

Performance of Coherent Optical Networks Incorporating Kramers-Kronig Direct-Detection Receivers Part II: Single-Sideband Transmission

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Abstract A single-sideband (SSB) transmission has been adopted in modern coherent optical networks to increase the bit rate capacity and maximum reach. Recently, direct-detection (DD) technique, which does not use a local laser, has been proposed to retrieve the phase of the complex optical signal from the photocurrent at the receiver side. This technique uses Hilbert transform-based Kramers-Kronig (KK) algorithm and has been mostly investigated for less than 100 Gbps optical networks. The aim of this paper is to design and performance investigate KK-based coherent optical networks operating with 200 Gbps and beyond data rates under SSB transmission. A virtual carrier-assisted coherent optical network configuration supported by KK-based DD technique is designed using VPIphotonics ver.11 software. The configuration uses only one laser where the information is embedded in its field using a SSB modulation. A virtual assisted-optical carrier is generated by making the message modulates a radio frequency (RF) subcarrier before using optical modulation. The configuration is designed to support 16-QAM single-polarization (SP) signaling with 200 and 400 Gbps bit rates and dual-polarization (DP) multiplexing to support 400 and 800 Gbps networks. The effect of various design and system parameters on the transmission and bit error rate characteristics are investigated. Simulation results show the SSB configuration can support maximum reach of 360 and 180 km for SP 200 and 400 Gbps, respectively.

Keywords Single-sideband (SSB), Direct-detection (DD), Single-polarization (SP), Dual-polarization (DP)

1. Introduction and Related Work

1.1. Introduction

Advanced high-bit rate optical networks faces two main challenges [1]. The first one is related to the limited available bandwidth of the electrical/optical and optical/electrical devices to support the high bit rate. Note that it is important to use low-order modulation formats to avoid sensitivity penalties due to system impairments. The second challenge is the increased effect of fiber chromatic dispersion as the bandwidth of the modulated carrier increases. To solve these challenges simultaneously, SSB transmission has been proposed in the literature since it reduces the bandwidth of modulated optical signal to the half [2,3]. One of the techniques used to generate an optical SSB modulation is to generate a SSB-modulated RF subcarrier which is used to modulate the output of the CW laser. This type of optical modulation is called SSB subcarrier modulation (SCM) which offers low cost

implementation [4]. Direct detection (DD) scheme has been investigated to recover the message at the receiver side bit. The performance is limited by SSBI generated after the single-PD detection. Recently, KK-based DD receiver has been proposed to reduce the effect of SSBI [5,6].

The aim of this paper is to design high-bit rate (200 Gbps and beyond) SSB coherent optical networks incorporating direct-detection optical receivers. Optical signal processing is used at the transmitter side to produce high-order coherent modulation format and Kramers-Kronig (KK) algorithm is to implemented using DSP after photodetection in the receiver side. The goal is achieved through the following steps

- (i) Design and performance investigation of single-polarization 200 and 400 Gbps SSB coherent optical networks supported by KK-DD receivers. The effect of various design and system parameters on the bit error rate (BER) and transmission performance are to be addressed in details.
- (ii) Applying polarization-multiplexing technique to double the transmission bite rate for the networks designed in step (i).

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Received: Jun. 18, 2021; Accepted: Jun. 28, 2021; Published: Jul. 26, 2021

Published online at <http://journal.sapub.org/ijnrc>

1.2. Related Works

In 2017, Li et al. [7] assessed the performance of DD transceivers employing electronic dispersion compensation (EDC) combined with digital DSP-based receiver linearization techniques. Experiments were performed on a 4×112 Gb/s WDM DD SSB QAM Nyquist-subcarrier-modulation (SCM) system operating at a net optical information spectral density of 2.8 b/s/Hz in transmission over up to 240 km of standard single-mode fiber (SSMF) links. The experimental study was focused on the effectiveness of performing EDC either at the transmitter (Tx-EDC) or at the receiver (Rx-EDC) in DD-SCM transceivers combined with different receiver linearization techniques. The experimental results indicate that the performance difference of Tx and Rx-EDC depends on the effectiveness of the linearization scheme that is used, and that they can achieve similar performance if the beating interference is effectively suppressed. Therefore, it becomes possible to perform the EDC at the receiver rather than at the transmitter, which simplifies the system operation since knowledge of link dispersion is not required at the transmitter. In 2018, Li et al. [8] experimentally demonstrated a bidirectional-passive optical network (PON) based on the KK receiver and 50 km 7-core fiber. The middle core was used to deliver the seed light to optical network unit (ONU) for colorless upstream transmission. The upstream and downstream signals were transmitted simultaneously over the same outer core for each ONU. The design simultaneously coped with the induced signal-signal beating interference (SSBI) and Rayleigh backscattering noises. A low-cost self-homodyne detection using only one PD was used at both optical line terminal (OLT) and ONU. By this means, the signals and local oscillator for upstream and downstream transmission all originate from the same laser which was located at OLT. The results show that SSBI could be effectively eliminated and the fiber dispersion can also be digitally compensated due to the reconstruction of the complex field of the received signal in the KK-based receiver. In the experiment, the carrier-to-signal power ratio (CSPR) and the frequency gap between the upstream and downstream signals were investigated. Furthermore, bidirectional transmission of 60 Gbps SSB-Nyquist-16-QAM signals over 50 km 7-core fiber was successfully achieved, and the frequency gap between the upstream and downstream signals was only 3 GHz. In 2018, Li et al. [5] used KK scheme to achieve 4×168 Gbps WDM DD SSB 64-QAM Nyquist-SCM signal transmission over 80 km of uncompensated SSMF. The joint optimization of the optical carrier-to-signal power ratio (CSPR) and the sampling rate used for the KK algorithm was experimentally studied. The sensitivity of the KK scheme's performance to the sampling rate was compared with alternative recently proposed single-stage and two-stage linearization filters. Both the back-to-back and transmission evaluations indicate that, of the three schemes, the best performance was

