Long-Reach PON Based on SSB Modulated Frequency-Shifted QAM and Low-Cost Direct-Detection Receiver with Kramers–Kronig Scheme

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Abstract. As PON systems move towards terabit/s aggregated data rates with longer transmission distance, optical coherent receivers become preferred due to their high tolerance to power fading from fiber transmission. To solve the high complexity and high cost problems of optical coherent receivers, a scheme for complex QAM signal transmission with simple direct detection is recommended in this paper. The scheme based on optical SSB modulation with frequency-shifted QAM signals and low-cost single-ended PD provides an efficient low-cost solution for long reach coherent PON. Due to its minimum phase property of the optical SSB modulated signal, Kramers-Kronig scheme can be used to reconstruct the complex QAM signal from the received intensity signal. The efficiency of the proposed scheme is validated by both numerical simulations and experiments for both QPSK and 16-QAM modulated signals. By using standard commercially available components, the experiments demonstrated that the combination of SSB modulation of frequency-shifted QAM signal and its single-ended PD receiver with KK scheme can support SSMF transmission over 75 km for both QPSK and 16-QAM signals with receiver optical power penalty less than 1.5 dB.

Keywords: Fiber optics communication · Modulation · Optical communications

1 Introduction

Recently, the live-streaming of high definition video multimedia and cloud computing using remote storage of data are evolving steadily. As a result, the demand for high volumes of data keeps increasing the transmission speed requirements in both short- and long-reach optical access network [1]. As the expanding coverage of modern metropolitan areas leads to longer transmission distance, the Long-reach passive optical network (LR-PON) is proposed. LR-PON is a promising solution of optical access

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networks and is able to combine the capacity of metro and access networks by extending the coverage span of the transmission [2]. Direct detection (DD) has been the main technology for LR-PON because of its low cost and simple structure. However, as PON moves towards terabit/s aggregated data rates, several shortcomings have come out including power fading due to chromatic dispersion (CD) at high symbol rates and long transmission distance plus limited modulation formats.

To solve the problems of PON transmission with DD, coherent PON has been proposed which achieve information modulation on both amplitude and phase [3–5]. A much higher tolerance on power fading from fiber dispersion is also possible with coherent PON and digital optical coherent receiver with electrical dispersion compensation. Traditional optical coherent receivers require one local oscillator (LO) laser, one 90°optical hybrid, and two balanced detectors with four photodiodes (PDs) in total. Even for some simplified coherent receivers where the LO laser is replaced by optical carrier sent from the source [6], coherent receivers are still high cost due to their high implementation complexity for PON applications [7].

Single-side band (SSB) signal with pulse amplitude modulation (PAM) is another known way to overcome power fading problem from DD and it can also double the optical spectrum efficiency [8–10]. However, as the fiber CD accumulates for LR-PON, the influence of signal-to-signal beating interference (SSBI) from square-law detection of PD cannot be neglected. Different digital signal processor (DSP) techniques for SSBI mitigation have been proposed in [11, 12]. Kramers-Kronig (KK) scheme with DD is able to alleviate the SSBI very well by fully reconstructing the optical field signal from the detected photocurrent signal [13–15].

Unlike SSB-PAM which is limited to amplitude modulation, quadrature amplitude modulation (QAM) can provide much more choices on modulation schemes. In this paper, we recommend a scheme for complex 16-array QAM signal transmission with simple DD for LR-PON. Optical SSB modulation of frequency-shifted QAM signal and single-ended PD with KK scheme for QAM signal reconstruction are combined to achieve the low-cost and efficient scheme for coherent LR-PON. The paper is organized as follows. Section 2 explains the fundamental principles of the proposed schemes. Numerical simulations are then used to validate the proposed scheme in Sect. 3 followed by experimental results in Sect. 4. Section 5 concludes the paper.

