multi wavelengths, and tunable laser was therefore presented in [26] for next generation optical access network, but was limited to overall 40 Gbps and expensive. Recently, two models for the generation of OMC from a single laser source were proposed [24], [25], but their capacity was not sufficiently high due to limited number of comb lines. The hardware was also not as cost effective as in the proposed model in this paper. OMC can provide numerous carriers from a single directly modulated laser with a cheaper setup. So deploying cost effective high Gbps supportive OFCG in next generation WDM-PON system is believed to be an attractive solution. The striking advantage of such setup is cost effectiveness and reduced size of network unit with least power management in WDM-PON system.

In this paper, a new technique is proposed for closely spaced OMC that is utilized at optical lime terminal (OLT) of WDM-PON system. The proposed cost effective OMC comprises of two MZMs in cascade with one amplitude modulator, the modulators (AM, $MZM_{1,2}$) being driven by only one microwave source of 30 GHz. In the proposed model, a conventional RF source is used instead of fiber-bragg grating or other specially tailored sources, because in this model the flatness of the OMC depends on the optimum DC biasing of MZMs. Contrary to the work referred [3]–[25], [28]–[31], no phase shifter and electrical amplifier have been used in the current setup. Furthermore, it offers a large number of multi-carriers in cascade mode and generates maximum number of carriers in cascaded mode (∼61) with a least amplitude difference. Furthermore, an amplitude modulator has been used for the first time in cascade configuration producing maximum number of comb lines than in the referred work [3]–[10], [23]–[25]. The generated optical frequency comb (OFC) is tightly spaced for WDM-PON system i.e. ∼30 GHz. Number of comb lines in the generated comb is 60 with TNR >40 dB. The spectral power deviations of the generated OFC is up to 1 dB. The proposed OFC is deployed in WDM-PON system for downlink and uplink transmissions, which show decent outputs. This way, a high capacity next generation PON system is designed with cost effective arrangements at optical line terminal (OLT). At OLT side, each carrier is separated by an optical filter modulated with 10 Gbps data using differential phase shift keying (DPSK); here DPSK is a modulation technique which we have used for modulating 10Gbps data rate across each frequency tone. All the carriers were multiplexed and transmitted through SSMF span of 25 km. On receiving side at the optical network unit (ONU), filters are used to detect each carrier's frequency, followed by half power splitter that is used for splitting the signal into two. Among the both, the first half is de-modulated at ONU, while the second half signal is used for re-modulating the signal in the uplink transmission based intensity modulated on-off-keying (IM-OOK). Colorless transmission is achieved at ONU side by utilizing the downlink signal power. The system performance is analyzed in terms of power losses, bit error rates (both at downlink and uplink transmission) and eye diagrams of the transmission. In due course, the detailed power budgeting is calculated, which validates the achieved results. The main contributions are summarized as follows:

- The novel cascaded cost effective OMC generator is discussed in section II with results which validates the novelty of the technique.
- The source arrangement at OLT side of conventional WDM-PON is replaced with OMC generator.
- High number of users are entertained in next generation optical access network.
- Downlink and uplink transmissions are discussed in details with the help of power penalties across different channels. The obtained eye diagrams show quality of the results.
- Finally, the detailed power budgeting is discussed, which is important parameter for any access network. It shows the continuous functionality of the optical access system.

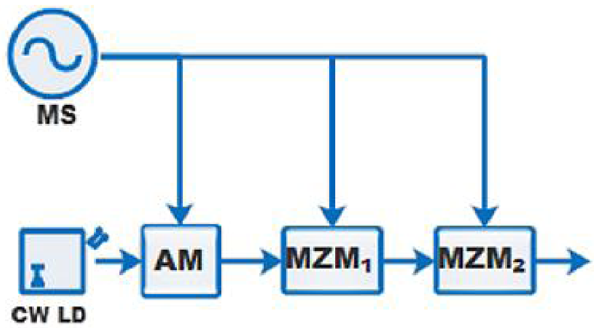

FIGURE 1. Schematic presentation of OMC generator.

II. THEORETICAL INVESTIGATION OF THE PROPOSED OPTICAL MULTICARRIER GENERATOR

Deploying OMC in optical access system benefits in reduction of number of laser sources at OLT side by providing high bandwidth for data transmission and entertaining large number of users. Laser is in cascade mood connected with one amplitude (AM) and two MZMs for the generating OMC signal, while the modulators are driven by RF signal where no amplifier or phase shifter is used, therefore, making it very cost effective (Fig 1). A continuous wave laser diode (CW-LD) is used having frequency ~192.15 THz, line width 10 MHz and an output power of 15 dBm. In the proposed technique, a broader spectrum containing 61 frequency tones is achieved, having frequency spacing ~30 GHz and high TNR ~40 dB. The generated comb is designed to have least variations in its OMC tones. Detailed explanation of OMC generation along with results is given below. OMC is also called optical frequency comb (OFC), throughout the manuscript both the terminologies are used.

