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# 6.4 Tb/s (32 × 200 Gb/s) WDM direct-detection transmission with twin-SSB modulation and Kramers–Kronig receiver

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We experimentally demonstrate 6.4 Tb/s wavelength division multiplexed (WDM) direct-detection transmission based on Nyquist twin-SSB modulation over 25 km SSMF with bit error rates (BERs) below the 20% hard-decision forward error correction (HD-FEC) threshold of $1.5 \times 10^{-2}$. The two sidebands of each channel are separately detected using Kramers–Kronig receiver without MIMO equalization. We also carry out numerical simulations to evaluate the system robustness against I/Q amplitude imbalance, I/Q phase deviation and the extinction ratio of modulator, respectively. Furthermore, we show in simulation that the requirement of steep edge optical filter can be relaxed if multi-input–multi-output (MIMO) equalization between the two sidebands is used.



## 1. Introduction

With the growing demand for ultra-high-speed transmission solution to data center interconnection as well as metro networks, direct-detection (DD) has been attracting more and more attention due to its lower cost and easier integration compared with coherent detection system. For intensity modulation and direct detection (IM–DD) systems, the negative frequency and the positive frequency sidebands of the signal spectrum are conjugate symmetric, while the phase delay induced by chromatic dispersion (CD) is the same for both sidebands. After square-law detection of the DD receiver, the power fading effect is caused by the interference of the two sidebands, which would be a major limit to the transmission distance and capacity [1]. To overcome this problem, single-sideband (SSB) subcarrier modulation (SCM) [2] is proposed to remove one of the two sidebands using digital Hilbert transformation.

One shortcoming of the SSB system, however, is that it wastes half bandwidth of digital-to-analog convertor (DAC) at transmitter side since it has only one sideband of information. Hence, twin-SSB system, where two groups of different signals are modulated onto the left-sideband (LSB) and right-sideband (RSB) respectively, is proposed to make full use of the DAC bandwidth [3–6]. From another point of view, the twin-SSB scheme can also be understood as two independent SSB signals sharing the same carrier together. Therefore, the twin-SSB signal can achieve higher spectral efficiency by saving half of the guard spacing, and require lower launch power by saving half of the carriers in SSB wavelength division multiplexed (WDM) systems. Nevertheless, the corresponding cost is 3 dB degradation of receiver sensitivity since signal splitting is needed at the receiver to duplicate the shared carrier for both sidebands.

Another disadvantage of SSB system is the signal–signal beat interference (SSBI) caused by the square law detection of photodiode (PD) [7]. Among the recently proposed SSBI cancellation schemes [7–9], the Kramers–Kronig (KK) receiver has shown its superiority to reconstruct the complex optical field of the SSB signal from its amplitude waveform, once the minimum phase condition is satisfied [9]. In this way, the power ratio of the SSB signal compared to the carrier can be increased, and the optical signal-to-noise ratio (OSNR) margin will accommodate more wavelength channels.

In this paper, we experimentally demonstrate 32-channel 16-ary quadrature amplitude modulation (16-QAM) twin-SSB Nyquist-SCM WDM signal generation with 65 GHz channel spacing and over 25 km transmission with direct detection. The two sidebands of each channel are separately detected without multi-input–multi-output (MIMO) equalization. The gross bitrate is up to 6.4 Tb/s (200 Gb/s × 32) with 200 Gb/s (25 Gbaud × 4 × 2) per channel. The net data capacity is 5.20 Tb/s with 162.6 Gb/s per channel with consideration of frame redundancy and 20% hard-decision forward error correction (HD-FEC) overhead. Signal–signal beat interference (SSBI) is compensated with the KK receiver. In addition, the impact of the imaginary crosstalk caused by I/Q gain imbalance, I/Q phase derivation, and the modulator extinction ratio (ER) are investigated, respectively. To suppress the

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residual crosstalk after optical filtering, the requirement of the filter edge roll-off can be relaxed after applying MIMO equalization.

