80-GBd Probabilistic Shaped 256QAM Transmission over 560-km SSMF Enabled by Dual-Virtual-Carrier Assisted Kramers-Kronig Detection

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Abstract: We demonstrate transmission of 80-GBd probabilistic shaped 256QAM over 560-km SSMF, a record reach at 400-Gb/s line rate using single laser and direct detection, enabled by probabilistic constellation shaping and dual-virtual-carrier assisted Kramers-Kronig detection.

OCIS codes: (060.4510) Optical communications; (060.4080) Modulation

1. Introduction

In the past few years, direct detection (DD) [1-2] and self-coherent detection (SCD) [3] have attracted a lot of research interests for the short to medium reach optical networks due its simple structure, cost effectiveness and low power consumption. However, the reach for double sideband (DSB) pulse-amplitude-modulation (PAM) signal is usually very limited at 200-Gb/s or beyond data rate, because of fiber chromatic dispersion (CD) and high required optical signal-to-noise ratio (OSNR) [2]. Carrier assisted single-sideband (SSB) signal can avoid the CD induced power fading, but signal-to-signal beat inference (SSBI) is inevitable due the square-law detection of single-end photodetector (PD). To solve this problem, a technique called Kramers-Kronig (KK) receiver [4-5] has recently been proposed. Compare with conventional DD, KK has the advantage of better linearization on the optical channel by mitigating the SSBI, which means lower carrier-to-signal power ratio (CSPR) thus lower required OSNR at same BER [6]. However, KK scheme also has a few drawbacks. In addition to the extra computation complexity, KK also needs to generate and detect SSB signal, requiring much higher (≥ 2x) electrical bandwidth at both transmitter and receiver than coherent detection at the same symbol rate. In [7], a virtual-carrier assisted single-sideband (VSSB) scheme was proposed to generate SSB signal at baseband and add a RF tone as carrier using only a two-channel digital-to-analog converter (DAC). This scheme greatly simplified the transmitter structure and halved the required electrical bandwidth for transmitter, but not for receiver. In [8], 112-GBd PAM4 was successfully transmitted over 80-km standard single mode fiber (SSMF) using VSSB-KK scheme combined with IQ imbalance mitigation. Later on in [9], 90-Gbd 32QAM signal transmission over 560-km of SSMF using KK scheme was achieved, but this scheme requires two external cavity lasers (ECLs), an extremely high bandwidth (~85GHz) PD, and a high sampling rate & bandwidth (256-GSa/s, 103-GHz) digital oscilloscope (DSO). All these schemes are based on high bandwidth components. In this paper, we propose a novel dual-virtual-carrier assisted KK scheme (DVC-KK) to further relax the electrical bandwidth requirement on receiver, at the cost of additional PD. Under this novel scheme, high symbol rate signal (e.g., 80-GBd) can be generated and detected using commercial-available components with same or similar electrical bandwidth as for coherent detection. In addition, we also employed probabilistic shaped (PS-) 256QAM [10] to improve the system performance and extend reach. By combining both techniques, we have achieved transmission of 80-GBd PS-256QAM (400-Gb/s line rate, 320-Gb/s net rate) over 560-km SSMF with EDFA-only amplification.

2. Dual-Virtual-Carrier assisted Kramers-Kronig (DVC-KK) Detection

Rather than adding a single RF tone to one side of the DSB spectrum [7-8], we add two RF tones to both sides of the spectrum, and also partition the DSB spectrum into two (negative and positive) sidebands for KK detection. This process is realized by the transmitter DSP (Tx-DSP) as depicted in Fig. 1. Hilbert transform (HT) is first applied on the Nyquist filtered in-phase (I) and quadrature (Q) tributaries of QAM signal, followed by complex conjugation if it is for negative sideband (Fig. 1, (ii) and (vi)). After SSB generation, a DC offset is then added to each SSB signal to generate carrier (see (iii) and (vii)). The carrier assisted SSB signals are subsequently frequency shifted to the opposite side of the spectrum by +Δf (for negative band) and –Δf (for positive band), see (iv) and (viii), where Δf is the spacing between the two sidebands. The frequency shifted SSB signals are then recombined in time domain to form a complete DVC assisted DSB signal (see (ix)). The DVC signal is then processed for S21 compensation, and resampled to the digital-to-analog converter (DAC) sampling rate before loading to the DAC. At receiver, the DVC signal is first filtered by two optical filter served as optical de-interleaver centered on the negative and positive sideband of the signal. Each carrier bearing SSB signal is then fed into one PD for detection. The receiver DSP (Rx-DSP) first resamples the received signal to 2x Baud rate, followed by the KK algorithm[4],frequency domain equalization (FDE), adaptive time-domain equalizer (TDEQ), post equalizer (Post-EQ), QAM demodulation, and BER analysis.