The frequency of laser is f_0, while its amplitude and phase is A_0 and φ_{in} respectively. The phase noise of the laser is modeled using probability density function, which is given as:

$$f(\Delta\varphi) = \frac{1}{2\pi\sqrt{\Delta f dt}} . e^{-\Delta\varphi^2/4\pi\Delta f dt} \tag{1}$$

The phase difference among two consecutive time instants is given by $\Delta\varphi$, where dt is the time discretization. For the phase difference $\Delta\varphi$, zero mean and variance $\sim 2\pi\Delta f$ are assumed for the Gaussian random variable between two successive time instants, where Δf is linewidth of laser.

The output of amplitude modulator is a sequence of harmonic tones with components $f_0 + nf$, where f represents the RF frequency. The number of harmonic is given by n, while $n = [0, 1, 2, 3, \ldots]$. The field at the output of amplitude modulator can be given as:

$$E_k = |E_0| \sum_{n=-\infty}^{+\infty} E_{n,k} Cos[2\pi(f_0 + nf)t + \theta_{n,k}] \tag{2}$$

In (2), $E_{n,k}$ and $\theta_{n,k}$ show the amplitudes and phases of the components, which can be given as:

$$E_{n,k} = \frac{1}{2}[\cos(b_k + n)\frac{\pi}{2}]J_n(\frac{c_k\pi}{4}) \tag{3}$$

$$\theta_{n,k} = [1 + n + (-1)^n]\frac{\pi}{2} + n\phi_1 + \phi_k \tag{4}$$

In (3) and (4) b_k represents the DC offset, c_k represents the amplitude from peak-to-peak (PP) and ϕ_k denotes k^{th} modulator representing the phase of the drive signal.

The amplitude modulator is connected with two MZMs in cascade, where V_{bias1} and V_{bias2} are the biasing voltages of the two MZMs. The input RF signals to MZM_1 and MZM_2 can be given as $E_1\cos(2\pi f_s t)$ and $E_2(2\pi f_s t + \Delta\varphi)$ respectively, where $\Delta\varphi$, the phase shift, should be zero for the reason that no phase shifter is used in the proposed OMC generator, and E_1 and E_2 are the amplitudes of RF signal. After applying (2) to the input of MZM_1, the output of MZM_1 can be given as [23]:

$$E_{MZM_1}(t) = \frac{\sqrt{2}}{2}|E_0| \sum_{n=-\infty}^{+\infty} E_{n,k} . \begin{bmatrix} J_n\left(-\frac{\pi E_1}{V_{\pi 1}}\right) . \exp\left(j\frac{\pi V_{bias1}}{V_{\pi 1}}\right) \\ +J_n\left(\frac{\pi E_1}{V_{\pi 1}}\right) \end{bmatrix} . Cos[2\pi(f_0 + nf)t + \theta_{n,k}] \tag{5}$$

At the second MZM, the output spectrum in OMC form can be expressed as:

$$E_{MZM2}(t) = \sum_{n=-\infty}^{+\infty} E_{n,k}(E_1, E_2, V_{bias1}, V_{bias2}, \Delta\varphi) . Cos[2\pi(f_0 + nf)t + \theta_{n,k}] \tag{6}$$

The above equation can be used to find the final OMC spectrum as given:

$$P_{MZM_2}(t) = \sum_{n=-\infty}^{\infty} \left|E_{n,k}\left(E_1, E_2, V_{bias1}, V_{bias2}, \Delta\varphi\right)\right|^2 . \delta.[f - (f_0 + nf_s)t + \theta_{n,k}] \tag{7}$$

In the above equations, E is used for amplitude of the carrier, $V_{bias1}, V_{bias2}, V_\pi$ represent the biasing and half-wave voltages of Mach-zehnder modulators, J_n presents the Bessel function (nth-order). Conferring (7), the RF signal's power and the basing voltage applied to the modulators are the points to create the flattened OMC signal. As only the flattened carriers are required, the rest of weak sidebands can be suppressed by the given condition:

$$An\left(A_1, A_2, V_{b-1}, V_{b-2}\right) = \begin{Bmatrix} k(k \neq 0) & n = -30, 30 \\ 0 & otherwise \end{Bmatrix} \tag{8}$$

Equation (8) can be obtained by least square method, and the flattened OFC can be generated by using appropriate values of biasing voltage values of MZMs and proper amplitudes of RF signal conferring (8).

A. SIMULATION RESULTS

The design of optical multi-carriers is achieved by keeping the line width of laser less than 10 MHz. The output power of laser is kept at 15 dBm with dynamic noise and 3 dB and −100 dB with threshold noise. The sample rate and iteration of both the RF source and laser source is 6.4e+11Hz and 1, correspondingly. The half wave voltage, extinction ratio, symmetry factor and bias voltage of the modulators have been cautiously selected. The half wave voltage of both MZMs is 4.5V, biasing voltage is 7V, extinction ratio is 35-40dB and symmetry factor is 0.955.

