1.12Tbps-16QAM Uncompensated Long-Haul Transmission Employing a New Self-Oscillating Optical Frequency Comb Generator Both at Transmitter and Receiver

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***Abstract*—A new optoelectronic oscillator (OEO) is implemented for a novel self-sustained flat-topped self-oscillating optical frequency comb generator (SO-OFCG), which can be deployed in terahertz optical transmission. The OFCG is designed from a cascaded configuration of an electro-absorption modulator and a polarization controller. In this work, the radio frequency source of a traditional-OFC scheme is replaced by the OEO. The frequency spacing of the generated spectrum is defined by the OEO∼20 GHz that contains 15-healthy frequency tones. The carriers are modulated using the 16-quadrature amplitude modulation technique and transmitted across an SSMF implemented in a loop to complete a fiber span of 80 km-240 km. Overall, 1.12Tbps transmission can be achieved with the help of the given setup. At the receiver side, a homodyne coherent receiver is designed using the proposed OFCG to receive the signal. The conventional local oscillator lasers are replaced by the SO-OFCG generated from the received central optical carrier. Through offline DSP, the received optical signals are remunerated from various signal distortions and nonlinear impairments by utilizing digital backpropagation, constant modulus algorithm, and blind phase search algorithm at the receiving end. The system is analyzed regarding the bit error rate, symbol error rate, Q-factor, and error vector magnitude.**

***Index Terms*—Terahertz broadband transmission, self-oscillation, optical frequency comb, quadrature amplitude modulation, optoelectronic oscillation loop.**

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I. Introduction

The traffic of broadband terahertz (THz) technologies is growing at an unprecedented rate due to the emergence of bandwidth-hungry applications. The optical industry is working hard to create novel strategies for increasing the overall capacity of deployed optical networks both at wired and wireless mediums [1], [2]. Optical communications have permeated numerous domains of science and technology and evolved into a crucial and fast evolving topic, attracting interdisciplinary study [3], [4], [5]. The transformative impact of photonics on the development of science and technology is appreciable, including the emerging traits like quantum and topological photonics [3]. Similarly, the integrated photonics aims to inspire further developments for scalable solutions, particularly emphasizing on-chip lasers and their integrations into various systems [4]. Coupled with rapid progress in electronics, the silicon photonics are driving performance gains in terms of speed and bandwidth [5]. Recent advancements in the field of optical communications have enabled the way to deal with high data rate transmission, particularly when one or more multiplexing techniques are considered [6], [7], [8]. The solution to achieve the bit rate enhancement is wavelength division multiplexing (WDM) which also shows resilience towards fiber impairments such as chromatic dispersion [9]. Increasing the number of WDM channels has received much attention for obtaining a high data rate. However, this increase also enables increasing the seed complexity of optical-to-electronic and electronic-to-optical conversion [10], which would result in a data rate that is much higher than what the optoelectronic senders and receivers can handle.

A bank of lasers or laser arrays in a conventional WDM system provides unmodulated optical carriers at the transmitter side. The frequencies of these channels must be properly adjusted to achieve high accuracy and produce specific channel frequency spacing, also known as frequency interval [11], [12], which also increases the cost and complexity of the system. A similar setup of laser arrays should also be used at the receiver side to recover the transmitted data in case of coherent detection. To overcome this limitation, scientists have proposed to use of OFCs to replace the conventional setup of laser arrays in the WDM systems [9], [13], [14]. Low-cost, easy-to-implement and scalable new solutions are required. The OFC is one such technology that offers diverse characteristics of transmitting higher data rates at lower costs [15], [16]. The data rate can be further enhanced upon employing the OFC scheme in an advanced n-QAM modulation technique, as the system can transmit 2n symbols per carrier per bit [17]. This way, a huge amount of bandwidth can be produced to cope with the demands of broadband THz technology. Another interesting frequency combs called microcomb soliton microcombs have diverse applications in the imaging, and in low noise microwave generations [18], [19]. The OFC can be generated by various techniques, including single or cascaded configurations of optical modulators [20], [21], [22], [23], radio frequency shifting loops (RFS) [24], [25], mode-locked lasers [26], [27], [28], and self-oscillation loops [27], [29], [30], [31], [32], [33], [34], [35], [36]. The RFS loops and mode-locked lasers also produce efficient results, but the system complexity is greatly increased. Furthermore, a dedicated external RF source is mandatory to drive the optical modulators, which may result in a poor phase noise portrayal of the OFC, particularly when a high RF frequency is used [31]. This limitation can be addressed by using the self-oscillation (SO) loops to create a microwave RF signal that can also be regarded as an optoelectronic oscillator (OEO) In all the cases for generating an OFC, the motivation is to produce a feasible signal in the optical domain directly, allowing it to be processed and distributed photonically. The key application of OFCG is in the optical access network, because of its potential for having many frequency carriers of interest.

