Coherent Self-superposition aided SSB Nyquist 16QAM Synthesis from Twin-SSB Nyquist QPSK with Reduced DAC Resolution Requirement

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Abstract: An FWM-based coherent self-superposition technique is proposed and demonstrated to synthesize 12.5-Gb/s SSB Nyquist 16QAM from Twin-SSB Nyquist QPSK, which effectively relaxes DAC resolution requirement. An equalization algorithm is also proposed for such approach's detection.

1. Introduction

Recently, the optical communications field is witnessing the revival of interest in direct-detection (DD) receivers, which are often viewed as a promising simple and low-cost alternative to their coherent counterparts, especially in the short- and intermediate-reach applications (≤ 800 km). Single-sideband (SSB) signaling with DD exhibits good tolerance to the dispersion-induced power fading and higher spectral efficiency than double sideband (DSB) formats. The recent development of digital linearization techniques such as signal-signal beating interference (SSBI) cancellation and Kramers-Kronig algorithm [1-2] provide effective ways to compensate for the linear optical effects such as chromatic dispersion at the receiver side even with DD reception, making SSB-DD more attractive. To further improve the spectral efficiency, Nyquist pulse-shaping is usually applied when generating SSB quadrature amplitude modulation (QAM) signals. However, the generation of high-order SSB Nyquist QAM signals always brings the higher resolution requirement, i.e. effective number of bits (ENOB), for digital-to-analogue converters (DACs) in the transmitter.

In this paper, through optical subcarrier processing (OSP) based coherent self-superposition, subcarriers in a twin-SSB Nyquist QPSK signal are coherently merged for synthesizing SSB Nyquist 16QAM signal. To detect the synthesized SSB 16QAM Nyquist signals, a hierarchical blind phase search (HBPS) algorithm is proposed to combat the possible distortions caused by the imperfect phase offset between two original QPSK subcarriers in the twin-SSB signal. In this work, we experimentally demonstrate the synthesis of a 12.5 Gb/s SSB Nyquist 16QAM signal from a 2×6.25 Gb/s twin-SSB Nyquist QPSK.

2. Operation Principle

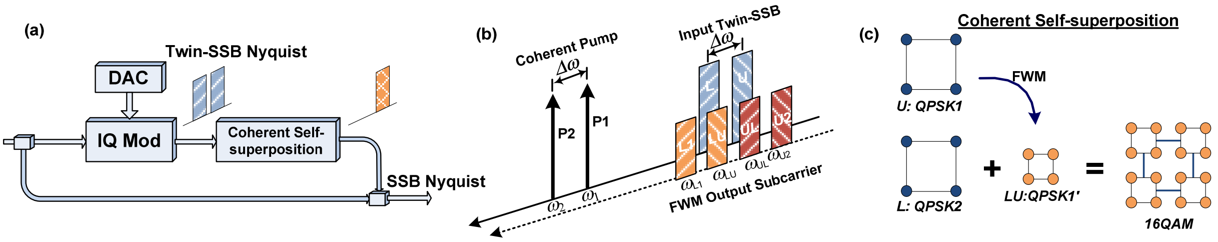

Fig. 1. (a) Operation principle of the OSP-aided SSB Nyquist QAM generation; (b) FWM-based coherent self-superposition; (c) High-order QAM generation based on the coherent self-superposition.

Figure 1(a) illustrates the operation principle of the proposed OSP-aided SSB Nyquist higher-order QAM generation scheme from a twin-SSB lower-order QAM. An in-phase/quadrature (IQ) modulator is first deployed to synthesize a twin-SSB signal with independent data in the lower and upper sidebands and lower modulation orders. The following OSP-based coherent self-superposition is then deployed to merge two subcarriers with a desired coupling ratio and phase difference, thus generating an SSB-Nyquist higher-order QAM subcarrier with an increased modulation order. By combining with a CW optical carrier, the SSB-Nyquist higher-order QAM can be finally obtained. In the proposed scheme, the electric-optic (EO) approach is deployed to synthesize lower-order QAM subcarriers. The followed OSP is used to coherently superpose the subcarriers for the high-order QAM generation. Therefore, it effectively releases the resolution requirement for the DAC compared with the conventional EO approach.

