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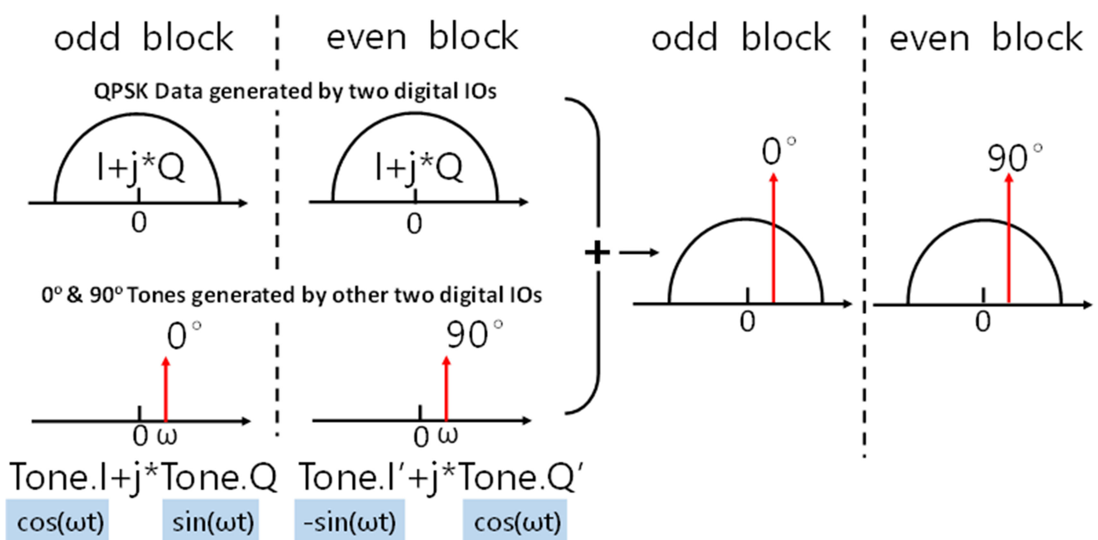

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Abstract: Direct detection (DD) is one of the most attractive solutions for short and medium reach optical fiber transmission in comprehensive consideration of digital signal processing (DSP), power consumption, and cost. Various single side band (SSB) DD techniques have been widely investigated to detect and process the complex signal. In this paper, we propose a novel approach which uses only high-speed digital input/outputs (IO) to generate both quadrature phase shift keying (QPSK) signal and virtual carrier signal. A transmission of 4 × 32 Gb/s QPSK signal over 1200-km standard single mode fiber (SSMF) in block-wise manner has been successfully demonstrated. Only a single polarization in-phase-and-quadrature (IQ) modulator and one single photodiode (PD) are used for each channel. Compared with conventional DSP of coherent detection, the DSP in the proposed scheme is also simplified that only fixed frequency compensation is required without additional phase noise elimination. The overall system complexity has been greatly reduced.

Index Terms: Direct detection, delta-sigma modulation, block-wise phase switch, virtual carrier.

1. Introduction

Fast growing demand on metro and data center traffic involves great challenges in realizing cost-effective and high-performance direct detection systems at data rates beyond 100 Gb/s and transmission reaches over 100 km [1]–[5]. DD is one of the most attractive solutions for short and medium reach optical fiber transmission in comprehensive consideration of digital signal processing, power consumption, and cost. However, the fiber dispersion-induced fading severely limits the signal rate and transmission reaches. For the needs of systems with higher rate and longer reaches, various SSB DD techniques have been widely investigated to detect the complex signal using a single or a few photodiodes, such as block-wise phase switching [1], Stokes vector detection (SVD) [2], and Kramers-Kronig (K-K) detection [3]–[5]. For instance, a phase switching