The remainder of this paper is organized as follows. In Section 2, the generation and reception of twin-SSB signal are introduced together with DSP flows and experimental setup. Section 3 presents the experiment results. The impact of two kind crosstalk in twin-SSB system are evaluated in Section 4. Finally, conclusions are drawn in Section 5.

## 2. DSP stack and experimental setup

### 2.1. DSP stack

The diagram of the DSP is shown in Fig. 1(a)–(b). At the transmitter, the bit stream is mapped to 16-QAM first. After up-sampling, the signal is digitally shaped using root raise cosine (RRC) filter with a roll-off factor of 0.01. The preamble includes two 64-symbol synchronization sequences and four 128-symbol training sequences. 25 600 data symbols are transmitted after the preamble. The structure of the transmitted signal frame is shown in Fig. 1(c). Therefore, the net bit rate of a single channel can be calculated as 162.6(=200 Gb/s/1.2/26240 × 25600) Gb/s with consideration of both frame redundancy and 20% HD-FEC overhead. To suppress the residual crosstalk from the opposite sideband, a guard band should be set based on the edge roll-off of the optical filter. Larger guard band will degrade the signal quality due to the limited bandwidth of the IQ modulator. In our scheme, 3 GHz guard band is chosen. Therefore, the frame is then up-converted by a subcarrier ($F_c$) with the frequency 0.62 times to the symbol rate ($F_s$). A digital Hilbert filter is applied to remove the RSB and the LSB of two individual up-converted signals, respectively. Then the filtered signals are combined and down-sampled. At the receiver, the signal is firstly re-sampled to $4 \times F_s$ to confirm the performance of the KK receiver [10]. After the KK receiver, the signal is down-converted and matched filtered. After synchronization, the signal is equalized with a $T_s/4$ ($T_s$ means the symbol time period) spaced training sequence based time domain equalization. A finite impulse response (FIR) filter is extracted from the training sequence with the taps updated by the recursive least square (RLS) algorithm. The FIR filter is subsequently used to equalize the data. Then a $T_s$ spaced decision-directed RLS filter is respectively used to improve the signal quality tracing the time-varying channel response, whose cost function is constructed by the distance between the filtered symbol and the nearest points in the 16-QAM constellation. Finally, the bit error rate (BER) is calculated by error counting based on measuring a total of $\sim 5 \times 10^6$ bit samples. It should be noted that no electronic CD compensation is applied for the transmission distance of 25 km in our experiment.

Fig. 1(d) shows the detail of the KK receiver. To emulate the direct component (DC) of the carrier that is blocked by the electrical amplifier (EA) after the photodiode (PD), we first add a real number $C$ to the received signal $I(t)$. Then the amplitude of the optical field is recovered by square root operation. As shown in Eq. (1), the phase $\varphi(t)$ of the optical field is reconstructed as a Hilbert transform pair of the logarithm of the amplitude. Finally the complex optical field $E'(t)$ is recovered by the multiplication of the amplitude and the phase as in Eq. (2). Before proceeding to the next DSP stage, the DC term are removed by the mathematical expectation operation *mean* $\{\cdot\}$ as in Eq. (3).

$$\varphi(t) = \frac{1}{\pi} p.v. \int_{-\infty}^{\infty} dt' \frac{\ln \sqrt{I(t') + C}}{t - t'}. \quad (1)$$