As the key processing unit in the synthesis, the OSP, coherent self-superposition, could be implemented by either second-order or third-order nonlinearities. It has been demonstrated to perform the data aggregation [3, 4]. Herein, four-wave mixing (FWM) in highly-nonlinear fiber (HNLF) is deployed for fulfilling the data aggregation. As shown in Fig. 1(b), a coherent two-carrier light (ω_1 and ω_2 with a $\Delta\omega$ spacing) serves as pump in FWM, while the twin-SSB Nyquist signal (ω_S), consisting of lower (L) and upper (U) sidebands with a separation of $\Delta\omega$, acts as an input signal. Once the phase matching condition is satisfied, the replicas denoted in orange and red in Fig. 1(b) are generated alongside the input signal with lower and upper sidebands (L1 and U1, L2 and U2). Since the two-carrier pump and twin-SSB have the same carrier separation ($\Delta\omega$), the generated upper sideband (U1) and lower sideband (L2) overlap with the lower (L) and upper (U) sidebands, respectively. Owing to the coherence between two carriers in the pump, the spectrum overlapping leads to a coherent superposition between the upper and lower subcarriers, resulting in a self-superposition between upper and lower subcarriers. In this process, the subcarriers are first replicated through FWM, and then, with the identical spacing between subcarriers in twin-SSB and coherent pump carriers, the subcarriers are coherently superposed. As illustrated in Fig. 1(c), if the upper and lower subcarriers are encoded in independent QPSK formats, after adjusting the coupling ratio and relative phase difference properly, through the vector addition enabled by the coherent self-superposition, a high-order QAM, i.e. 16QAM, could be finally synthesized. The coupling ratio could be adjusted by tuning the conversion efficiency in FWM, while the relative phase difference could be changed by manipulating the phase difference between two carriers of the pump. It should be noted that, such approach can significantly relax the required DAC's ENOB in the generation of high modulation formats, thus may lead to significant power and cost reductions.

3. Experimental Setup and Results

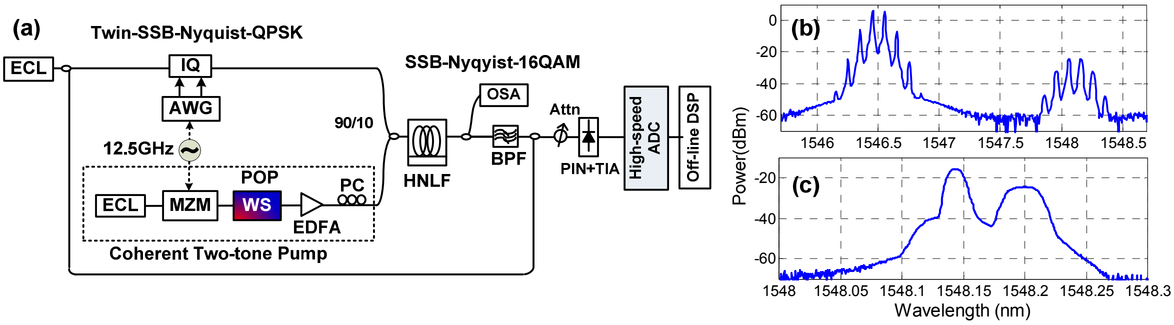

Fig. 2. (a) Experimental setup; (b) Measured optical spectrum after HNLF; (c) Measures optical spectrum of the synthesized SSB Nyquist 16QAM.

To validate the proposed synthesis scheme, an experiment was carried out to generate a 12.5 Gb/s SSB Nyquist 16QAM from a 2×6.25 Gb/s twin-SSB Nyquist QPSK with DD reception based on the proposed OSP-aided synthesis approach. Figure 2(a) shows the experimental setup. Light from an external cavity laser (ECL, 1548.1 nm) served as the laser source. A portion of the power was fed to an IQ modulator to generate a twin-SSB Nyquist QPSK signal at 2×6.25 Gb/s. Each nested Mach-Zehnder modulator (MZM) in the IQ modulator was biased at the null point and driven by signals from two arbitrary waveform generators (AWGs, Tek70001a) to generate a twin-SSB Nyquist QPSK signal at 2×6.25 Gb/s with a spacing of 12.5 GHz. Light from another ECL (1546.5nm) was modulated by a dual-drive MZM driven by a 12.5 GHz RF clock to first generate an optical comb with a 12.5 GHz line spacing. The followed programmable optical processor (POP, e.g. WaveShaper) based on liquid crystal on Silicon (LCoS) was deployed to pick up two comb lines to generate a two-carrier coherent pump for the OPS-based coherent self-superposition. After the power amplification, the two-carrier coherent pump was fed to a piece of HNLF together with the twin-SSB QPSK. To ensure the equal spacing between symbols in the resultant constellation without introducing any distortions, it is crucial to optimize the operating conditions in the OPS-based data aggregation. The phase difference between two pump carriers and the launched pump power, influencing the relative phase angle and the coupling ratio between the two QPSK sidebands in the data aggregation, respectively, should be well managed. The phase difference between two pump carriers could be adjusted by manipulating the phase profile of the pump by configuring the POP. The HNLF has a length of 150 m, attenuation coefficient of 0.9 dB/km, nonlinear coefficient of 18 W/km, zero-dispersion wavelength of 1548 nm, and dispersion slope of around 0.02 ps/nm^2/km. Figure 2(b) shows the measured optical spectrum after the HNLF with a launched pump power of 23 dBm and a signal power of -5.7 dBm. After the OSP-based coherent self-superposition, the synthesized Nyquist 16QAM data subcarrier at 1548.2 nm, corresponding to ω_{UL} in Fig. 1(b), was picked up by an optical filter and combined with the other portion of light from the laser source to form the SSB Nyquist 16QAM signal with a carrier-to-signal power ratio (CSPR) of around 5.5 dB. The corresponding optical spectrum is shown in Fig. 2(c).