achieved using the KK scheme (provided a sampling rate corresponding to at least 2.75 sample per symbol was used for the KK algorithm). The optimum performance being achieved at 6 samples per symbol. This experimental analysis quantified the trade-off between the linearization performance and the DSP sampling rate in high spectral efficiency 64-QAM DD receivers. In 2019, Zhu et al. [9] presented a comparative study of equalization-enhanced phase noise (EPPN) and phase-to-amplitude (P2A) noise with CD pre- and post-compensation in SSB transmission and KK-DD systems, respectively. The interplay of laser phase noise and fiber dispersion on an optical SSB Nyquist shaped four-level pulse amplitude modulation (4-PAM) signal in KK receiver was investigated numerically. The main results show that the EPPN in a DD-KK receiver dominates the system noise with the relaxed signal-to-noise ratio (SNR). Further, the P2A noise in CD post-compensation scheme is relaxed due to the complex field recovery with KK receiver. These conclusions were drawn from simulation of 56-GBaud 4-PAM signal over 100-km SSMF transmission. In 2020, Wang et al. [4] proposed new optical modulator configuration for KK receiver-based optical SSB DD systems to cope with SSBI for long-reach optical interconnect and 400 GZR. They analyzed the principle of dual-drive Mach-Zehnder modulator (DD-MZM)-based SSB modulation due to its low cost compared with in-phase quadrature (IQ) modulator. The results indicate that SSBI does not exist in back-to-back after square-law DD, and EDC cannot be realized at the transmitter due to the nonlinear modulation of DD-MZM. Simulation results were reported for both 25 GHz SSB conventional DD-MZM-based scheme and new proposed scheme incorporating discrete Fourier transform spread discrete multi-tone (DFT-S DMT). The BERs of the proposed and conventional schemes with optical signal-to-noise ratio (OSNR) of 26 dB were 1.2×10^{-3} and 1.7×10^{-2} , respectively, after 80 km SSMF transmission with pre-EDC. In 2020, Al-Qadi et al. [2] experimentally demonstrated the simultaneous generation and transmission of 12 channels SSB 16-QAM signals at 18 GBaud per channel using a single mode locked laser (MLL). This laser acts as an optical comb with 25 GHz line spacing. A total net data rate of >800 Gbps was achieved over 78 km of SSMF. Direct detection with a single PD is used at the receiver and optical field reconstruction was performed based on the KK algorithm to provide SSBI cancellation and allow for EDC. A BER of less than 2×10^{-3} was reported after transmission which was lower than the threshold of hard-decision (HD) forward error correction (FEC) with 7% overhead (BER threshold = 3.8×10^{-3} was assumed). Numerical simulations were also performed to assess the impact of noises from the laser source and the receiver front-end on the system performance. Receiver noise was found to be the most important limiting factor for the BER of this system. A linear PD capable of accepting high signal

optical power with large dynamic range and high responsivity is critically important to improve the optical signal-to-noise ratio (OSNR) performance in these systems.

It is clear from this literature survey that most of the work was reported for a single-polarization (SP) KK receiver-based optical networks with less than 100 Gbps data rate per single channel. It is interesting to address the performance of such networks for higher-bite rate SP transmission (for example, 200 and 40Gbps). Further, one can redesign the system using DP multiplexing to double the transmission bit rate. The effect of system parameters needs to be investigated for these advanced systems. These issues are considered in this work.

2. Single-Sideband/Direct Detection Transmission

Figure 1 shows a simplified block diagram of the optical SSB-SCM transmitter. The RF SSB M-QAM signal is used to modulate the CW laser (optical carrier) through IQ optical modulator. The RF subcarrier frequency f_{sc} is set to $\geq (1+r)R_s/2$ where r is the roll-off factor of the root-raised cosine filter used for pulse shaping the M-QAM electrical pulse and R_s is the symbol rate. A unmodulated carrier component is added during the electrical-to-optical conversion achieved by the IQ modulator [6].