$$E'(t) = \sqrt{I(t) + C} \exp[i\varphi(t)]. \quad (2)$$

$$E(t) = E'(t) - mean\left\{E'(t)\right\}. \quad (3)$$

### 2.2. Experimental setup

Fig. 2 shows the experimental setup of the WDM Nyquist twin-SSB-SCM transmission system. At the transmitter, 32 WDM channels spaced at 65 GHz frequency grid are sourced by 32 external cavity lasers (ECLs), which are coupled by two 16 × 1 polarization-maintain couplers (PMCs) and a cascaded 2 × 1 PMC. The line-width of each laser is ∼100 kHz. An arbitrary waveform generator (Keysight M8196A) operating at 92 GSa/s generates 25 Gbaud 16-QAM Nyquist twin-SSB-SCM signals. The signals drive the IQ-modulator to generate the optical twin-SSB channels. It should be noted that decorrelation between different wavelengths channels is not needed, since each neighboring sideband carries different information. The bandwidth of the AWG is 32 GHz and the IQ modulator is 25 GHz. The IQ modulator is biased above the null point to provide a direct-current (DC) component for the optical carrier. Before launched into a 25 km SSMF link, a polarization-maintaining erbium-doped optical fiber amplifier (PM-EDFA) is used to adjust the launch power. At the receiver side, the signal is first split into two copies for LSB and RSB detection, respectively. Two optical filters (Yenista Optics XTM-50) are used to select each desired sideband before detection. The signals are respectively detected by two PDs with 50 GHz bandwidth and subsequently amplified by an EA with 50 GHz bandwidth. The electrical signals are sampled by a real-time digital storage oscilloscope (Keysight DSA-X 96204Q) operating at 160 GSa/s to perform off-line digital signal processing (DSP). In our experiment, the LSB/RSB are separately processed without MIMO equalization.

## 3. Experimental results

There are two kinds of crosstalk in twin-SSB systems [4]. One is the imaginary crosstalk caused by the mismatch of I/Q response of the modulator, and the other is the residual crosstalk from the opposite sideband after optical band-pass filter (OBPF) with unideal edge.

We first investigate the influence of the imaginary crosstalk in the twin-SSB signal generation. As shown in Fig. 3(a), we measure the optical spectrums of LSB/RSB and twin-SSB signal at the transmitter with 0.01 nm resolution, respectively. The imaginary noise is successfully suppressed to ∼20 dB lower than the SSB signal for both sidebands. In this way, similar BER performance between the LSB/RSB are ensured. The optical spectrum of OBPF at the receiver is shown in Fig. 3(b), which has an edge roll-off of 800 dB/nm. Fig. 3(c) shows the measured optical spectrums of 32-channel WDM signal at the transmitter, before OBPF, and filtered LSB/RSB, respectively. A gain tilt can be observed in the spectrum before OBPF, which is caused by the EDFA at the receiver side. Fig. 3(d) shows the details of the dashed region in Fig. 3(c). The filtered LSB and RSB curves are measured after the OBPF, which confirms that most of the uninterested sideband has been removed, leading to low residual filtering crosstalk. The lower amplitude of filtered spectrum is owing to the insertion loss of the OBPF.

Fig. 4(a) shows the BER of LSB/RSB versus total launch power with/without the KK receiver after 25 km SSMF WDM transmission, respectively. The carrier-to-signal power ratio (CSPR) is defined as a ratio between the power of carrier and the aggregate power of LSB and RSB as in Eq. (4). In our experiment, the CSPR is fixed as 8 dB to ensure the minimum phase condition. The BER decreases and becomes flat at 16 dBm launch power. The BERs of LSB and RSB can be reduced from $4.3 \times 10^{-2}$ and $4.4 \times 10^{-2}$ to $1.0 \times 10^{-2}$ and $9.9 \times 10^{-3}$, respectively. Fig. 4(b) shows LSB/RSB BERs of all the 32 channels with/without the KK receiver. The lower BERs of long wavelength channels results from the gain tilt of EDFA, which agrees well with Fig. 3(b). Fig. 3(c)–(f) displays the typical constellations with/without the KK receiver for LSB/RSB of the 16th wavelength at 16 dBm launch power after 25 km transmission. It should be noted that the KK receiver is a digital linearization algorithm for SSBI mitigation, and the comparison is performed without changing system configuration. We can find that the constellation points become more concentrated with the KK receiver.

$$CSPR(dB) = 10 \cdot \log 10 \frac{P_{carrier}}{P_{LSB} + P_{RSB}}. \quad (4)$$