The output of laser (Fig 2(A)) is obtained by generating the single carrier frequency with many weak sidebands. As the RF drive signal of 12dB (power) with 2a.u amplitude and 30GHz frequency is passed through the AM, many sidebands are energized attaining specific values, but still there prevails only a limited number of carriers capable of carrying data signals, as shown in Fig 2(B). Same RF signal is passed through the MZM-1 and MZM-2. The output of AM is passed through MZM_1 by generating a comb of stable carriers, yet the amplitude difference remains high and still there exist some weak sidebands, which are needed to be energized, as shown in Fig 2(C). The number of carriers are also limited throughout this process. By cascading it with another MZM, the output reaches to a maximum number of carriers with least amplitude difference, as shown in Fig 2(D). In this case, the number of carriers generated is 61 with >40 TNR and very less amplitude excursions. The amplitude excursions noted are less than 1 dB at sides, while less than 0.5 dB for 55-57 carriers (average ~1 dB), as shown in Fig 2(D). The TNR of the selected optical carriers is greater than 40 dB, which is very flat with minute fluctuations in its comb lines. Furthermore, high side mode suppression ratio (SMSR) over 35 dB is observed during the simulations/results. All these results are achieved using a modern simulation tool called OptiSystem [33].

The proposed OFCG is compared with all the referenced techniques and is demonstrated in table 1 with full details. It is claimed that the generated number of carriers in our model is greater in all the cascaded configurations. It is even comparable to most of the techniques using RFS loops in terms of number of carriers, with good TNR, and least amplitude difference.

We have graphically compared the proposed technique of OFCG with cascaded configurations and with RFS loop configuration. Figure 3 (a) shows the comparison of proposed technique with the cascaded configuration; similarly, 3(b) shows the comparison of the proposed technique with those techniques which have used the OFCG using RFS loop.

Any OFC is dependent on the number of carriers, high TNR and least amplitude difference between the comb lines. Under this definition, we found our technique stronger than the referenced work.

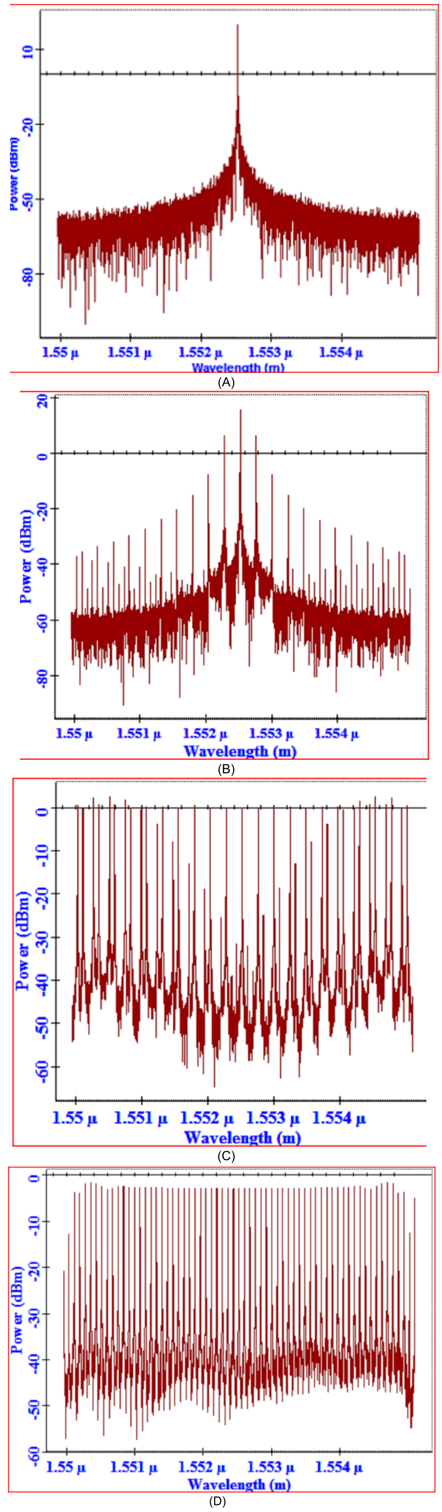

FIGURE 2. Generation of optical frequency comb. (A): laser's output; (B): Output of amplitude modulator; (C)&(D) shows the output of MZM_1 and MZM_2.

III. OPERATIONAL ANALYSIS OF OMC GENERATOR IN HIGH CAPACITY WDM-PON

New arrangements for OLT in WDM-PON system is hereby introduced by providing high bandwidth for triple play services to many users supporting overall 610 Gbps. There are numerous advantages of using OFCG in such a system, including reduced system size, cost effectiveness of laser sources or tunable lasers by providing high bandwidth for data transmissions in PON system and entertaining large number of users. Conventionally, multiple laser sources or single powerful tunable laser source was required

TABLE 1. Demonstrating the comparison between difference methods for OFCG.

Ref.	Frequency tones/lines	TNR (dB)	A.D (dB)	Configuration	
				Cascaded	Using loop
[2]	21	30	2.5		✓
[3]	16	20	3	✓	
[4]	7, and 9	10	0.3-0.5	✓	
[5]	11	18	1.1	✓	
	19	20	4.3		
[6]	15	25	1	✓	
[7]	53	30	10	✓	
[8]	25	20	5	✓	
[9]	11	15	1.9	✓	
	9	7-8	0.8		
[10]	38	38	6	✓	
[11]	100	25	5		✓
[12]	60	36	1-4		✓
[13]	50	17	1		✓
[14]	50	38	2		✓
[15]	50	22.5	1		✓
[16]	50	25	2.5		✓
[17]	80	11-16	6-11		✓
[19]	8-26	10-35	2		✓
[20]	20	25	5		✓
[21]	24	18	1.5		✓
[22]	23	38.3	0.5		✓
[23]	9	23	1	✓	
[24]	4	20 dB	1.5	✓	
[25]	40	40 dB	1	✓	
[28]	15	40	3	✓	
[29]	11	25	2		✓
[30]	113	26	5		✓
[31]	9,11,13	22	1-2.1		✓
[32]	12	17	1	✓	
Current	**61**	**40**	**1**	✓	

to provide such arrangements in WDM-PON system, which used to cost heavily. The proposed OFCG can provide triple play services to 61 users, where each user have data