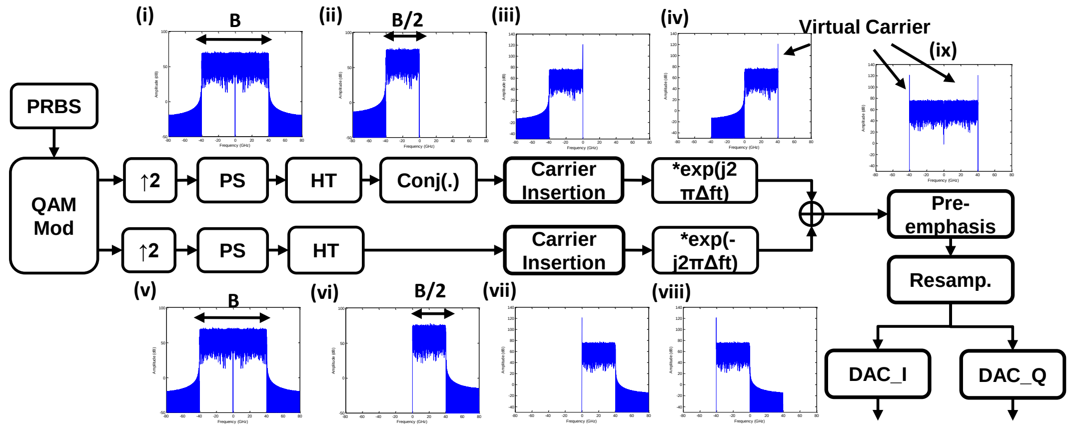

Fig. 1 Tx-DSP for DVC signal generation. Insets: signal spectrum (i)(v) after square-root-raised-cosine pulse shaping; (ii)(vi) after Hilbert transform (SSB); (iii)(vii) after virtual carrier insertion; (iv)(viii) after frequency shift; (ix) after combination. PS: pulse shaping, HT: Hilbert transform.

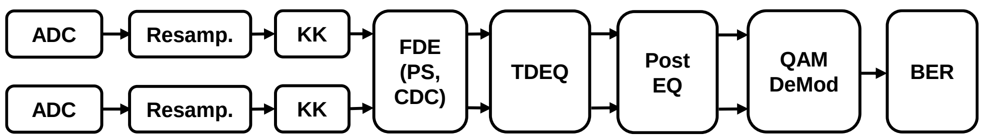

Fig. 2 Rx-DSP for DVC signal detection. PS: pulse shaping, CDC: chromatic dispersion compensation.