Many researchers have proposed various topologies for generating OEO deployed for generating the OFC, this paragraph summarize most of the state-of-the-art techniques offered for designing OEO based OFCG. In [27], the authors proposed a OEO loop for OFC generation based on dual-mode microcavity laser. The OEO loop was designed by launching the optical signal into a SMF1 which is then detected by a photodetector (PD), following by two electrical amplifiers (EAs) to compensate the loss of the link. The amplified RF signal is used to drive the two electro-optic modulators to accomplish OFC. J. Liu et al. demonstrated OFC based on OEO, where in OEO loop [32], the modulated light coming out of MZM is fed to dispersion shifted fiber that is deployed to realize the energy storage function for decreasing the phase noise in the signal, followed by the PD for converting the optical signal to electrical signal. In this feedbacking topology, the RF-BPF and EAs are deployed for selecting the resulted oscillation and for compensating the link loss. After the first EA, 50% of the amplified signal is deployed to run the RFS loop and the rest of the power is used to drive the EO modulator [32]. A SO based OFCG was implemented based on a dual loop mechanism that successfully generated 23 comb lines with a bit low frequency spacing and high amplitude difference [29]. The authors deployed the proposed SO-OFCG for a RoF link that operated at 94.8 GHz. For designing the OEO, a dual-loop based balanced detection mechanism is deployed through feedbacking loop with two different sized fibers, each fiber is feed to a PD with a specific bandwidth and responsivity, followed by a band pass filter for selecting the desired available microwave signal. The filtered signal is then passed through a low noise amplifier followed by a power splitter of 50:50 ratio, whose one output is used to drive the DDMZM and is connected to EA (electrical analyzer) for monitoring and measurement purposes. Similarly, the same authors proposed almost same SO based OFCG with low frequency spacing was proposed in [30], which has produced 23 comb lines with frequency spacing of 11.8 GHz. X. Xie et.al. proposed a single loop based OEO for OFCG [31]. In this article for designing the OEO, the OEO loop replaces single mode fiber with a long zero dispersion optical fiber for realizing the delay and received an oscillating signal with a low phase noise. The optical fiber is followed by a PD for converting the signal to electrical, then the signal is feed to BPF and a phase shifter. In the OEO loop two EAs are deployed to provide enough gain in the feedbacking: one amplifier is a low noise and the second one is a high-powered amplifier [31]. An OEO based phase conjugate resonator act as an OFCG was proposed in [33], with a propagating-forward four-wave mixing effect, which oscillates and provides a spontaneous emission that exhibits OFC like properties: specific frequency spacing and phase coherence. The authors in [34] proposed a coherent 7-lined OFC based on a microwave signal of low phase noise signal. The RF signal is generated from Raman-pumped Brillouin, where stimulated Brillouin scattering (SBS) is exploited for frequency selection∼11 GHz frequency shift, because the SBS has narrow-gain bandwidth∼30 MHz in a SMF [34]. Q. Zhao et.al. proposed a self-oscillating based OFC in [35]. The OEO loop is designed from passing the amplified light through fiber Bragg grating (FBG) via circulator, which is divided into 60:40 ratios through an OC. The 40% was separated for measurements and the 60% of light was further divided in two halves that were then injected into SMFs of different lengths, which are then detected by PDs and then combined, which is amplified by EA. The amplified electrical signal is passed through a BPF and 50:50 coupler, where half of the signal was fed to the external modulated light source and the rest is again passed through an EA and then used to drive the modulator for OFCG.