2 Principles of the Scheme

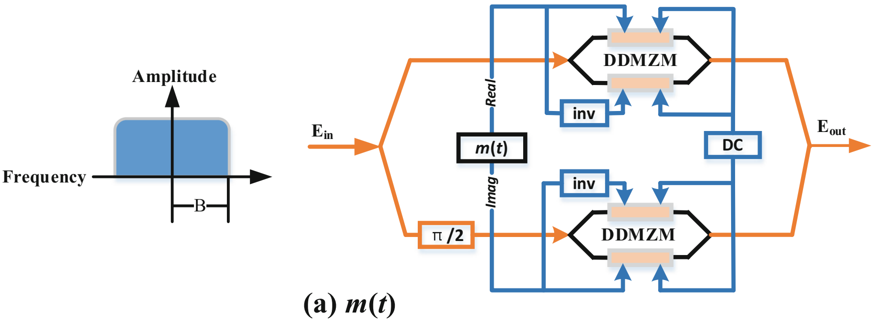
2.1 Principle of SSB Modulation of the Frequency-Shifted QAM Signal

Suppose that the complex signal $m(t)$ is a conventional bandwidth-limited QAM signal, its spectrum is shown Fig. 1(a) where B is the signal's bandwidth. To modulate the signal onto optical carrier, an IQ modulator based on two intensity modulating Mach-Zehnder modulators (MZMs) is commonly used. A relative carrier phase difference exists between the upper and lower arm of the IQ modulator, and the real part and imaginary part of the signal $m(t)$ are used to drive each one of the two MZMs.

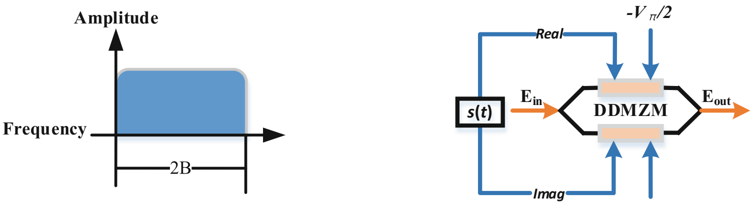
Different from conventional IQ modulation for QAM signal, we propose in this paper to use a single dual-drive MZM (DDMZM) to modulate the frequency-shifted

QAM signal as a SSB signal. To do this, we first achieve frequency shifting of the QAM signal as shown in Eq. (1) where B is the signal's bandwidth. The spectrum of the frequency-shifted QAM signal $s(t)$ is shown in Fig. 1(b). If the signal $s(t)$ is written in the form of its real part and imaginary part, it can be shown that $s_i(t)$ is actually the Hilbert transform of $s_r(t)$, which is the same as required for SSB modulation [13].

$$\begin{aligned} s(t) &= m(t)\exp\left(j2\pi Bt\right) \\ &= s_r(t) + js_i(t) \end{aligned} \tag{1}$$



(a) $m(t)$



(b) $s(t)$

Fig. 1. Signal spectrum and its modulation scheme comparison for the conventional QAM signal (a) and the frequency-shifted QAM signal (b).

Figure 1(b) also shows how to achieve the SSB modulation of the frequency-shifted QAM signal by using a DDMZM. The DDMZM consists of two parallel phase modulators with separate radio frequency (RF) input ports and direct current (DC) bias ports. The DDMZM output optical field can be written as [10]

$$E_{out}(t) = E_{in}\left[\exp(j\pi\frac{V_{r1}(t)+V_{b1}}{V_\pi}) + \exp(j\pi\frac{V_{r2}(t)+V_{b2}}{V_\pi})\right] \tag{2}$$

Where E_{in} stands for the input optical field, $V_{r1}(t)$ and $V_{r2}(t)$ are the radio frequency signals applied to each one of the two branches, and V_{b1} and V_{b2} are the DC voltage bias which will induce a constant phase shift between the two branches. V_π is the half-wave voltage parameter of the MZM. To obtain an optical SSB signal, the real part and imaginary part of the signal $s(t)$ are used as the two radio frequency signals, that is

$V_{r1}(t) = s_r(t)$, $V_{r2}(t) = s_i(t)$. Moreover, it is important to set the two DC bias voltages as $V_{b1} = -V_\pi/2$, $V_{b2} = 0$. Under the assumption that the $s_r(t)$ and $s_i(t)$ are small signals, the output of DDMZM can be found as

$$E_{out}(t) = E_{in}\left[1 - j + \frac{\pi}{V_\pi}(s_r(t) + js_i(t))\right] \tag{3}$$

In the above equation, $E_{in}(1\text{-}j)$ is the optical carrier signal. Since $s_i(t)$ is actually the Hilbert transform of $s_r(t)$, an optical SSB signal is obtained.