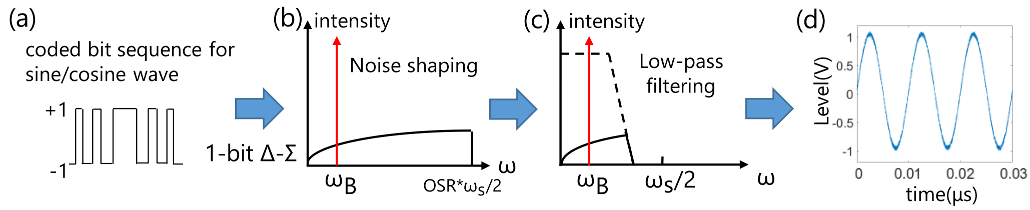

Fig. 1. (a) Coded binary sequence for sine/cosine wave. (b) Oversampling and noise shaping push quantization noise to the higher range. (c) Analog lower-frequency RF-tone filtered using low-pass filter. (d) RF-tone sine/cosine wave generated after filtering.

technique has been reported that a 40-Gb/s orthogonal frequency division multiplexing (OFDM) signal is transmitted over 80-km SSMF within a single polarization [1]. An optical carrier with switched phase is inserted in the transmitter to assist the single PD to re-construct the complex signal in every two consecutive time slots. However, an additional optical branch to generate the assisted optical carrier has to be used in this scheme. To increase the net rate using polarization multiplexing, a demonstration of a 1.26-Tb/s line rate over 100-km SSMF transmission using Stokes vector receiver has been reported in [2]. The SVD receiver is constructed with two balanced-PDs and two single-end PDs. Compared with coherent detection, nearly 75% of the optical bandwidth for two polarizations has been utilized. In the other hand, for the extraordinary performance in suppressing carrier-to-signal power ratio (CSPR), various DD transmission schemes with K-K detection have been studied. Most recently, a 5-channel wavelength-division multiplexing (WDM) DD transmission over 80 km SSMF has been demonstrated with a net data rate per channel of 432 Gb/s [3]. For such technique, allocating an assisted optical carrier is critical for K-K detection. In the report [3], an additional laser source must be frequency controlled and allocated beside the signal. To save the laser source, another approach which slightly offsets the IQ modulator bias is employed to generate such an optical carrier [4]. However, precisely controlling of the offset bias could involve heavy implementation complexity to the transmitter. In the report [5], very high-speed digital-to-analog converters (DACs) are required to digitally generate virtual optical carrier beside the signal. All the above-mentioned techniques require additional radio frequency (RF) or optical components, which may increase the overall system cost and complexity.

Recently, a signal generation method of delta-sigma modulation in mobile fronthaul has attracted huge attention [6], [7], in which analog signal can be generated through the 0/1 output by over-sampling and noise shaping. In this paper, we first use high speed digital IOs to generate the low-frequency RF-tone signal. The phase of RF-tone is digitally programmed based on delta-sigma modulation. The QPSK signal is simultaneously generated by other two IOs, which is electrically combined with sine/cosine RF, and then fed into the optical IQ modulators. We use the block-wise phase switching manner to transmit 4 × 32 Gb/s QPSK signal over 1200-km SSMF. Only a single polarization IQ modulator and a single PD is used for each channel. Moreover, in the DSP, only a fixed frequency offset is needed to be compensated without any extra phase noise. Compared with the existing various SSB-DD techniques, the system complexity is greatly simplified.

2. Principle

Different from traditional Nyquist sampling limited by the number of quantization bits, which would bring quantization noise in the Nyquist zone, delta-sigma modulation uses one or very few quantization bits to modulate analog signal using oversampling and noise shaping technique [8]. Oversampling can firstly extend the Nyquist zone, and spread the quantization noise over a larger range. Noise shaping transfers the energy of quantization noise from low-frequency end to the high-frequency end, which will reduce the lower-band noise substantially. Based on this, we can design and generate the sine/cosine analog waveform using 1-bit IO out port followed by a RF low-pass filter to remove the high frequency part, as shown in Fig. 1. Phase of the analog signal can be easily coded in the delta-sigma modulation design.