A novel scheme for self-sustained flat-topped OFCG and for low noise RF signal is offered and demonstrated here. This scheme replaces the conventional laser array at the OLT side of an optical communication network with the self-oscillating OFC (SO-OFC) generator. Compared to the majority of cited works, the OEO loop offered in this scheme is simple and cost-effective, producing a stable and flattened OFC with higher frequency spacing. The OEO replaces the traditional RF source, offering 15 comb lines with a frequency spacing of 20 Gbps. A coherent optical communication system for downlink transmission based on a SO-OFC generator at the OLT and ONU sides, replacing the laser array at the OLT side as a transmitter and local oscillator source at the ONU side is presented here. Electro-absorption modulators (EAM), in contrast to traditional Lithium-Niobate (LiNbO3) MZMs, provide a better and fast response with lower power consumption. Meanwhile, EAMs have seen widespread application as transmitters in high-speed and long-haul optical transmissions due to the ease with which they can be integrated with lasers while maintaining a relatively modest size. In the proposed scheme, the SO OFC is generated by the cascaded configuration of the EAM and polarization controller. The self-oscillation loop is configured by employing a high-speed PIN-photodetector, an electrical amplifier, a standard single-mode fiber, and a bandpass Bessel filter. The scheme generates an overall 15 healthy carrier signals. These signals are individualized using wavelength division de-multiplexer incorporating rectangle optical filters. 20 Gbps 16-quadrature amplitude modulation (16QAM) data is modulated on each carrier and collectively transmitted across 240 km standard single-mode fiber in loop structure without using a dispersion compensation fiber in the transmission line. On the receiving end, gaussian optical filters are used to recognize the carrier signal and detect the in-phase and quadrature-phase of the input signal using a 16QAM receiver. Furthermore, digital signal processing is performed to aid in recovering the signal from various nonlinear impairments and signal distortions. The system is analyzed in terms of the error vector magnitude, bit error rate, symbol error rate, and constellations of the received signal.

The introduction section of this paper covers all the related literature and comparisons. The second part has discussed the detailed theoretical background of the proposed scheme, then the main principal of the scheme is proposed and the results are discussed. The third sections discuss the deployment of the proposed scheme in a long-haul optical network with results. The results are discussed in terms of bit error rate (BER), error vector magnitude (EVM), and symbol error rate (SER) vs different fiber optic cable lengths. The last section discusses the conclusion of the scheme.

The main highlights in the paper can be given as under:

- A novel and cost-effective self-oscillating optical frequency comb generator is proposed in this paper where the optical comb is designed from a cascaded configuration of electro-absorption modulator and a polarization controller driven by the designed oscillator.
- The conventional microwave source is replaced with the designed OEO signal.
- The microwave signal is generated by passing the optical signal via a standard single mode fiber, a PIN Photodetector, an electrical amplifier, and a band-pass Bessel filter. By deploying the proposed scheme in an optical access network, we can perform 1.12 Tbps 16QAM uncompensated long-haul data transmission across 80 km to 240 km SSMF.
- An optical frequency comb source is deployed both at the transmitter and the receiver side.

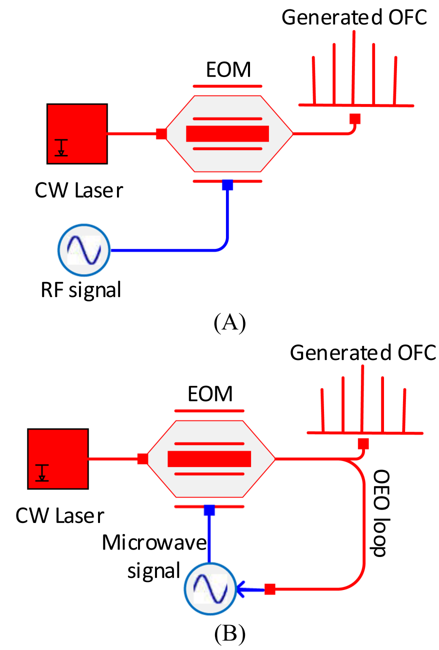

Fig. 1. Optical frequency comb generations, the red and blue lines show the optical and RF signals respectively. (a) Using a conventional RF source for generating the OFCG, RF: Radio frequency generator, CW: Continuous wave laser source, EOM: Electro-optic modulator, OFC: Optical frequency comb and (b) using optoelectronic oscillation loop for generating the RF signal in an OFC, OEO: Optoelectronic oscillator.