2.2 Principles of Direct Detection of SSB Signal with Kramers-Kronig Scheme

Figure 2 compares the conventional optical coherent receiver and direct detection of SSB signal. For conventional QAM modulation, an optical coherent receiver with two balanced detectors is required as shown in Fig. 2(a). One of the balanced detector is used to recover the real part of the received complex QAM signal and the other one is used to recover its imaginary part. Since each balanced detector consists of two PDs, four PDs are required for the optical coherent receiver totally. Moreover, a LO working at the same wavelength as the transmitter must be available for the optical coherent receiver which might be expensive for optical network unit (ONU) of PON systems.

Instead using an optical coherent receiver to recover the complex QAM signal, a simple single-ended PD for the SSB modulated frequency-shifted QAM signal is used in the proposed system as shown in Fig. 2(b). The output of the single-ended PD can be written as

$$I(t) = \eta|E_{out}(t)|^2 + n(t) \tag{4}$$

Where $I(t)$ is the photocurrent produced by the PD, η denotes the responsivity of the PD, and $n(t)$ is the noise of the PD. It is clear from the equation that the phase information of the transmitted signal will be lost due to the square-law detection nature of a PD. To recover the complex signal of $s(t)$ from the received real signal of $I(t)$, KK scheme is used in the following. Compared with the optical coherent receiver with two balanced detector, the proposed single-ended PD receiver is much cheaper as no local laser diode is required at the receiver side.

The key of KK scheme relies on whether the received signal is of minimum phase [13]. For SSB modulated optical signal with an optical carrier of sufficient power, the signal can be written as

$$b(t) = A + m(t)\exp(j2\pi Bt) \tag{5}$$

Where A is constant. It can be shown that $b(t)$ is a minimum phase signal when $|A|$ is large enough. As described in [13], under this condition, the KK scheme can be used to reconstruct the signal $E_m(t)$ from the intensity signal of the minimum phase signal as follow

$$\phi(t) = \frac{1}{2\pi} p.v. \int_{-\infty}^{+\infty} dt' \frac{\log[I(t')]}{t - t'} \tag{6}$$

$$E_m(t) = \left\{ \sqrt{I(t)} \exp[j\phi(t)] - E_0 \right\} \exp(-j2\pi Bt) \tag{7}$$

Where $\phi(t)$ is the phase part of the minimum phase signal, $I(t)$ is the photocurrent produced by the PD which is proportional to the field intensity as in Eq. (4), *p. v.* denotes the Cauchy principal value of the integral [16]. $E_m(t)$ is the reconstructed complex field signal transmitted through fiber.

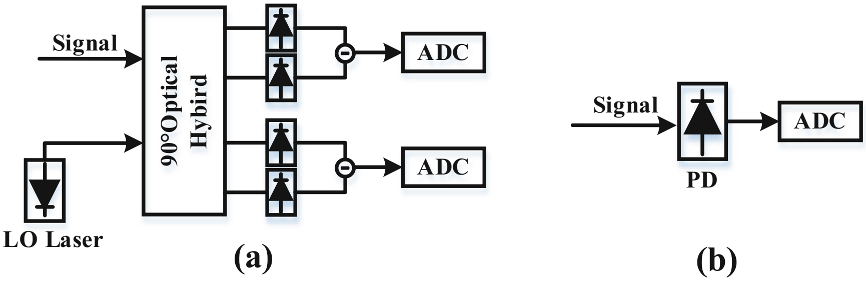


Fig. 2. Comparison of conventional optical coherent receiver (a) and direct detection of SSB signal with single-ended PD (b).

After using the KK scheme to reconstruct the field signal, we can obtain the QAM signal by doing an inverse frequency shifting of Eq. (1). Then, the QAM signal can be further processed with conventional digital signal processing functions as used in digital optical coherent receiver.