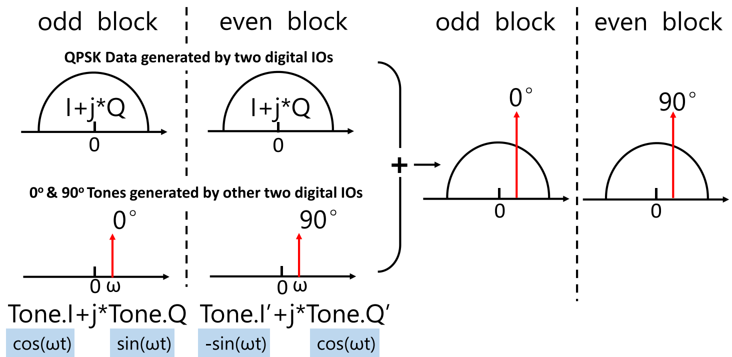

Fig. 2. The combination of block-wise phase switching QPSK and 0°/ 90° RF-tone in the transmitter.

The combination of block-wise phase switching QPSK and RF-tone in the transmitter is shown in Fig. 2. The QPSK data is generated by the first two high speed digital IOs, while the two 0°/90° analog waveforms are generated by another two IOs. The cosine and sine waves form an SSB tone. The tone phase is switched between 0° and 90° by designing the codes in the delta-sigma modulation for the two consecutive data blocks. The real and imaginary parts of the QPSK signal and RF-tones are then electrically combined respectively to be fed into one optical IQ modulator. Every pair of even and odd blocks is loaded with the same data. Compared with traditional coherent systems, the spectrum efficiency per photodiode is the same [1].

At the receiver side, the detected current I_1 (in-phase part) and I_2 (quadrature part) are

$$I_1 = \left|E_C + E_S\right|^2 = \left|E_C\right|^2 + 2\,\mathrm{Re}\left(E_C^* E_S\right) + \left|E_S\right|^2 \quad (1)$$

$$I_2 = \left|E_C j + E_S\right|^2 = \left|E_C\right|^2 + 2\,\mathrm{Im}\left(E_C^* E_S\right) + \left|E_S\right|^2 \quad (2)$$

where E_C is the virtual carrier, and E_S is the signal. The detected current can be presented in a complex form as

$$\widetilde{I} = I_1 + I_2 j = (1+j)\left|E_C\right|^2 + 2E_S E_C^* + (1+j)\left|E_S\right|^2 \quad (3)$$

In the optical back-to-back case, since very few fiber propagation effects occur on the signal, the summation of $|E_C|^2 + |E_S|^2$ can be treated as a constant. Thus, most of the term $|E_C|^2 + |E_S|^2$ can be filtered by AC-coupling effects at PD end or average calculation in DSP. In this case, the power requirement of supported carrier could be very low, which can lead to a low CSPR value. However, after the transmission, the effect of fiber propagation severely degrades the signal quality. We need to either increase the CSPR value to suppress the signal-signal beat interference (SSBI), or use advanced SSBI evaluation and compensation technique. To simplify the concept of the proposed technique, we only enhance the CSPR to suppress the SSBI in this paper. Thus, under high CSPR condition, $\widetilde{I}$ is presented as

$$\widetilde{I} \approx 2E_S E_C^* \quad (4)$$

In this way, we can recover E_S by

$$2E_S = \widetilde{I} E_C / \left|E_C\right|^2 \quad (5)$$

It is worthy to point out that the timing synchronization and recovery are critical.

3. Experimental Setup

Fig. 3(a) shows the experimental setup of the proposed block-wise QPSK direct detection scheme. The four high speed digital IOs are emulated by using Keysight M8195A arbitrary waveform