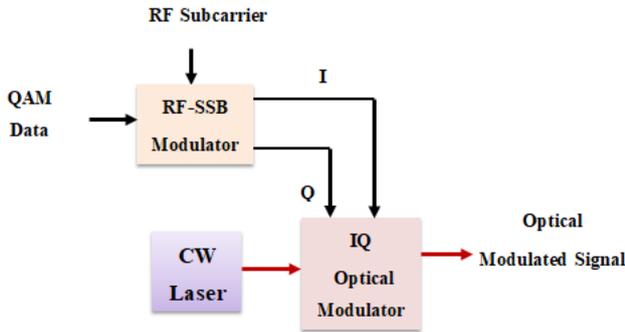


Figure 1. Schematic of a SSB-SCM Transmitter

The optical signal at the optical modulated output $e_o(t)$ can be expressed as

$$e_o(t) = e_c(t) + e_s(t) \quad (1a)$$

where $e_c(t) = E_c e^{j\omega_c t}$ is the carrier component with E_c is a constant and represents the amplitude of the optical carrier. Further the $e_s(t)$ is the modulated carrier component

$$e_s(t) = s(t) e^{j2\pi\omega_{sc} t} e^{j\omega_c t} \quad (1b)$$

where $s(t)$ is the baseband SSB signal and $\omega_{sc} = 2\pi f_{sc}$ is radian subcarrier frequency. Combining eqns. (1a) and (1b) yields

$$e_o(t) = [E_c + s(t) e^{j\omega_{sc} t}] e^{j\omega_c t} \quad (2)$$

It can be shown that $y(t) = E_c + s(t) e^{j\omega_{sc} t}$ is a minimum phase signal when $f_{sc} \geq$ electrical message bandwidth B_{me} and E_c is large enough compared the peak of

$|s(t)|$ [10]. In this case KK receiver can be used to detect the message with negligible SSBI.

3. Performance Investigation of SSB KK-based DD Optical Networks

Two SP SSB/DD point-to-point networks are implemented in VPIphotonics environment to deliver 200 and 400 Gbps data rates in the C band ($\lambda \approx 1550$ nm). 16-QAM signaling is used for the electrical SSB QAM modulator. The KK algorithm is implemented in the receiver side to retrieve the complex data phase from the photocurrent. The main system parameters are listed in Table 1.

3.1. Performance of 200 Gbps SSB SCM 16-QAM System

Figures 2a-d show signal spectra at different points of the system. The corresponding received constellation diagram is depicted in Fig. 2e. The system is simulated for a single-span transmission link (i.e., $L = 80$ km) using $P_s = 6$ dBm, $r = 0.01$, CSRP = 12 dBm, $f_{sc} = 25.5$, and OBPF bandwidth = 60 GHz. Figure 2a shows the spectrum of the generated electrical SSB QAM signal and the figure indicates that this signal has 50 GHz-bandwidth ($\approx (1+r)R_s$). Note further that the constellation diagram is clear which ensures a low BER ($BER=3.1 \times 10^{-5}$).

Table 1. Values of the main system parameters used in the simulation

Parameter	Symbol	Value
Laser frequency	f_c	193.1 THz
Signal power launched to the fiber	P_s	6 dBm
Booster amplifier gain		16 dB
Booster amplifier noise figure		5.5 dB
RF subcarrier frequency	f_{sc}	25.5 GHz for 200 Gbps 51 GHz for 400 Gbps
SMF span length	L_s	80 km
OBPF central frequency *		193.13 THz for 200 Gbps 193.15 THz for 400 Gbps
OBPF bandwidth		60 GHz for 200 Gbps 120 GHz for 400 Gbps
Carrier-to-signal power ratio	CSRP	12 dB
Raised-cosine filter roll-of-factor		0.01
MZM	Extinction ratio	50 dB
	V_{PI}	5 V

* OBPF central frequency = $f_c +$ RF subcarrier frequency).

The CSRP is controlled by the MZM offset voltage. The investigation reveals that the CSRP increases linearly with the MZM predistortion DC offset voltage (see Fig. 3). An

offset voltage of 0.86 V produces a 12 dB CSPR.

A parametric study is also conducted to address the effect of system parameters on the BER performance. The results can be used as a guideline to choose the parameters values that optimize the BER characteristics. Figures 4a-c illustrate the effect of carrier-to-signal power ratio CSPR, optical power launched to the fiber P_s , and subcarrier frequency f_{sc} , respectively. A 80 km-SMF transmission link is used to produce the simulation results. Investigation the results in these figures highlights the following findings

- (i) Figure 4a indicates that a minimum BER of 1.6×10^{-5} is achieved when $\text{CSPR} = 11$ dB. Increasing CSPR further toward 14 dB will increase the BER slightly ($\text{BER} \approx 3.1 \times 10^{-5}$). Keeping the BER less than BER_{th} requires $8 \text{ dB} < \text{CSPR} < 17 \text{ dB}$.
- (ii) The BER performance does not affected by signal launched power to the fiber when it is less than 12 dBm. Increasing P_s beyond 12 dBm increases sharply the BER due to fiber nonlinear optics. The BER exceeds the BER threshold level when $P_s > 13.5$ dBm.
- (iii) The BER exceeds the threshold level when the RF subcarrier frequency ≥ 32 GHz. It should be stated here that using $f_{sc} < 25$ GHz affects strongly the system performance leading to a $\text{BER} \approx 0.5$.