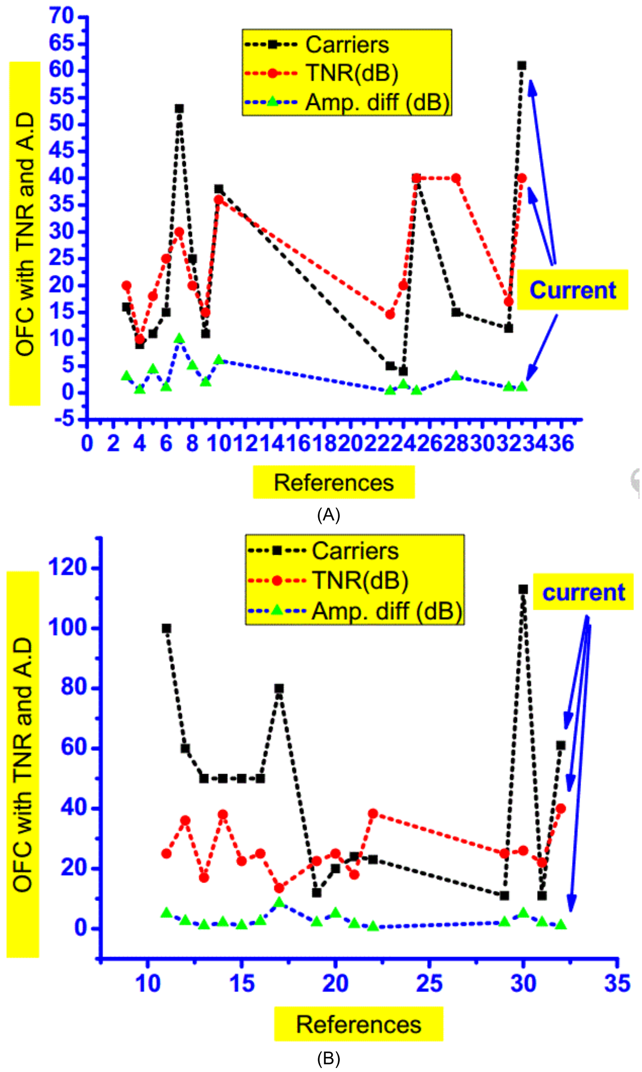

FIGURE 3. Comparison of the proposed technique with the referenced OFCGs based on cascaded and RFS loop configurations. (A) Comparison of proposed technique with OFCGs in cascaded mode. (B) Comparison proposed technique with OFCGs using RFS loops.

∼10 Gbps both in downlink and uplink transmissions using DPSK based modulation in the downlink and IM-OOK based data signals in the uplink data transmission. Depending on the parameters of OFC lines, 57 carriers were utilized in the transmission. Fig. 4 shows the overview of proposed OFC-based high capacity WDM-PON system entertaining 57 users in full duplex transmission. The simulations show good results, suggesting that the offered OMC generator is deployable in WDM-PON system. As shown in the Fig. 3, erbium doped fiber amplifier has been used after amplifying the OFC at OLT side. Optical filter of certain frequency was used at transmitter side to ride over user data at specific frequency. DPSK based data ∼10 Gbps was modulated with respective carrier frequency and the data of 570 Gbps was multiplexed before injecting into the fiber.

As the frequency spacing between the OMC comb lines is 30GHz, it can also support data rate higher than 10Gbps. Similarly, even higher data rate transmission is also

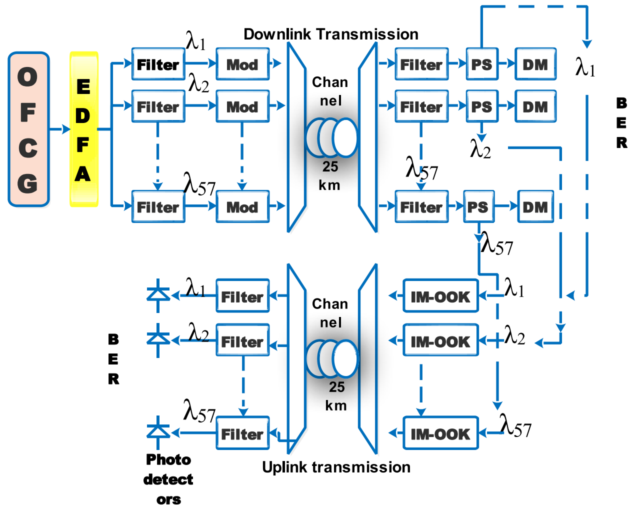

FIGURE 4. Full simulation model of high capacity WDM-PON based on OMC generator. Mod: DPSK based transmitters, PS: Power splitter, DM: demodulation, BER: Bit error rate.