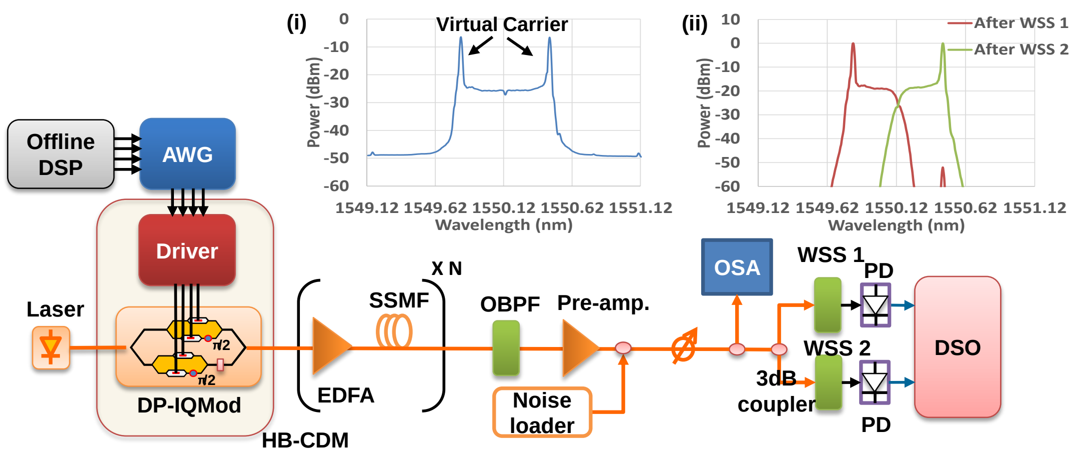

Fig. 3 Experimental setup for DVC-KK transmission. Insets: (i) Optical spectrum before receiver; (ii) optical spectra after WSS.

3. Experiment and Results

Experiment is further conducted to verify our proposed scheme. The experimental setup is shown in Fig. 3. At transmitter, an Emcore external cavity laser (ECL) operating at 1550.12 nm (193.4 THz) with 100-kHz typical line-width is used as the laser source. 32QAM and PS-256QAM (SE = 5.0 b/s/Hz) DVC signal with Baud rate B = 80Gsym/s, pulse shaping factor $\alpha = 0.01$, and sideband spacing $\Delta f = (1+\alpha)*B/2$ is first generated offline, then loaded onto a Keysight arbitrary waveform generator (AWG) with a sampling rate of 120-GSa/s. The AWG output is connected to a Neophotonics high-bandwidth coherent driver modulator (HB-CDM, $f_{3dB} > 40$GHz) biased at null point to generate optical signal. Instead of launching combined DVC signal into one polarization, we choose to launch the two SSB signals into orthogonal polarizations in order to maximize the electrical SNR due to low DAC effective number of bits (ENOB) at high frequency. It is worth noting that single-pol modulation is still possible with improved DAC ENOB. The optical signal is then launched into a fiber link consisting of 7-spans of 80-km SSMF (CD ≈ 16.65 ps/nm/km) with one EDFA per span for transmission. The average span loss is about 18.8 dB. A 200-GHz optical band-pass filter (OBPF) is placed before the pre-amplifier to eliminate out-of-band ASE noise. At receiver, the optical signal is first equally divided into two by a 3-dB coupler, each filtered by a 50-GHz wavelength selective switch (WSS) centered at 193.375 THz or 193.425 THz, and then fed into one of the two Finisar PDs (BPDV3120R, f_{3dB} =

70GHz, use one port only) for signal detection. The PD outputs are then sampled by a 160-GSa/s Lecroy digital storage oscilloscope (DSO) with 65GHz bandwidth, and finally processed offline using Matlab program.

The experimental results are shown in Fig. 4 and Fig. 5. Fig. 4shows the BER vs. OSNR curve at back-to-back (B2B) under various CSPR conditions. At 25% FEC threshold (BER = 4e-2), the optimal CSPR is 6- and 5-dB, and the required OSNR is 31.8- and 28.6-dB for 32QAM and PS-256QAM, respectively. The 3.2 dB OSNR gain by PS-256QAM is attributed to the better tolerance to Gaussian noise than 32QAM by the capacity-approaching shaping technique. Fig. 5 shows the system performance after 560-km SSMF transmission. Because the signal PAPR has significant impact on the KK performance [6] which increases with fiber CD, we applied 95% CD pre-compensation at transmitter. Fig 5 (i) shows the BER vs. launch power performance for 32QAM and PS-256QAM with CSPR ranging from 5 to 7 dB. The optimal launch power is around 8~9 dB for both modulation formats, and the optimal CSPR is about 9 dB. The minimum BER is 6.8e-2 (32QAM) and 3.85e-2 (PS-256QAM), with only the BER for PS-256QAM below FEC threshold. We choose a same system condition of CSPR = 9 dB and launch power = 9 dBm to further test the BER vs. OSNR performance after fiber transmission, and the result is shown in Fig. 5(b). Compared with back-to-back, the maximum achievable OSNR after transmission is 32 dB, and the OSNR penalty is about 2.1 dB at FEC threshold for PS-256QAM.