Figure 5 depicts the variation of BER with the length of the transmission links. The results reveal that a maximum reach of 360 km can be achieved using the design parameters listed in Table 1.

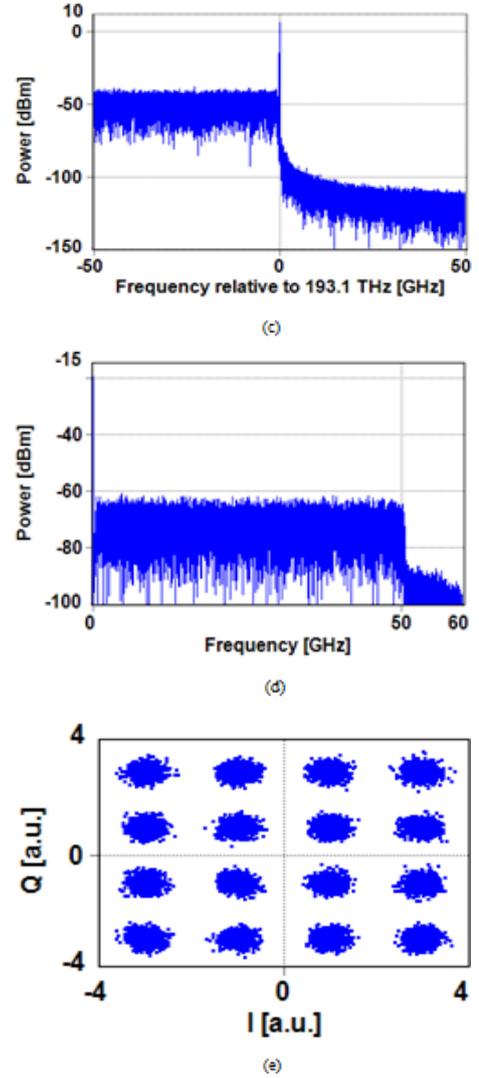
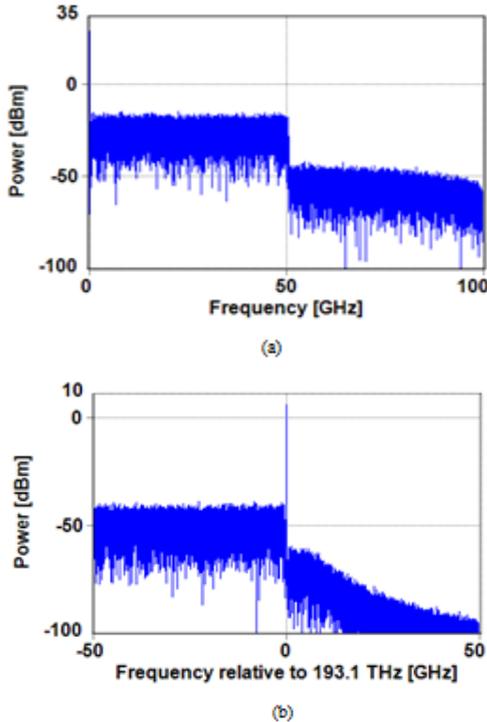
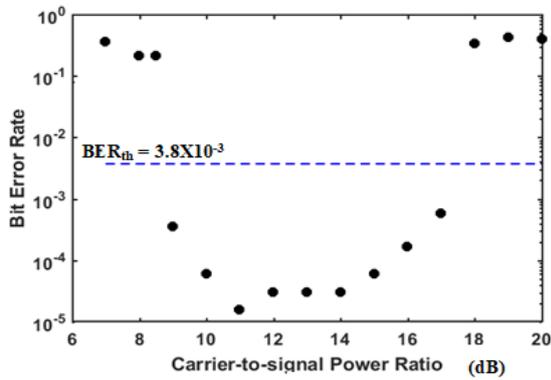
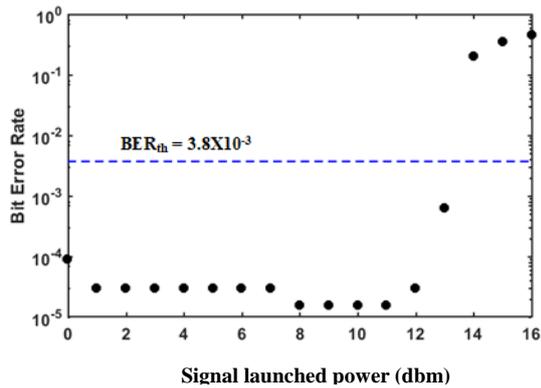


Figure 2. Spectra and received constellation diagram of SP 200 Gbps SSB SCM 16-QAM system. (a) Spectrum of the electrical SSB QAM signal. (b) Spectrum after fiber transmission. (c) Spectrum of the optical signal at transmitter output. (d) Spectrum of the electrical photocurrent. (e) Constellation diagram at the DSP output