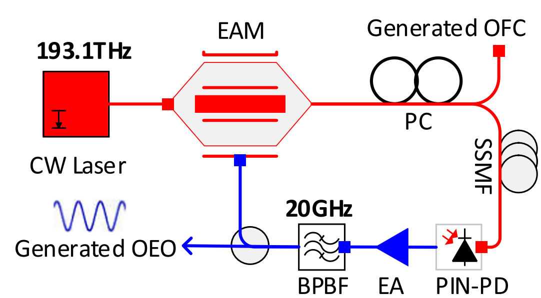

Fig. 2. Schematic of the proposed OFCG. PC: Polarization controller (rest of the components are already defined above).

II. Principle of Operation and Simulation Results

Traditionally, the OFC generators are driven by a dedicated external RF source which drives the optical modulators and specifies the frequency spacing of the generated optical frequency comb. In this scheme, an optical signal is converted to a microwave signal using the OEO loop. The generated RF signal is then used to drive the optical modulator where the output of the CW laser is also injected into the modulator. The output of this process is a series of evenly spaced optical frequencies that form an OFC. The spacing between the optical frequencies is determined by the frequency of the RF signal used to modulate the optical signal. Fig. 1(a) illustrates the generation of an OFC using electro-optic modulators driven by an RF signal. On the other hand, the generation of an OFC source using an OEO loop is demonstrated in Fig. 1(b). In this method, a feedback loop is constructed to generate the optoelectronic oscillator which determines the frequency spacing of the OFC source.

The SO-OFC is essentially an OFC generator with OE feedback loop: that is the OFC is photo detected and produces an RF signal with a fundamental frequency difference/spacing, which is the fundamental frequency used to drive the OE modulator and thus produces OFC by completing the loop. Therefore, the SO-OFC has the advantage of eliminating the need for an external RF source while maintaining the low-phase noise characteristics of the OEO. The OEO feedback loop, shown in Fig. 2, consist of a single-mode fiber, PIN photodetector, electrical amplifier, and bandpass Bessel filter to generate a stable and coherent RF signal at a specific frequency. This RF signal is then fed back to the EOM to stabilize its bias point and ensure a stable output frequency comb. The single-mode fiber plays a crucial role in this feedback loop. It is used to delay the RF signal by a specific amount, to allow the photodetector and amplifier to operate properly. The length of the fiber is 1.5 km of standard single mode fiber, it also helps in improving the Q factor. This delay ensures that the feedback signal is in phase with the modulating signal and can properly stabilize its bias point. Afterwards, the signal is detected and converted to an electrical signal using a high-speed PIN photodetector. The PIN photodetector converts the optical signal from the fiber into an electrical signal, which is then amplified by an electrical amplifier$\sim$13.5 dB amplification is performed. The bandpass Bessel filter is then used to extract a bandwidth of 1 MHz and specify the desired frequency spacing of the SO-OFCG. The resulting RF signal is then fed back to the EAM, where it is used to stabilize the bias point and ensure a stable output frequency comb. The self-oscillating RF signal generated by this feedback loop is typically sinusoidal and has a frequency determined by the round-trip delay of the feedback loop. Overall, the feedback loop plays a crucial role in generating a stable and coherent optical frequency comb through the electro-optic modulation of a CW laser. By using an OEO signal to stabilize the modulator's bias point, the output frequency comb can be made more stable and accurate.