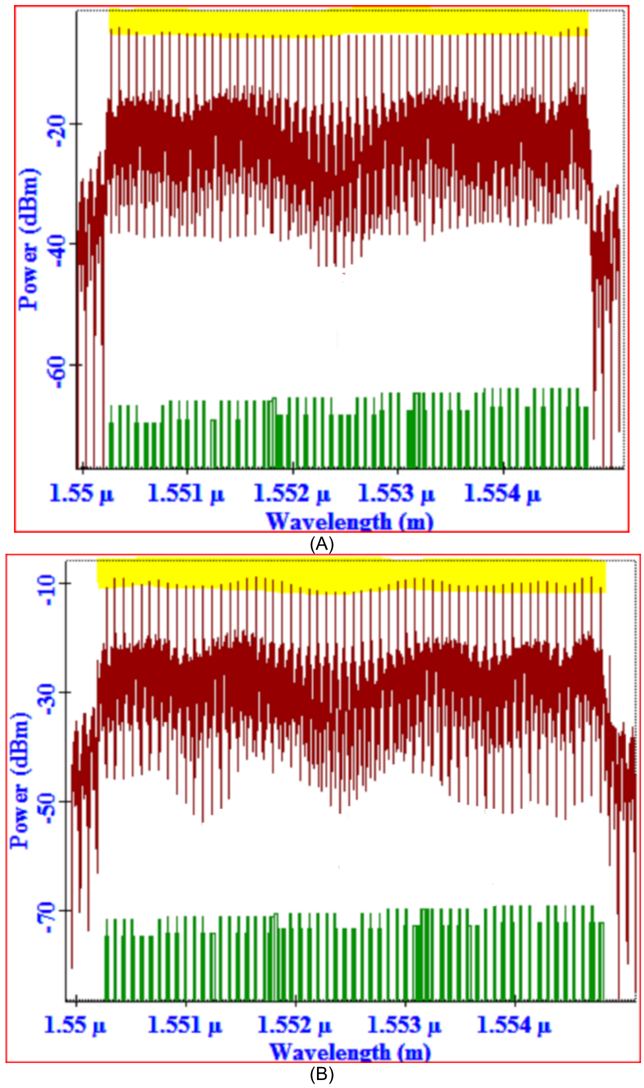

FIGURE 5. Simulated results for the downlink transmission. (A) Downlink multiplexed signal before transmission at OLT side; (B) Received signal after at optical network side after 25 km fiber.

achievable by deploying high level modulation techniques supporting more data bits per frequency. On ONU side, after receiving the data, optical filters are deployed again with the selected frequencies. Before demodulation, half power splitters are used that splits the signal into a pair; half of the signal is demodulated, while the other half is used for re-modulating the signal of 10 Gbps. First half is demodulated by using DPSK based receiver, while the second half is re-modulated by using IM-OOK. On ONU side, user data of 10 Gbps, using IM-OOK based modulation is multiplexed and ridden across the same fiber span (SSMF), whereas on OLT side, after receiving the data signal of 570 Gbps, optical filters are used again to detect the user data. IM-OOK-based receivers are used to detect the signals. More significantly, on both OLT and ONU sides, bit error rate analyzers are used to detect the signals of certain BER ratio. Both the downlink and uplink transmissions have been explained in detail in coming subsections with detailed power budgeting of the system.

A. DOWNLINK TRANSMISSION ANALYSIS

At OLT side after photonic filters, DPSK-based modulated data ~10 Gbps is generated against 57 tones. In this way, 570 Gbps data transmission becomes possible in next generation optical access network. DPSK based modulated data of 570 Gbps is transmitted through SSMF span of 25 km. The simulated results for the downlink signal are shown in Fig 5(A), showing the multiplexed signal before transmitting it across the fiber. The received signal is also shown in the Fig 5(B), showing that the signal is not altered by the attenuation factor of the fiber. On receiving side, fork with splitting ratio of 1:57 is used to receive the multiplexed signal. Next to fork, optical Gaussian filters are used of fixed frequencies similar to OLT side. SSMF span ~ 25 km is used with dispersion slope of 0.075 ps/nm^2/km, differential group delay ~0.2 ps/km, effective core area ~80um^2 and dispersion parameter ~16.75ps/nm/km, while attenuation per kilometer is ~0.2 dB/km. Power splitters of 3 dB are used to tap off the signal into two. One part is received by DPSK based receiver consisting of a Mach Zehnder interferometer, a pair of parallel balanced photo-detectors, a subtractor and a low pass filter. This parallel arrangement and the subtractor cancel the delayed signal. The results of four random channels are analyzed for convenience. The frequencies of carriers at the selected channels are 192.84 THz (1554.6 nm), 192.87 THz (1554.37 nm), 192.90 THz (1554.13 nm) and 192.93 THz (1553.89 nm). The results are examined in terms of power penalties, bit error rate (BER), received optical powers and received eye diagrams for the downlink and uplink transmissions. For achieving different BERs against each channel, optical attenuator is used to attenuate the signal. This way, we achieve different optical powers against different BER values, as graphically demonstrated in Figure 7.