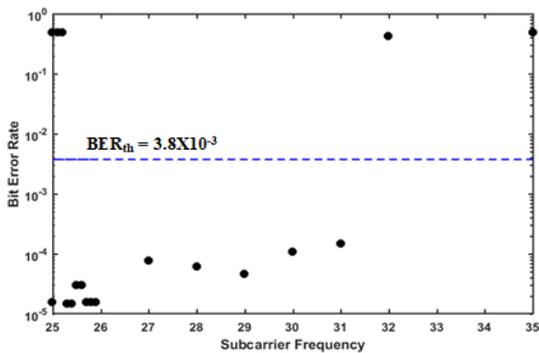
Figure 3. Variation of carrier-to-signal power ratio with MZM voltage



(a)



(b)



(c)

Figure 4. Variation of BER of SP 200 Gbps SSB SCM 16-QAM system with (a) Carrier-to-signal power ratio. (b) Signal launched power. (c) Subcarrier frequency

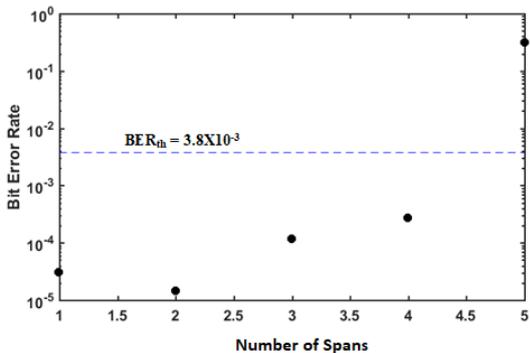
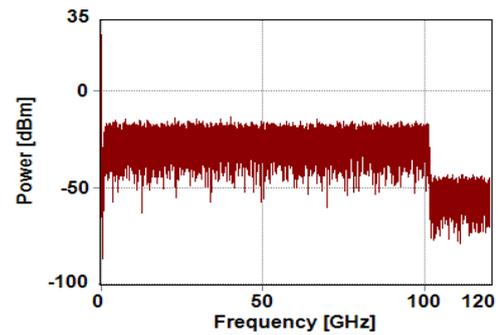


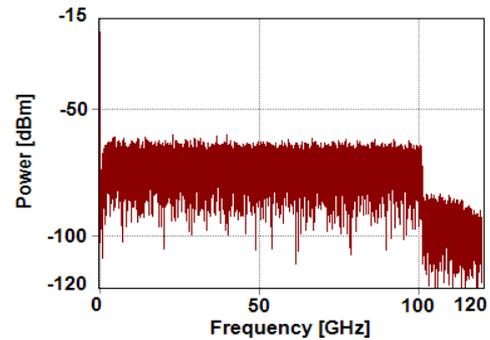
Figure 5. Variation of BER of SP 200 Gbps SSB SCM 16-QAM with transmission distance measured by numbers of 80 km SMF span

3.2. Performance of 400 Gbps SSB SCM 16-QAM System

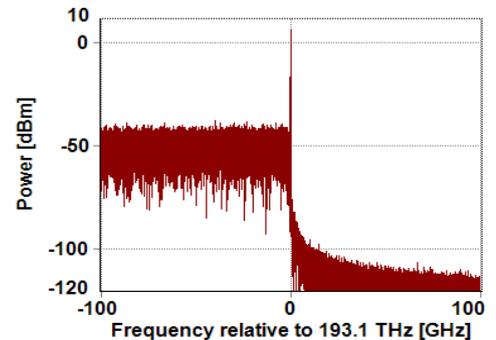
This subsection addresses the transmission performance of 400 Gbps 16-QAM system designed with SSB modulator and KK algorithm-based DD receiver. The system is implemented in VPIphotonics environment using the following parameters: $P_s = 6$ dBm, $r = 0.01$, CSRR = 12 dB, and $f_{sc} = 51$ GHz. For comparison purposes, the values of P_s , r , and CSRR are kept as in the 200 Gbps counterpart. Figures 6a-e show the spectra of the signals at different points of communication system in addition to the received constellation diagram. A single 80 km-SMF span is used to construct the transmission link. Figure 6a shows the spectrum of the generated the electrical SSB signal. The bandwidth of this signal is 100 GHz and it is in accord with the expected value of $(1+r)R_s$ where $R_s=100$ Gbps for the 400 Gbps 16-QAM signaling. The received constellation diagram (Fig. 6e) is clear and leads to a BER of 1.1×10^{-4} ($< BER_{th} = 3.8 \times 10^{-3}$).