3 Simulation Results

In order to validate the proposed scheme, numerical simulations based on VPI Transmission Maker and MATLAB are implemented. The schematic of the simulated system is a simplified version of the experiment setup shown in Fig. 4 to be included in the next section. In the simulations, standard single-mode fiber (SSMF) with a length of 75 km is assumed as for LR-PON. The attenuation coefficient of the SSMF is set at 0.2 dB/km. Other parameters of SSMF include dispersion coefficient D of 16 ps/nm/km, and nonlinear index of 2.6×10^{-20} m^2/W. At the transmitter side, a pseudo random bit sequence (PRBS) with 2^{17} bits is used for QAM modulation. Root raised cosine (RRC) filter with a roll-off factor of 0.1 is applied for pulse shaping. After the QAM signal is shifted in frequency, the real part and the imaginary part of the frequency shifted signal are fed into the two arms of DDMZM. The launch optical power is fixed at 0 dBm. A tunable optical attenuator before the PD is used for bit error rate test under different receiver optical power. The received signal is firstly proceed by the KK scheme to reconstruct the optical field. After the inverse frequency shifting for getting the base band signal, phase correcting and least mean squares (LMS) based feed forward equalizer (FFE) are applied before symbol decision making. Finally, the number of bit error is counted for BER computation.

In the simulations, 25 GBaud is assumed for transmission with both quadrature phase shift keying (QPSK) and 16-QAM. The net bit rate for the QPSK and 16-QAM signals are thus 50 Gbps and 100 Gbps respectively. As the KK scheme can help to recover the complex signal $s(t)$ from a single-ended PD, digital dispersion compensation can thus be applied instead of using dispersion compensation fiber (DCF). The linewidth of laser is set to 1 MHz.

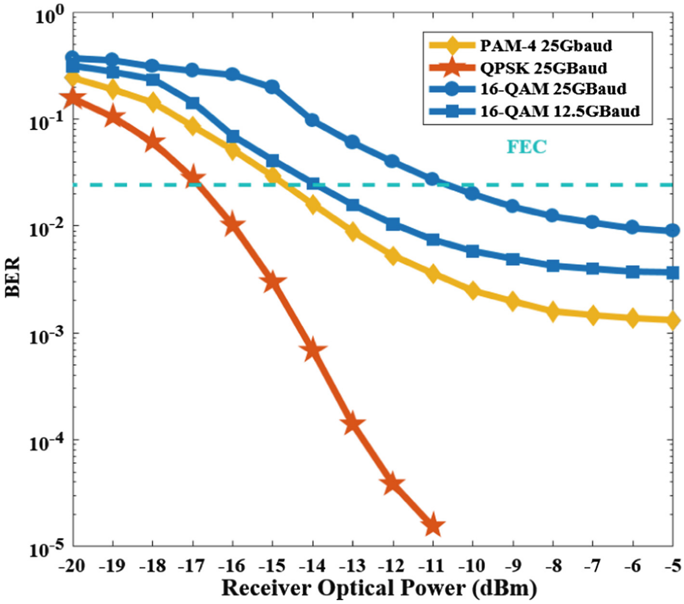


Fig. 3. BER performance comparison among different modulation schemes as the ROP varies.

Figure 3 shows the simulation results with the KK-based receiver for both QPSK (4-QAM) and 16-QAM. SSB modulated PAM-4 modulation scheme is also included in the simulation comparison. As expected, QPSK has the best performance among these modulations because there are only two levels on the real part and imaginary part of QPSK modulation. From the simulation results, it can be seen that the pre-forward error correction (FEC) BER lower than 2.4×10^{-2} can be achieved at a receiver optical power of −17 dBm for QPSK modulation.

For SSB-modulated PAM-4 signal, about 3 dB receiver optical power (ROP) penalty is observed as compared with the QPSK modulation. This ROP penalty is used to obtain a doubled spectrum efficiency as SSB-modulated PAM-4 can achieve the same transmission bit rate with only half of the signal bandwidth as compared with the QPSK signal.

Among the different modulation schemes, the SSB modulated frequency-shifted 16-QAM signal has the highest transmission rate, but about 6 dB ROP penalty is found as compared with the QPSK modulation at the same baud rate. However, if we reduce the baud rate of the 16-QAM signal to 12.5 GBaud, then a similar performance is found between the lower-rate 16-QAM signal and the SSB-PAM-4 signal at the same bit rate.