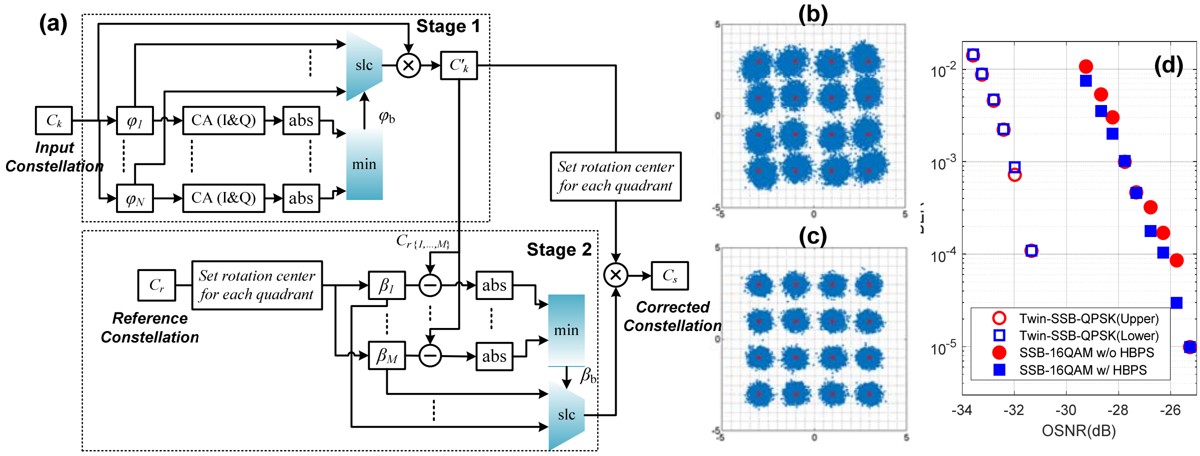

Fig. 3. (a) HBPS algorithm structure; Measured constellations before (b) and after (c) applying HBPS algorithm; Measured BER curves of the twin-SSB Nyquist QPSK and SSB Nyquist 16QAM.

To directly detect the synthesized SSB Nyquist 16QAM signal, a 20 GHz integrated optical receiver, consisting of a single photodiode (PD) and linear transimpedance amplifier (TIA), was used at the receiver side. The detected signal was then captured and digitized by a real-time storage oscilloscope operating at 50 GSa/s for offline digital signal processing (DSP) processing. Although the phase difference between two subcarriers in twin-SSB could be managed by programming the POP, the resultant 16QAM may suffer from the distortions due to an imperfect phase control. The algorithm structure of the deployed 2-stage HBPS is depicted in Fig. 3(a). The overall phase rotation of the constellation is first corrected in the first stage, while the phase offset in each quadrant (sub-QPSK) is compensated in the second stage. To figure out the proper constellation rotation angles, a reference constellation is first prepared, and a group of rotated reference constellations are obtained after applying a set of phase rotations over the original reference constellation. Then the constellation rotation angles could be decided by searching the minimum Euclidean distances between the detected symbols and the symbols in the rotated reference constellations. To evaluate the performance of the proposed algorithm, we intentionally biased the phase difference between two sidebands away from the optimal points. It led to distorted Nyquist SSB 16QAM constellations with Q factor of 16.8 dB, as shown in Fig. 3(a). After including our proposed two-stage HBPS, the compensated constellation is obtained with an improved Q factor of 19.7 dB, shown in Fig. 3(c).

To measure the bit-error rates of the input twin-SSB Nyquist QPSK and obtained SSB 16QAM, a variable optical attenuator (VOA) was placed before the receiver to adjust the received optical power (ROP) in order to measure the corresponding bit-error rates (BERs) at different ROPs. Figure 3(d) shows the measured BER curves for the input twin-SSB Nyquist QPSK and the synthesized SSB Nyquist 16QAM with error-free operations. Note that the gain of HBPS algorithm is almost negligible. This is because the phase and power ratios between two subcarriers have been well managed in the data aggregation.

4. Summary

We proposed and experimentally demonstrated a synthesis of 12.5 Gb/s SSB Nyquist 16QAM signal by coherent self-superposition from 2×6.25 Gb/s twin-SSB Nyquist QPSK with error-free operations. The demonstrated OSP-aided approach effectively relaxes the resolution requirement of the DACs in the transmitter.

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