(a)



(b)



(c)

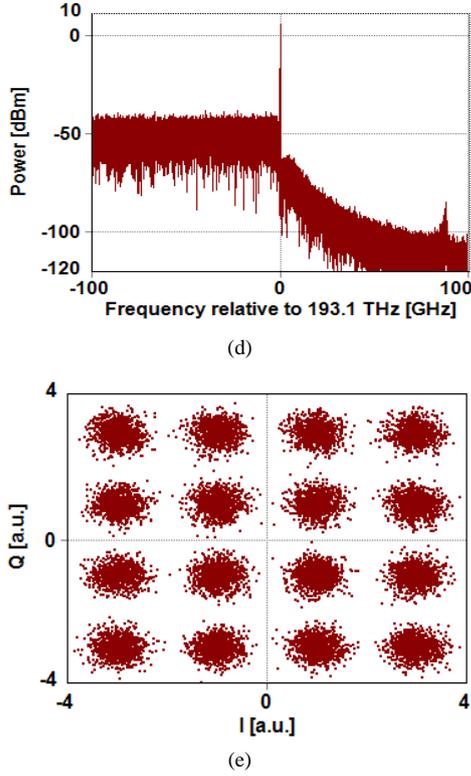


Figure 6. Spectra and received constellation diagram of SP 400 Gbps SSB SCM 16-QAM system. (a) Spectrum at the electrical SSB QAM signal. (b) Spectrum at the fiber input. (c) Spectrum of the optical signal at transmitter output. (d) Spectrum of the electrical photocurrent. (e) Constellation diagram at the DSP output

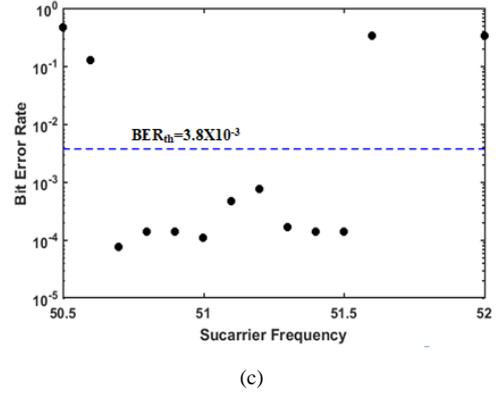
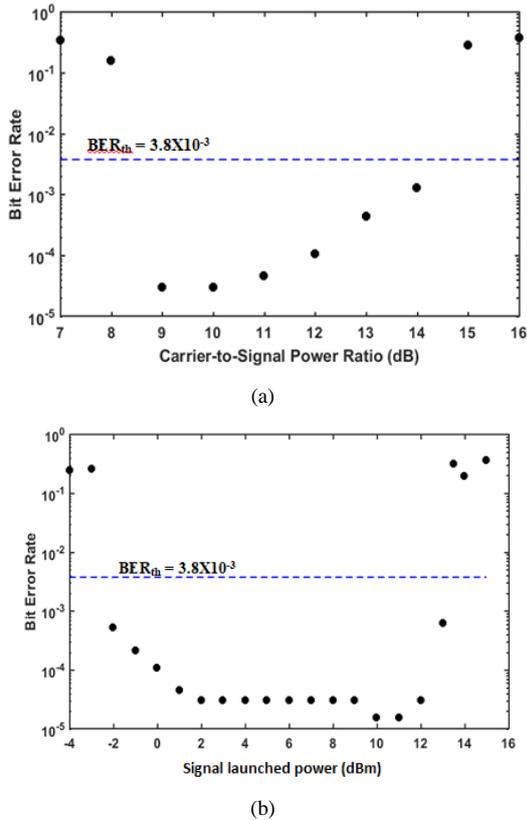


Figure 7. Variation of BER of SP 400 Gbps SSB SCM 16-QAM system with (a) Carrier-to-signal power ratio. (b) Signal launched power. (c) Subcarrier frequency

Parametric study is also conducted for this system and the results are presented in Figs. 7a-c. In these figures, the dependence of BER on CSPR, launched signal power P_s , and subcarrier frequency are presented, respectively, for a single-span link. The following conclusions can be drawn from the results in these figures

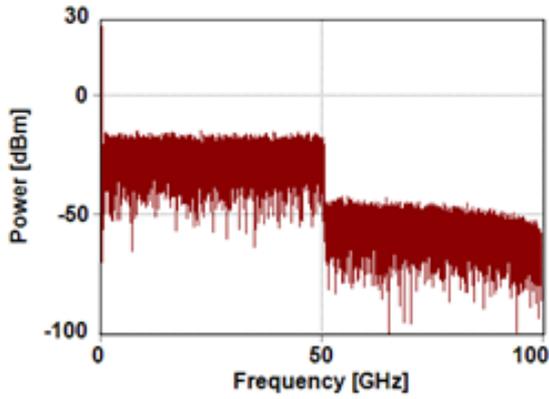
- (i) A minimum BER of 3.1×10^{-5} is obtained when the CSPR is between 9 and 10 dB. Further, a $BER > BER_{th}$ is obtained when the $14 \text{ dB} < \text{CSPR} < 8.5 \text{ dB}$.
- (ii) The BER is almost independent on launch power when $2 \text{ dBm} < P_s < 12 \text{ dBm}$. The BER exceeds the threshold when $P_s < -2 \text{ dBm}$ (due to reduced launch power) and when $P_s > 13 \text{ dBm}$ (due to nonlinear fiber optics).
- (iii) Low BER (less than BER_{th}) occurs when $50.7 \text{ GHz} < f_{sc} < 51.5 \text{ GHz}$.