4 Experimental Setup and Results

The experimental setup for the optical SSB modulation of the frequency-shifted QAM signal system is shown in Fig. 4. A PRBS with 2^{18} bits is used for QPSK and 16-QAM modulation and up-sampled to 4 samples-per-symbol at the transmitter side. An RRC filter with a roll-off factor of 0.1 is applied to generate the QAM modulated signal sequence. Then the signal is frequency shifted using Eq. (1). Arbitrary wavelength generator (AWG) of AWG700002A is used to generate the real part and the imaginary part of the signal, $s_r(t)$ and $s_i(t)$, at the highest sampling rate of 25GS/s for AWG700002A. Thus, the bit rates are 12.5 Gbps and 25 Gbps for QPSK and 16-QAM modulated signals respectively. A DDMZM biased at its quadrature point is used to generate the optical SSB signal. As the carrier to signal power ratio (CSPR) is an important parameter to optimize the system's performance, a pair of attenuators are used on the AWG's output signal to optimize the CSPR. The optical source used in the experiment has an output optical power about 12 dBm at 1550 nm wavelength. The optical signal power to be launched into the transmission fiber is fixed at 0 dBm and

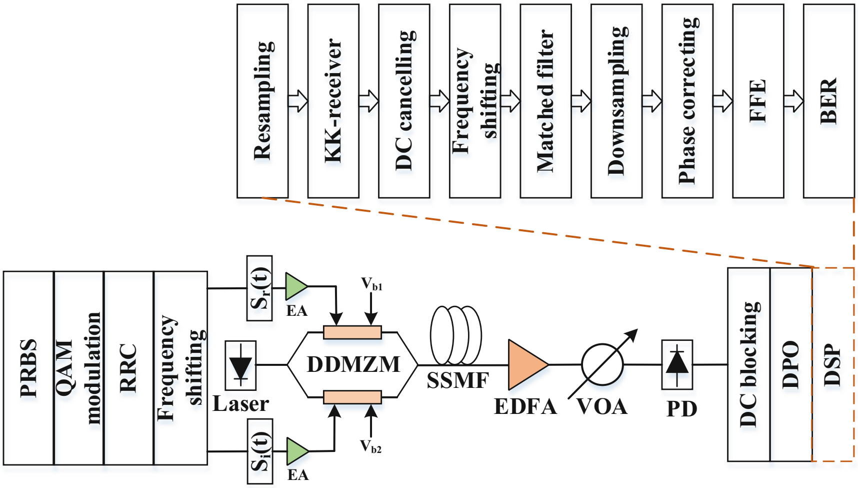


Fig. 4. Schematic of experimental setup. DPO: digital-processing oscilloscope.

75 km SSMF with an attention coefficient of 0.2 dB/km is used for transmission. At the receiver side, an Erbium-doped optical fiber amplifier (EDFA) and a variable optical attenuator (VOA) are used to compensate the transmission loss plus varying the ROP during the experiments.

To check whether the KK scheme can successfully reconstruct the complex QAM signal from single-ended PD with optical SSB modulation of frequency-shifted QAM signal, Fig. 5(a) shows the constellation diagram of the 16-QAM signal after the KK scheme. With a relatively high ROP, a clear 16-point constellation diagram is observed from Fig. 5 which proves the validation of the KK scheme with the proposed system. After phase compensation, the conventional rectangular 16-QAM constellation diagram is obtained as shown in Fig. 5(b).

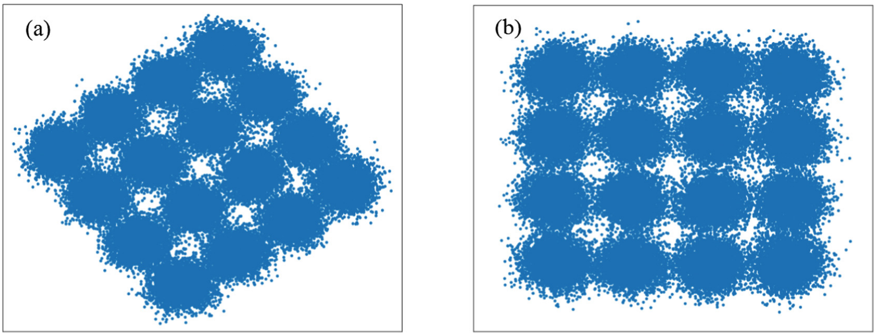


Fig. 5. The constellation diagram of the reconstructed 16-QAM signal after the KK scheme before phase compensation (a) and after phase compensation (b).