For the aforementioned 4 channels, the power penalties are examined at BER of 10^{-9}, and calculated by comparing the

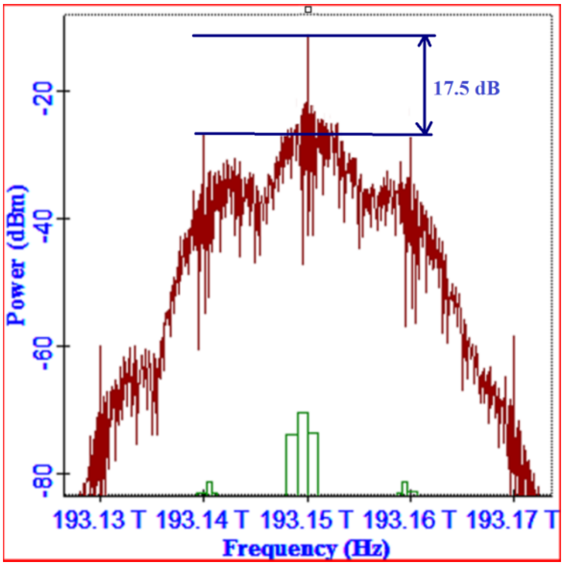

FIGURE 6. Received signal's spectrum at BER 10e-009 at ONU side of the selected channel.

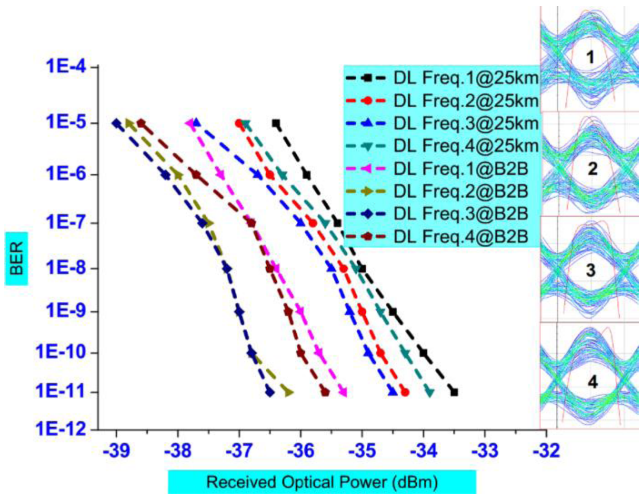

FIGURE 7. Graphical representation between the received optical power Vs achieved BER in downlink transmission for the said channels.

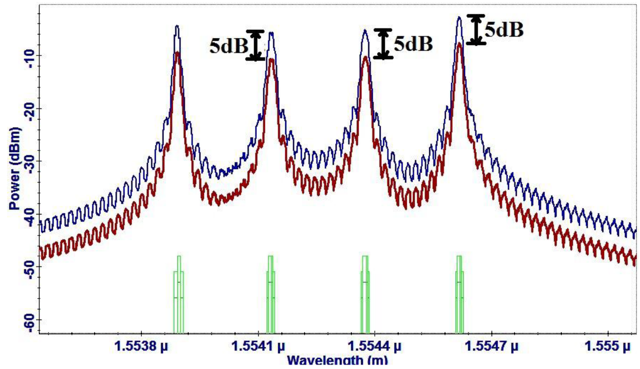

FIGURE 8. Comparison of the multiplexed signal of 4 channels before and after transmission in downlink.

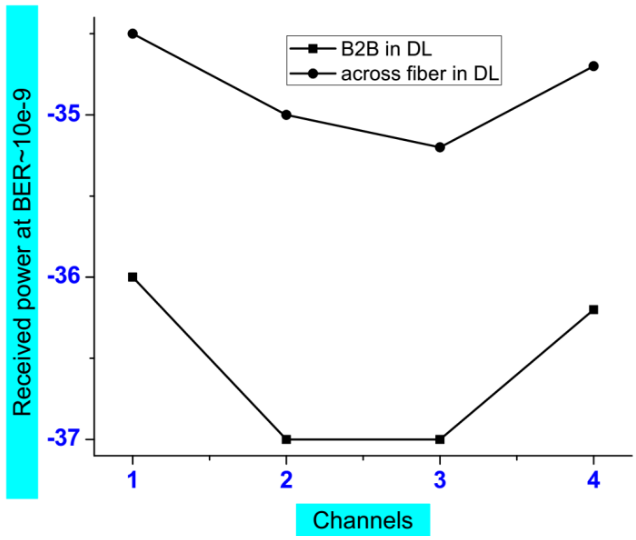

FIGURE 9. Received power for the selected channels at specified BER in downlink transmissions.

received optical powers by using SSMF span ∼25km and in B2B (back to back) configurations. The power penalties are noted as 1.5 dB, 2 dB, 1.8 dB and 1.5 dB at the four channels under observation. Given Fig. 7 shows the graphical representation of the received optical power and BER, as well as excellent eye diagrams of the four random channels for the downlink transmission. As obvious from the illustrations, these results guarantee the adoptability of the proposed OMC generator in WDM-PON that provides high capacity. Figure 8 shows the comparison between the transmission of selected 4 channels in the downlink transmission at OLT and ONU side (before and after transmission), and the 5dB loss across the 25 fiber span. This result is achieved in OptiSystem V-13 (licensed), by keeping the oscilloscope's resolution at 0.01nm.