The effect of transmission length on BER performance is also investigated and the results yield BER of 1.1×10^{-3} and 5.1×10^{-4} after one and two spans, respectively.

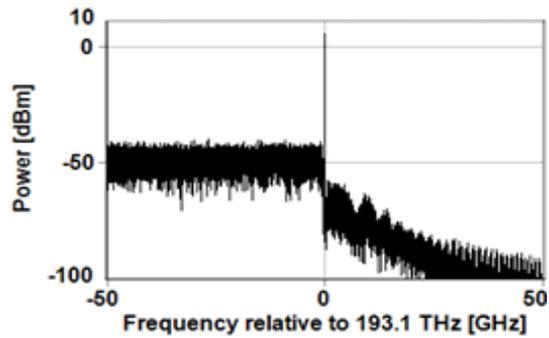
3.3. Design and performance Evaluation of Dual-Polarization SSB/DD Systems

The results reported in subsections 3.1 and 3.2 are used as a guideline to design DP counterparts carrying 400 and 800 Gbps, respectively. The DP system is designed using two identical subsystems sharing the same transmission link. Each of the two subsystems is designed for one of two perpendicular states of polarization. A single laser with 45° polarization angle to deliver two equal power-polarization components TE and TM (or X and Y).

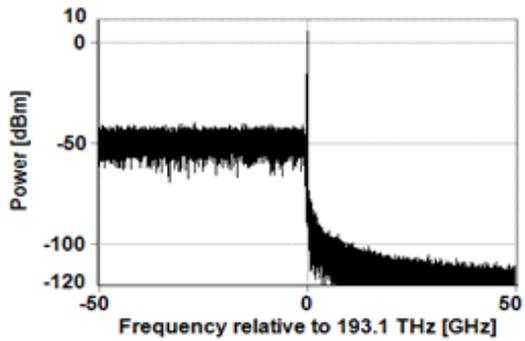
Figure 8 shows the DP simulation results corresponding to the DP 400 Gbps system operating with $L = 80 \text{ km}$. Note that both polarization systems offer almost identical results. The same conclusion can be drawn for the DP 800 Gbps system as shown in Fig. 9.



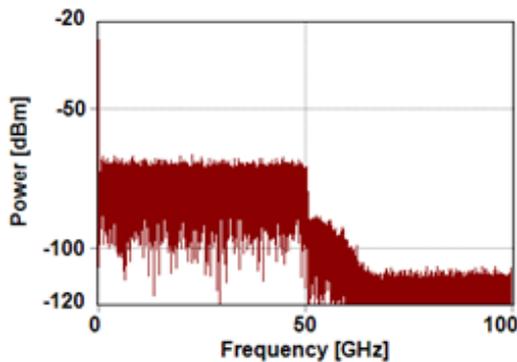
(a) Spectrum of the electrical SSB QAM signal.



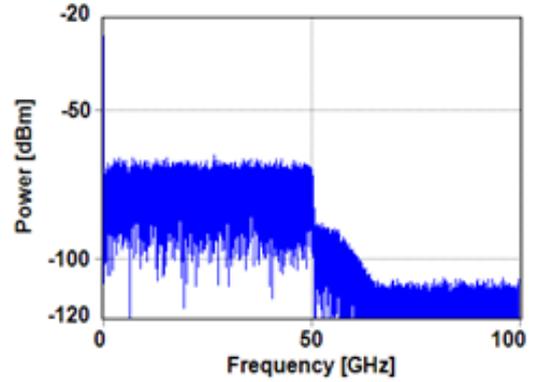
(b) Spectrum of the optical signal at transmitter output.



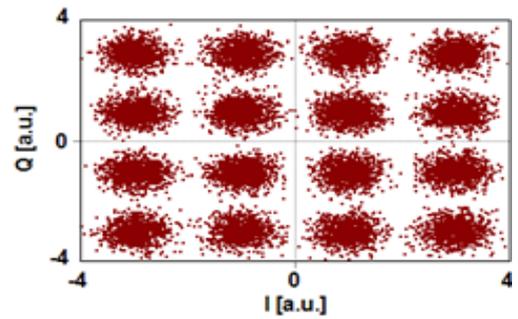
(c) Optical signal after fiber transmission.



(d) Spectrum of the electrical photocurrent for (TE).

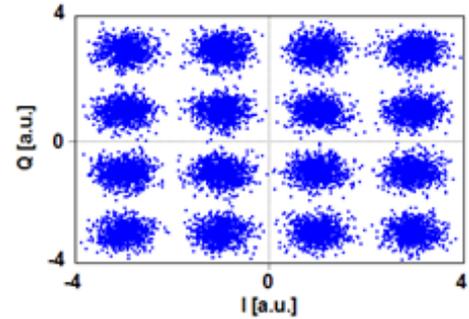


(e) Spectrum of the electrical photocurrent for (TM).