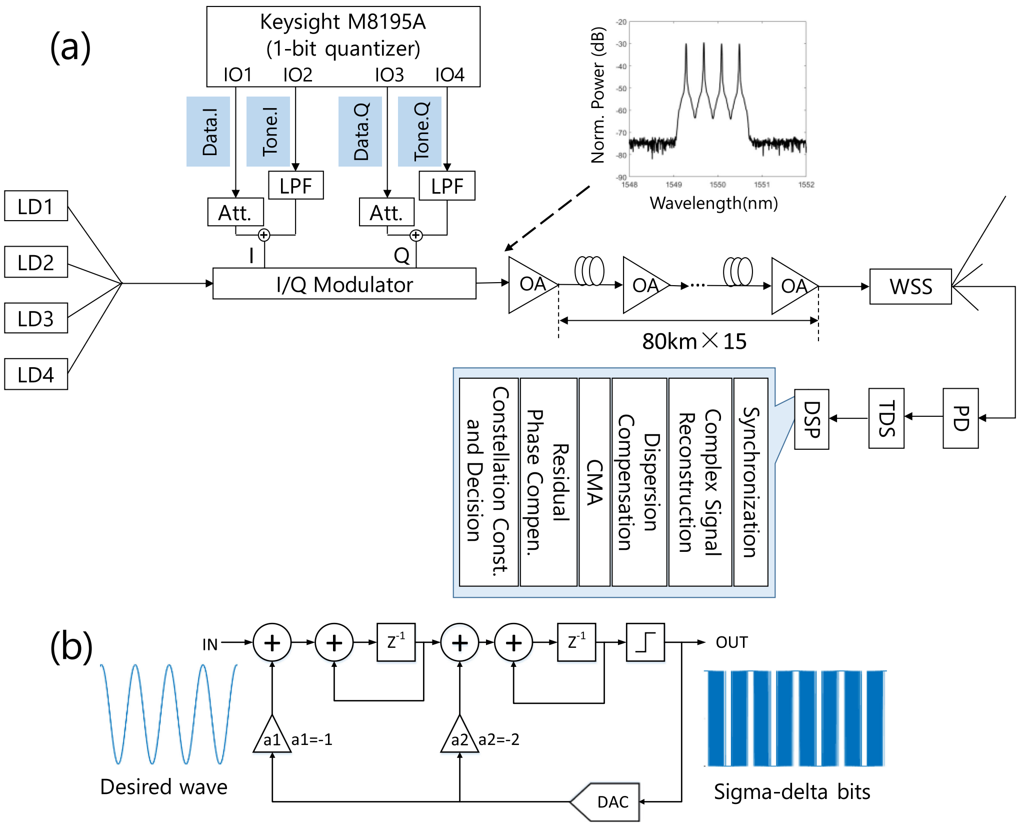

Fig. 3. (a) The experimental set up for block-wise QPSK single-PD direct detection transmission. (LD: laser diode, OA: optical amplifier, LPF: low-pass filter, Att.: attenuator). (b) The configuration of the delta-sigma modulator.

generator (AWG), which is only operated in 1-bit output manner. Due to the bandwidth limitation (∼23 GHz) of the AWG outputs, the four 1-bit signals are only operated at 32 GS/s. The first two IO ports are used to generate QPSK signal, which determines the data rate of the QPSK signal per channel at 32 Gb/s. Two attenuators are inserted to adjust the electrical data power, which is used to control the optical CSPR value. The other two ports are used to produce 128-MHz RF-tone using delta-sigma modulation. Compared to the RF-tone frequency, the operating rate of these two IOs is relatively high, which may lead to a little higher cost and power consuming. But for the easy timing synchronization purpose, we set these four IO ports at the same rate in this work. The configuration of the delta-sigma modulator used in our scheme is shown as Fig. 3(b). The order of the noise transfer function (NTF) is 2. The upsampling rate is 256. Each time signal block contains 200 × 512 samples. The phase of RF-tone switches for each block between 0° and 90°. Two electrical 100-MHz low-pass filters are inserted to filter the outer band quantization noise. Due to the low-pass filter effect and RF-tone phase jumping between the adjacent blocks, the first 50 RF-tone samples of each block are distorted. Thus, we utilize these 50 samples for timing synchronization. The in-phase and quadrature parts of the QPSK and RF-tone signal are then electrically coupled respectively, and then fed into an optical IQ modulator. Four laser sources are set at 1549.286 nm, 1549.686 nm, 1550.086 nm and 1550.490 nm with linewidth of 100 kHz. An Erbium-doped fiber amplifier (EDFA) is followed to control the launch power into the transmission fiber. The fiber link is composed of 15-span 80-km SSMF with EDFA amplification. At the receiver side, a single PD with bandwidth of 40 GHz for each channel is used, which is then sampled by