Figure 6(a) gives the experimental results on the BER performance of the SSB modulation of frequency-shifted QPSK and 16-QAM for both back-to-back (B2B) case and 75 km fiber transmission case. As the optical power launched into the fiber is low, there exists little fiber nonlinear effect in the system. Only a linear FFE is used for channel equalization like fiber dispersion compensation before the BER calculation. From Fig. 6(a), about 5−6 dB ROP penalty is observed between the QPSK and 16-QAM signal in the experiments when we consider the BER of 1.0×10^{-2} which is consistent with simulation results from Fig. 3. Moreover, the ROP penalty is less than 1 dB for QPSK signals after 75 km fiber transmission. However, this ROP penalty increases up to 1.5 dB for 16-QAM signals in the experiments if a pre-FEC BER of 2.4×10^{-2} is considered.

To utilize the highest sampling rate of our AWG in the experiment, the samples-per-symbol of its output electrical signal is reduced from 4 to 2.76. Consequently, higher baud rate can be supported in the experiment and the bit rates of the transmitted QPSK and 16-QAM signals are increased up to 18.125 Gbps and 36.25 Gbps, respectively. Figure 6(b) compares the BER performance of the low-rate modulated signals as in Fig. 6(a) and the high-rate modulated signals from down sampling after

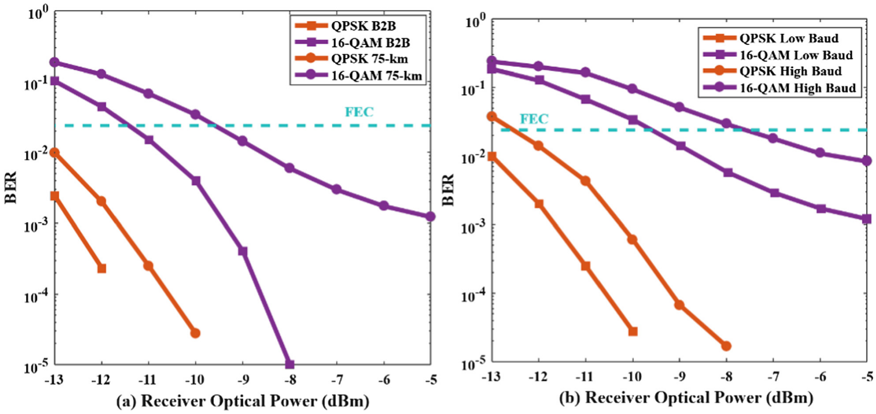


Fig. 6. BER performance comparisons from experimental results on the SSB modulation of frequency-shifted QPSK and 16-QAM between B2B and fiber transmission cases (a) and between high-rate and low-rate cases (b).

75 km fiber transmission in the experiments. At the pre-FEC BER threshold, both the QPSK and 16-QAM signals shows an ROP penalty about 1.5 dB.

5 Conclusions

Optical SSB modulation with frequency-shifted QAM signals with low-cost single-ended PD is recommend in this paper as an efficient low-cost solution for long reach coherent PON system. After simple frequency shifting on the QAM signal at the transmitter side, a single DDMZM can be used to generate the SSB modulated signal. At the receiver side, a single-ended PD without local laser diode can replace the expensive two balanced detectors from conventional optical coherent receiver. Since the optical SSB modulated signal is of minimum phase, KK scheme is available to reconstruct the complex QAM signal from the received intensity signal. The efficiency of the proposed scheme is validated by both numerical simulations and experiments for both QPSK and 16-QAM modulated signals for LR-PON communications. By using standard commercially available components, the experiments demonstrated that the combination of SSB modulation of frequency-shifted QAM signal and its single-ended PD receiver with KK scheme can support SSMF transmission over 75 km for both QPSK and 16-QAM signals with ROP penalty less than 1.5 dB.

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