(f) Constellation diagram at the DSP output

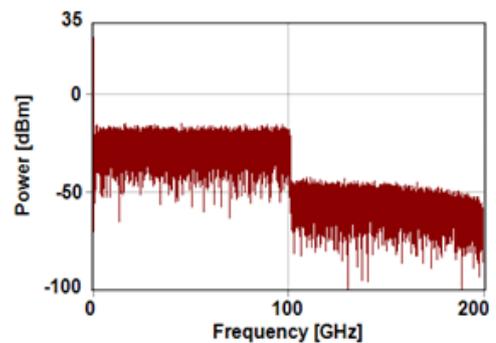
for (TE).



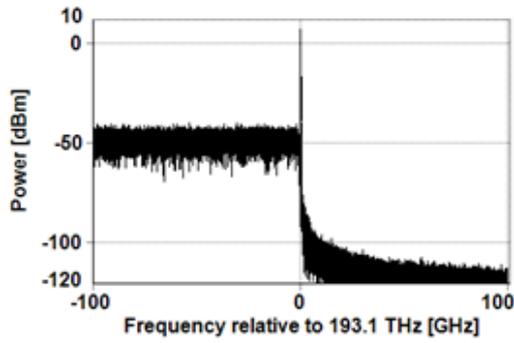
(g) Constellation diagram at the DSP output

for (TM).

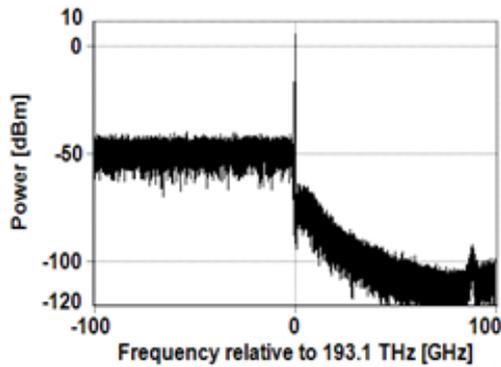
Figure 8. Spectra and constellation diagrams of DP 400 Gbps SSB SCM 16-QAM system



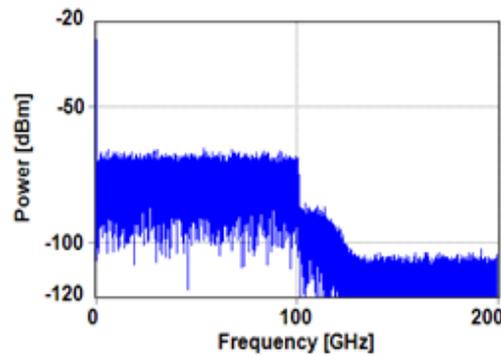
(a) Spectrum of the electrical SSB QAM signal.



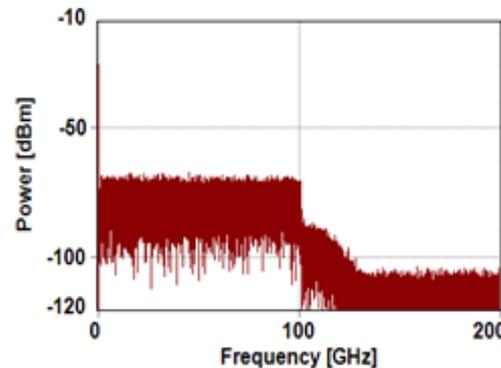
(b) Optical signal after fiber transmission.



(c) Spectrum of the optical signal at transmitter output.



(d) Spectrum of the electrical photocurrent for (TE).



(e) Spectrum of the electrical photocurrent for (TM).

Figure 9. Spectra of DP 800 Gbps SSB SCM 16-QAM system

4. Conclusions

A point-to-point optical network configuration has been designed using single-sideband (SSB) coherent modulation/KK direct detection schemes to support single-polarization (SP) 200 and 400 Gbps 16-QAM signaling. The design has been modified to double the transmission bit rates (400 and 800 Gbps) using dual-polarization (DP) multiplexing technique. The configuration uses a single laser at transmitter side and Kramers-Kronig algorithm to retrieve the complex phase of the received optical signal data from the photocurrent using Hilbert transform. In addition, DSP-based electronic chromatic dispersion is implemented at the receiver side. The main conclusions drawn for this study are

- (i) The configuration supports the transmission of SP 400 Gbps 16-QAM (DP 800 Gbps 16-QAM) signal over more than 100 km SSMF.
- (ii) The configuration is relatively less cost and more robust than configuration that uses two lasers since it uses a single laser at the transmitter.
- (iii) The KK-based receiver offers efficient direct-detection process for a single-sideband coherent-modulated optical signals operating at these high-bit rates.
- (iv) The configuration offers 360 and 180 km, maximum reach for SP 16-QAM signals operating with 200 and 400 Gbps data rates, respectively, when the second configuration is used.
- (v) There is an optimum value for the carrier-to-signal power ratio, $CSPR_{opt}$, of 12 and 12 dB when 200 and 400 Gbps SP 16-QAM signals are transmitted over a single span (80 km) of SSMF, respectively.

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