The proposed OFC generator consists of a CW laser connected with a EAM and a polarization controller. The OEO loop is also connected to the polarization controller and feedback to the optical modulator, as shown in Fig. 2. The CW laser is centered at 193.1THz frequency with a linewidth of 0.1 MHz and an initial power of 6.9 dBm. This optical signal is then passed through the EAM and polarization controller before entering the loop. In the loop, the optical signal is converted into an electrical signal which is used to drive the optical modulators and generate the optical frequency comb. The EAM and polarization controller generates and stabilizes the optical frequency comb signal which is driven by the OEO. The frequency of this oscillator is 20 GHz which demonstrates the frequency spacing between the OFC tones. This model is implemented in the OptiSystem and MATLAB simulation environments and the important simulation parameters are listed in Table I.

Overall, the generated comb contains 15 carrier frequencies with a high carrier-to-noise ratio (CNR)$\sim$over 45 dBm. The results of the generated OFC and the OEO can be seen in Fig. 3. It can be seen that the amplitude differences vary from left to right. These carriers are filtered using a Gaussian optical filter and individually passed through a 16QAM modulator where 20 Gbps data is overridden on each carrier (20 Gbps (bit rate) $*4$ (bits per symbol) $=$ 80 Gbps).

TABLE I
IMPORTANT SIMULATION PARAMETERS

Parameter	Value
Global Parameters	
Sequence Length	8192 bits
Samples per bit	16
Number of Samples	131072
Simulation Window	
Bit rate	20e+009
Time window	0.4096e-006 s
Sample rate	320e+009
CW laser	
Central frequency	193.1 THz
Linewidth	0.1 Mhz
Band Pass Bessel Filter	
BPBF Frequency	20 GHz
Bandwidth	1 MHz
Insertion loss	5 dB

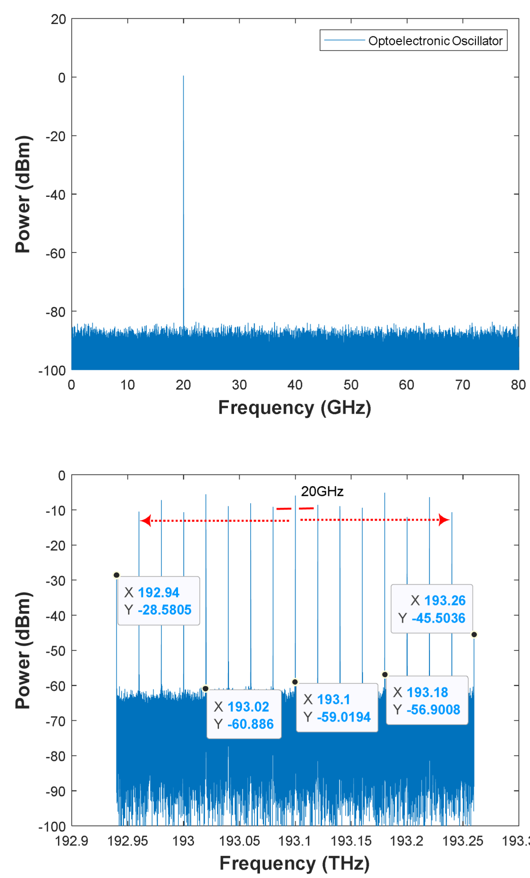

Fig. 3. Generated results of the proposed OFC generation scheme (a) generated OEO, (b) generated optical frequency comb.

III. RESULTS AND DISCUSSION OF THE 16QAM TRANSMISSION DEPLOYING THE OFCG

The generated OFC is used to transmit the 16QAM data signal with a carrier frequency f_c. As described earlier that frequency comb is a collection of equally spaced frequencies, we can use it to modulate the 16QAM signal on each of its carriers, individually. To do this, we can use a set of N carriers that are equally spaced in frequency and have a frequency spacing of Δf. We can then represent the 16QAM signal as a sum of complex symbols, where each symbol represents a different amplitude and phase modulation. We can denote the complex symbol for