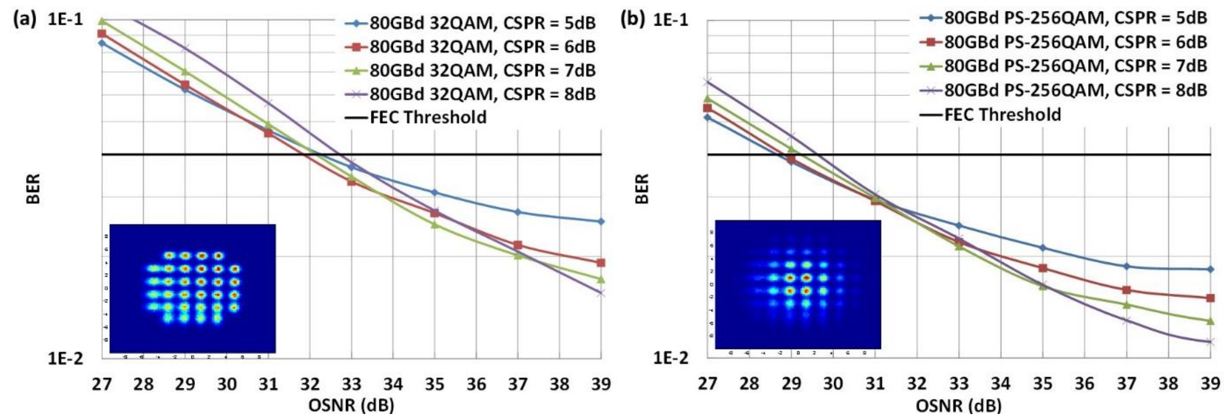

Fig. 4 BER vs. OSNR at back-to-back. (a) 80GBd 32QAM; (b) 80GBd PS-256QAM (SE = 5.0 b/s/Hz). CSPR = 5~8 dB.

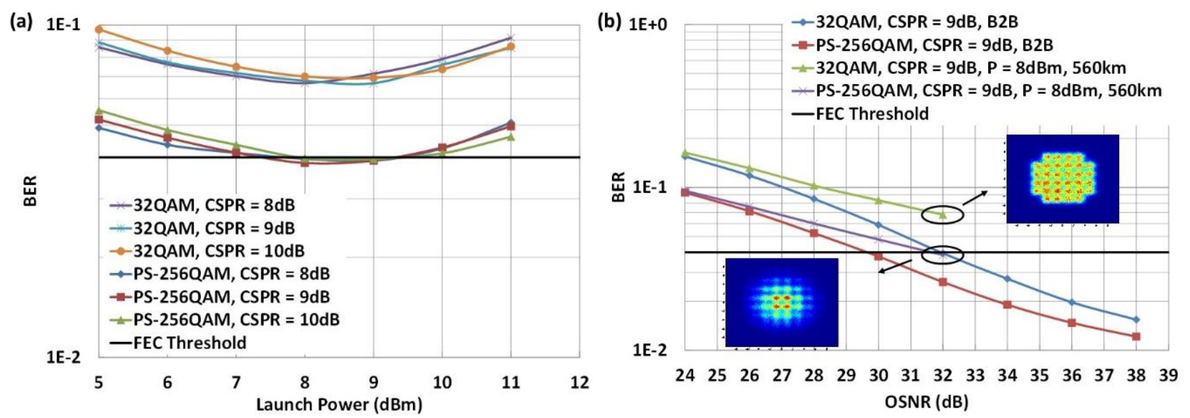

Fig. 5 Transmission result for 80GBd DVC-KK 32QAM and PS-256QAM after 560-km SSMF transmission. (a) BER vs. launch power, CSPR = 8~10 dB; (b) BER vs. OSNR, CSPR = 9 dB, launch power = 8 dBm.

4. Conclusions

We have proposed a novel dual-virtual-carrier assisted Kramers-Kronig scheme to relax the electrical bandwidth requirement on transceiver components. By employing PS-256QAM format, we have successfully transmitted 80-GBd signal over 560-km SSMF with BER below 25% FEC threshold.

5. References

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