Fig. 6 shows the received average signal spectrum of the selected channels at ONU side. It is believed that signal spectrum of each channel will almost be the same, which shows that the effect of channel cross talk is suppressed by filters at around 17.5dB. The SSMF usually have a dispersion of 20 ps/nm/km, and 10 Gbps signal have a bandwidth of about 0.4 nm. In this process, the product of the fiber's length ∼25km and dispersion of fiber ∼20 ps/nm/km, while the modulation bandwidth ∼0.4 nm is 200 ps. As we have the time slot for each carrier much larger than the calculated one, therefore, we achieve quite clearer eye patterns for the calculated BER $\sim 10e^{-9}$. We have observed the average BER patterns for the downlink transmission as discussed/showed in Fig. 7.

The fig. 7 shows the received power against measured BERs for the said channels. The inset in Fig. 7 shows the eye patterns for the selected channels, which confirm that all the signals were transmitted without any perceptible errors. The eye patterns are achieved with sampling oscilloscope (electrical) having the resolution of 0.01 nm in OptiSystem V-7. Fig. 9 shows the received optical power in the downlink transmission for the selected channels, as mentioned

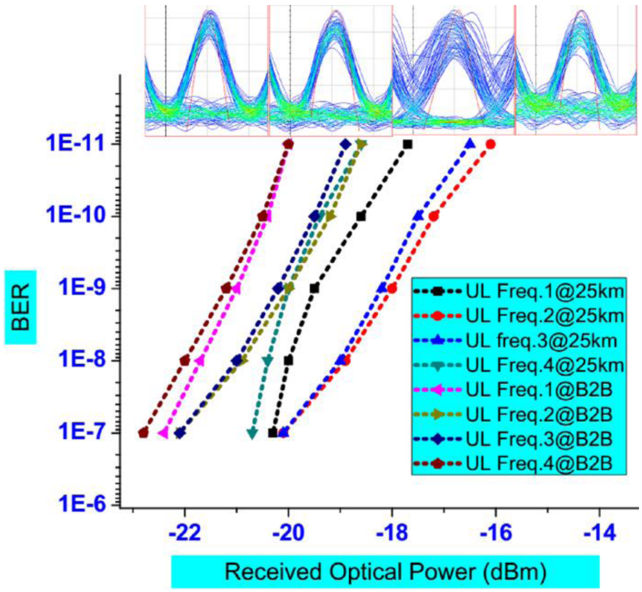

FIGURE 10. Graphical representation between the received optical power Vs achieved BER in the uplink transmission.

in Figure 8. The squares and circles show the received power for back to back configuration and as the transmission occurs across SSMF in the downlink transmission.

B. UPLINK TRANSMISSION ANALYSIS

Power splitters are used on ONU side to tap off the signal into two, where first half is de-modulated and the second half of the signal is used in re-modulating the IM-OOK based signal in the up-link transmission. Dual drive MZM based NRZ is also deployable in uplink transmission which is helpful in suppressing the carrier signals in uplink transmission. However to demonstrate the applicability of proposed OMC generator, IM-OOK is utilized in high capacity WDM-PON. On ONU, the multiplexed signal from the channels can be transmitted back towards OLT using the same optical multi-carriers over SSMF. As no extra special laser is used at ONU side for uplink transmission, therefore, a colorless ONU-based transmission is achieved. Due to the very large setup of the system, the uplink and downlink transmissions for four channels are performed. For receiving the signals back at OLT side, optical filters are used to separate the signals of specified frequencies. IM-OOK-based receiver is used at OLT side using photo-detector (APD) with dark current $\sim$ 10 nA and responsivity 1 A/W, the ionization ratio being kept at 0.9. After passing the signal through photo-detector, low pass filter is used.

The power penalties across each channel has been calculated by conducting several tests in the two aforementioned configurations and found to be 1.5 dB, 2 dB, 2 dB and 1.8 dB respectively. Fig. 10 graphically demonstrates the variations in the received power for different BERs in the uplink transmission. Similarly, the eye diagrams of the channels are shown for demonstrating the uplink transmission. Figure 11 shows the comparison between uplink transmission

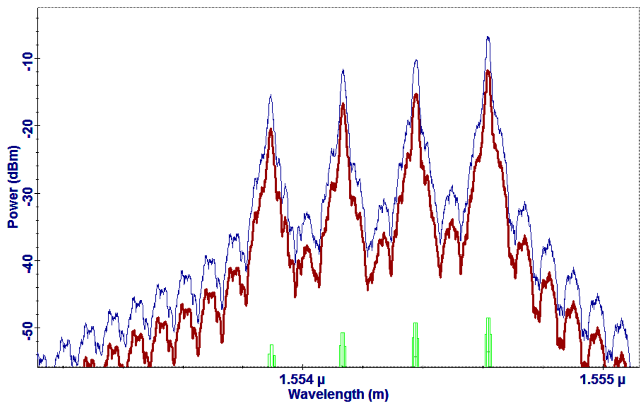

FIGURE 11. Comparison of the multiplexed signal of 4 channels before and after transmission in the uplink.