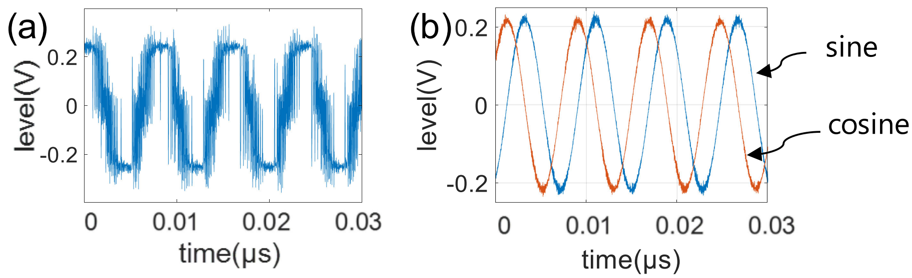

Fig. 4. The 32 GS/s coded sine/cosine binary sequence (a) before the RF low-pass filter and (b) after the RF low-pass filter.

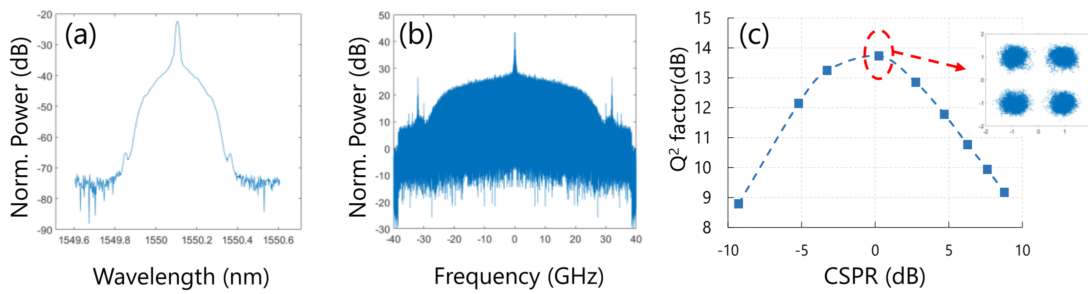

Fig. 5. Back-to-back measurement. (a) Optical spectrum. (b) Combined electrical spectrum. (c) Q^2 vs. CSPR curve and QPSK constellation.

a time-domain sampling scope (TDS) at 160 GS/s. The optical power into the single-end PD is constantly set at 5 dBm. The signal is offline processed. The digital signal processing includes (1) timing synchronization, (2) complex signal reconstruction, (3) dispersion compensation, (4) channel estimation using constant modulus algorithm (CMA), (5) residual frequency offset compensation, and (6) constellation construction and decision. In procedure (5), only a fixed frequency offset is needed to be compensated without any extra phase noise.

4. Results

Fig. 4(a) shows the IO output waveform loaded with the coded sine/cosine binary sequence. Due to the 3-dB bandwidth of the AWG output is less than 23 GHz, the waveform of binary output sequence in Fig. 4(a) is visibly a little filtered. After the RF low-pass filter (3-dB bandwidth is 100-MHz), clear cosine and sine can be obtained as shown in Fig. 4(b).

We first evaluate the 32-Gb/s single channel performance at back-to-back measurement. The influence of CSPR on the output quality Q^2 is investigated, which is defined as the ratio of the electrical signal power to the variance of recovered electrical signal [9]. Fig. 5(a) and (b) show the optical spectrum of single channel and the electrical spectrum of IQ modulator's input. Fig. 5(c) shows the Q^2 factor as a function of CSPR. The maximum value of Q^2 is 13.73 dB, when the CSPR is 0.26 dB. Because the optical power into the PD is fixed, further increasing the carrier power leads to the lower power of the signal and lower SNR and Q^2 quality. As discussed in the principle section, this optimum CSPR value is small. The corresponding QPSK constellation is inserted on the right-hand side of Fig. 5(c).