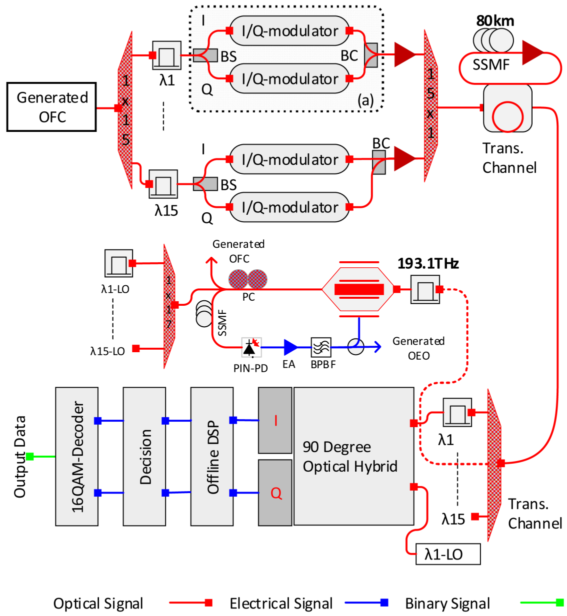

Fig. 4. Schematic diagram of the proposed self-oscillating optical frequency comb generation scheme and its deployment in the coherent 16QAM transmission network.

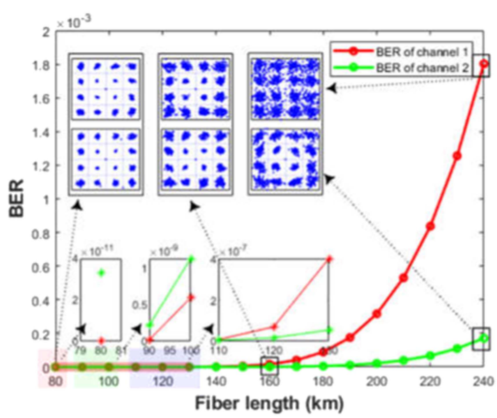

Fig. 5. Simulation results of the carrier 193.08 and 193.12 across 80 km to 240 km fiber transmission along with their constellation diagrams.

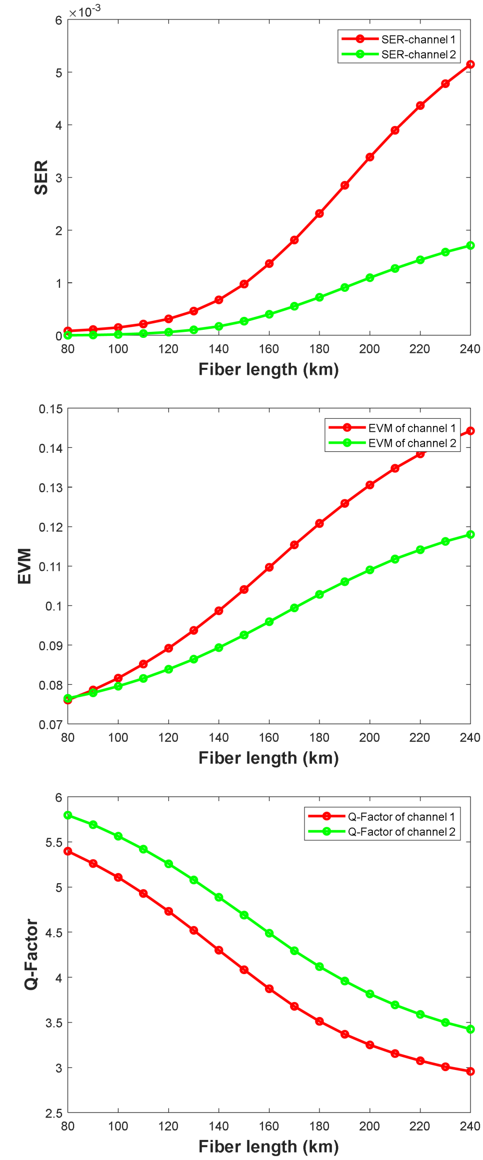

Fig. 6. Error vector magnitude (EVM), SER, and Q-factor of the selected channels.