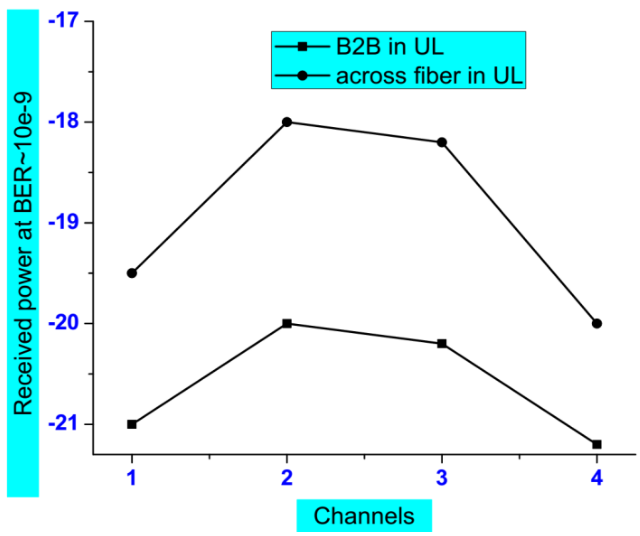

FIGURE 12. Received power for the selected channels at specified BER in uplink transmissions.

of four channels before and after transmission across the fiber span, it shows 5dB loss across the fiber.

Fig. 12 shows the received optical power in the uplink transmission for selected channels. The squares and circles shows the received power for back to back configuration and as the transmission occurs across SSMF respectively in the downlink transmission. Such minimum power penalties in downlink/uplink transmission demonstrate that the proposed setup is practically applicable in next generation optical access network.

C. POWER BUDGET CALCULATIONS

The power budgeting of the optical access system ensures the designer about the proper functionality of the system. It is the reason that the power budget of the proposed OMC based WDM-PON system is calculated. Generally the link budget (P.B) of the system can be encapsulated in the given equation:

$$P.B = P_T - P_R \tag{9}$$

TABLE 2. Power budget calculation for the downlink and uplink transmission.

Power losses across the channel of each carrier			
Power losses during DL transmission		Power losses in UL transmission	
Multiplexer	2 dB	Multiplexer	2 dB
Channel loss (fiber)	5 dB	Channel loss (fiber)	5 dB
Filter/D-mux loss	2 dB	Filter/D-mux loss	2 dB
Optical splitter	3 dB	--	--
Receiver's sensitivity	-37 dBm	Receiver's sensitivity	-21.5 dBm
OPB	23	OPB	6

where P_T is the transmitted power and P_R is the received power. According to the main setup shown in Fig (4), the channel losses include many optical losses. All the channel losses for each carrier are mentioned in equation (10).

$$\Sigma Loss_{comp.} = (\alpha \times K) + N \times L_C + L_{Mux/D-Mux} \quad (10)$$

where K shows the length of fiber, α is the attenuation constant of fiber, Lc is the loss across connector, Lmux/dmux is the loss across multiplxer/demultiplexer and SM is the system margin. Finally the optical power budget can be given as:

$$OPB = P.B - \Sigma Loss_{comp.} \quad (11)$$

All the losses during the downlink and uplink transmissions are mentioned in table 2. The receiver sensitivity is founded as -37 dB in the downlink transmission at BER 10e-009, while in the uplink transmission the receiver detects -21.5 dB power at the said BER. In the downlink transmission, the transmitted power across each channel is 2 dBm, therefore, enough power will be saved for future unseen losses by including all other losses in the downlink transmission and comparing it to receiver's sensitivity. Same is the case for the uplink transmission, where the transmitted power is equal to -6.5 dBm.

IV. CONCLUSION

We contribute in two different ways in the current research. A cost effective scheme has been proposed in this study for the generation of OMC and deployed at OLT in WDM-PON system. It suggests a very economical light source at network side by entertaining many users, where laser sources are replaced with the proposed OMC. No electrical amplifier, phase shifter, filter or attenuator is used in the proposed OMC generator. Due to proper biasing of intensity modulators, the generated OMC is very flat, having high TNR >40dB and minimum fluctuations <1 dB in its comb lines with frequency spacing equal to 30 GHz. With 60 multi-carriers, the proposed OMC is deployed in WDM-PON system, proposing a large capacity WDM-PON system. On OLT side, each carrier is separated by a filter and modulated with 10 Gbps data using DPSK, however, after halving the data on ONU side, each frequency is re-modulated with the same data size using IM-OOK. In this way, high capacity optical transmission is achieved, supporting 570 Gbps multiplexed data (by utilizing 57 carriers) in both the uplink and downlink transmissions. In both the transmissions of the proposed WDM-PON system, the thorough theoretical investigation and outcomes of simulation show the novelty and applicability of OMC in WDM-PON. Minimum power penalties are observed at BER 10^{-9}. The metrics of the suggested OMC comprises of several factors including bit error rate, eye diagrams and power penalties. Finally, the detailed power budgeting validates the results.

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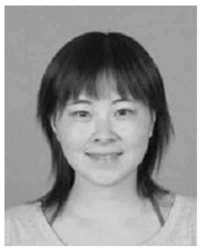

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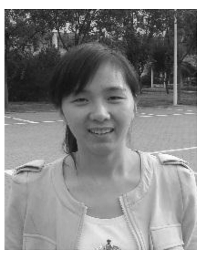

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