Fig. 6(a) shows the Q^2 factor versus launch power at various CSPR value for 32Gb/s single channel after 1200-km SSMF transmission. The Q^2 factor achieves optimum value of 7.76 dB at

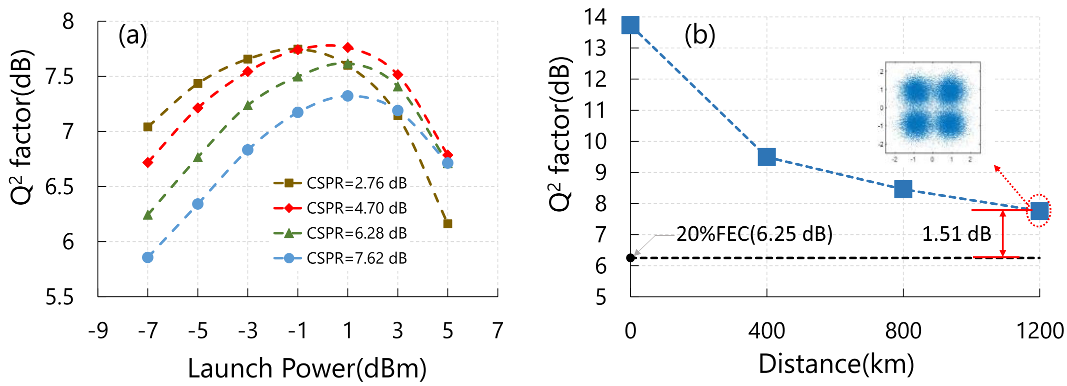

Fig. 6. Single-channel transmission performance. (a) Q^2 vs. launch power at 1200 km with different CSPRs. (b) Q^2 performance at different reaches and QPSK constellation at 1200-km.

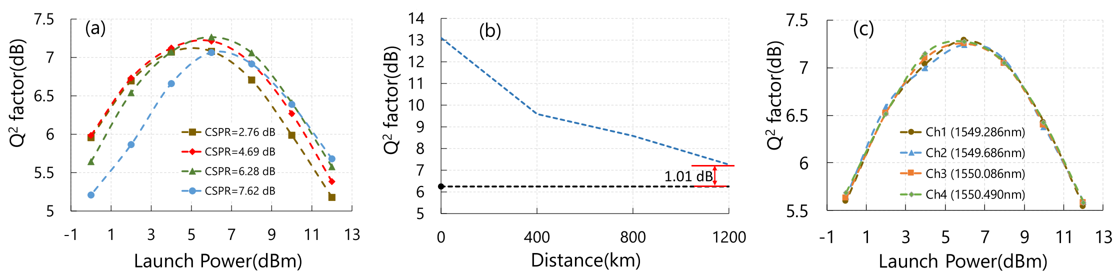

Fig. 7. Four-channel transmission performance. (a) Q^2 vs. launch power at 1200 km with different CSPRs. (b) Q^2 performance at different reaches. (c) Q^2 performance of different channels.

CSPR of 4.7 dB, while the optimized launch power is 1 dBm. Fig. 6(b) shows the optimum Q^2 factor performance at different reaches. There still exist a 1.51 dB margin to the 20% FEC threshold at 1200-km reach. The QPSK constellation is also inserted in this figure.

We also test the transmission performance with 4-channel case. Fig. 7(a) shows the Q^2 factor versus launch power at various CSPR value. The Q^2 factor achieves optimum value of 7.26 dB at CSPR of 6.28 dB, with the optimized launch power of 6 dBm. Fig. 7(b) shows the optimum Q^2 factor versus transmission reaches. A 1.01 dB margin to the 20% FEC threshold is still found after 1200-km transmission. Fig. 7(c) shows the 4-channel performance as a function of launch power at CSPR value of 6.28 dB.

5. Conclusion

We have successfully demonstrated a 4 × 32 Gb/s block-wise QPSK signal transmission over 1200-km SSMF. Both QPSK and carrier signal are generated using high speed IOs based on delta-sigma modulation instead of using any DACs. Compared with various SSB-DD techniques, applying the proposed approach can substantially reduce the system complexity. Under state of the art electronics technology, the IOs of commercialized electrical chip already support PAM-4 signal with rate up to 112 Gbps [10]. Thus, if higher delta-sigma order and polarization-multiplexing can be utilized, higher-rate performance is foreseeable.

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