the kth 16QAM symbol as S_k, then the 16QAM signals can be modulated onto the frequency comb by modulating the data on each of the comb channel, given by $f_k = f_c + k\Delta f$. The modulated signal can be represented as:

$$x\ (t) = \ Re\left\{\sum_{n=0}^{N-1} s_n e^{j2\pi(f_c+n\Delta f)t}\right\}$$

where *x(t)* shows the time-domain waveform of the modulated optical signal, *Re{}* denotes the real part of the expression, s_n shows the 16QAM signal modulated onto the nth subcarrier, with a complex amplitude of An, f_c presents the center frequency of the OFC, and n is the number of subcarriers. The complex amplitude An for each subcarrier can be calculated based on the 16QAM signal being transmitted, using the equation: $A_n = \sqrt{P_n}\ .e^{j\varphi_n}$, where P_n is the power allocated to the nth subcarrier, and φ_n is the phase shift applied to the subcarrier to represent the 16QAM signal. The summation over n in the equation represents the combination of all the subcarriers to generate the modulated optical signal. The real part of the complex sum is taken to ensure that the modulated signal is a real-valued waveform that can be transmitted over an optical fiber. We can then transmit this modulated signal over an optical fiber. At the receiver end, we can use a frequency comb to demodulate the signal by mixing it with the same set of carrier frequencies. Using a suitable decoding algorithm, we can then decode the 16QAM signals from the demodulated signal.

In the 16QAM modulator, the input bitstream is generated by a pseudo-random bit sequence generator (PRBS). The filtered signal is split into real and imaginary (I and Q) parts using the beam splitter (BS) which is injected into the in-phase and quadrature-phase (IQ) optical modulators. The signal from both ends is combined using an optical combiner to produce the desired 16QAM signal, shown in Fig. 4. A 15 × 1 optical multiplexer is used to syndicate the modulated carriers and inject the data to the transmission channel. In the transmission channel, a loop structure of single-mode fiber along with an optical amplifier to maintain the gain of the optical signal is used to preserve the transmission superiority. Each span of the loop structure contains 80 km single-mode fiber along with 18 dB optical gain. In total, three spans are used extending the fiber length to 240 km. On the receiving side, an optical DEMUX with the same number of channels is used to detach the optical signal and identify each carrier. Furthermore, optical homodyne receiver structure is used at the receiver side where the local oscillator (LO) is replaced by an identical OFC source used at the transmitter side, as can be seen in Fig. 4. However, the CW laser source is replaced by the received central carrier frequency (193.1 THz) which is dedicated to generating the LO-SO-OFC source. A 90-degree optical hybrid is used to recover the I and Q parts of the signal. In the offline DSP stage, the received optical signals are recovered from various signal distortions by utilizing digital backpropagation, constant modulus algorithm, and blind phase search algorithm.

The system promises decent performance in terms of BER, SER, and Q-factor. The BER performance of the proposed scheme at different instances of fiber span is shown in Fig. 5. It can be seen that the scheme offers optimum results for 80 km and 160 km fiber transmission and the BER value for 240 km is still below the threshold value. Furthermore, the constellation diagrams of channel-1 and channel-2 can also be seen in the insets of Fig. 5. Moreover, the EVM, SER, and Q-factor of the received channels can be seen in Fig. 6. Based on the obtained results, it can be concluded that the proposed SO-OFC generation scheme has the potential to be deployed in the 16-QAM coherent optical communication system over a fiber span of 80 km to 240 km.

IV. Conclusion

A novel SO-OFCG technique and its deployment in the coherent 16-QAM optical communication system is proposed and discussed. In the OFC generation scheme, the conventional RF signal is replaced with the generated optoelectronic oscillator which defines the frequency spacing among the generated carriers. Overall, 15 carriers are generated where the central carrier on the receiving side is used for generating the LO-OFC and the left and right carriers are used for 16-QAM data modulation in a long-haul network from 80 km to 240 km single-mode fiber transmission. The results have illustrated the transmission of 14$*$80 Gbps (1.12 Tbps) 16-QAM transmission over uncompensated fiber link of 80 to 240 km standard single-mode fiber. Additionally, the BER, SER, EVM, and Q-factor of the received channels along with their clear constellation diagrams strongly support the applicability of the proposed scheme in coherent optical communications. The central carrier frequency of the OFC is dedicated to generate the LO-OFC, hence no data is sent over it. If a separate laser source is employed to generate the LO-OFC, this channel can be used for data modulation, increasing the overall transmission rate to around 1.2 Tbps.

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