Linear optical sampling system based on simplified coherent reception

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***Abstract*—We study a fast linear optical sampling technique using a simplified coherent receiver. Considering the damage caused by optical fiber transmission signal, the numerical simulations are investigated for the proposed architecture. Compared with conventional methods, it reduces the hardware cost and has similar performance.**

Keywords—*Linear optical sampling, coherent detection, 3×3 coupler, single-ended photodetector*

I. Introduction

The conventional linear optical sampling method can monitor the amplitude, phase and polarization information of high-speed optical signals, which breaks through the problem that the traditional electrical sampling method is limited by hardware bandwidth [1-3]. However, the conventional method uses the coherent structure of 90 ° mixer and four balanced detectors, which increases the structural hardware complexity. The combination of 3x3 coupler and single-ended photodetector to achieve coherence has attracted attention as a method to reduce structural complexity [4]. Based on low-cost 3x3 optical coupler and 3 single-ended photodetectors, low-cost coherent OOK receiver can be realized [5]. Further combined with the elimination of direct detection (DD) and differential demodulation, the PI heterodyne DPSK receiver with simple architecture can be realized [6]. In addition, a high-speed four-level pulse amplitude modulation (PAM-4) eye pattern analyzer based on a simplified coherent structure uses a symmetric 3x3 optical coupler, which can effectively reduce the hardware cost and overcome the bandwidth limitation of traditional electrical characteristic solutions [7]. In this paper, we propose a fast linear light sampling method to simplify the coherent structure. The pulse laser is adjusted by the polarization controller (PC), mixed with the signal input in the 3x3 coupler, and the simplified coherent mixing is realized by the single-ended photodetector (PD) detection. We simulated the sampling performance of the proposed method under ideal conditions, and obtained clear constellation and eye diagrams. In addition, the sampling performance degradation caused by optical fiber transmission is also simulated numerically. Considering the damage caused by optical fiber transmission signal, we studied the performance of error vector amplitude (EVM) by numerical simulation based on PDM-QPSK system. The results show that the proposed simplified method can optimize the performance of EVM by increasing the signal optical power, especially the high-speed PDM-QPSK signal.

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II. Theoretically Analyze

A. Linear Optical Sampling System With Simplified Coherent Structure

The linear optical sampling system with simplified coherent structure proposed in this paper is shown in Figure 1, including continuous laser, arbitrary waveform generator, IQ-Machzend modulator, single-mode fiber, erbium-doped fiber amplifier, local oscillator (LO) pulse light source, polarization controller, 3 × 3 Coupler, single-ended photoelectric detector, low-pass filter and digital signal processing module.

In Fig.1, the continuous wavelength (CW) generated by a continuous laser is modulated by an arbitrary waveform generator and an IQ-Machzend modulator to generate a polarization multiplexing phase-shift keying signal as the signal under test (SUT) to be measured, and then transmitted through a certain length of single-mode fiber and amplified by an amplifier. The signal to be measured enters 3x3 Coupler with the local oscillator pulse light, after mixing in the coupler, the signal is detected and received by the single-ended photodetector, and the square sum of the three output signals is added through the low-pass filter to complete the analog-to-digital conversion to obtain the recovered baseband signal, and then the signal is further recovered by the digital signal processing module.

B. Coherent Detection

The realization process of coherent detection in Fig.1 is further analyzed mathematically. Assuming that the center frequency difference between the optical signal to be measured and the LO is $\Delta\nu$, and that the optical signal to be measured and the LO have random polarization state, the corresponding Jones vector can be written as equation (1):

$$E_S(t) = \begin{pmatrix} A(t)e^{i(2\pi\Delta\nu t)}\cos(\varphi) \\ A(t)e^{i(2\pi\Delta\nu t+\psi)}\sin(\varphi) \end{pmatrix} \tag{1}$$

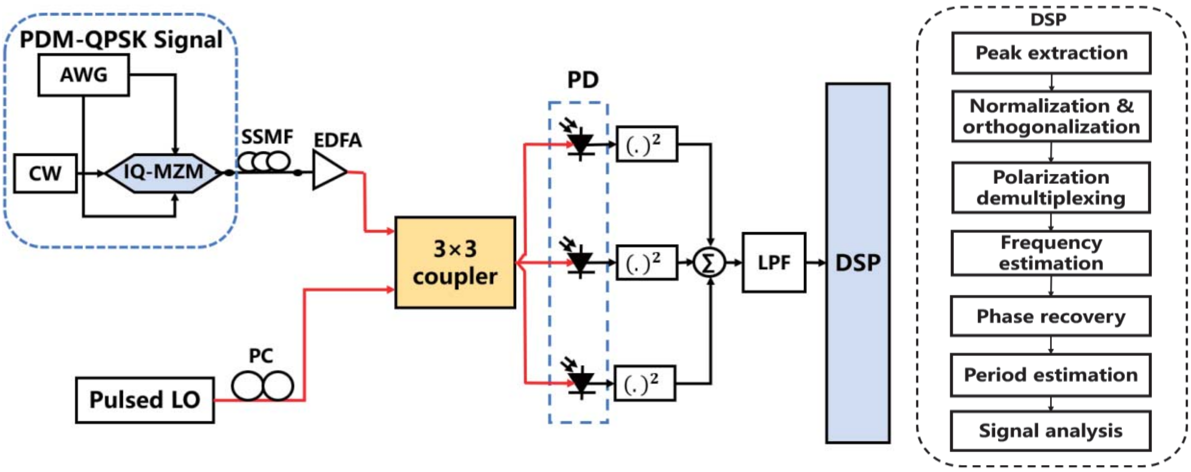


Fig.1.Structure diagram of simplified coherent linear optical sampling system

Where *A(t)* is the modulation amplitude, varphi is the direction of the polarization ellipse principal axis of the light to be measured, ψ is the polarization ellipse angle of the light to be measured (ψ =0 is linear polarization). Adjust the LO to circularly polarized light through the polarization controller, so that the polarization information contained in the LO can be determined. At this time, the relationship between the corresponding LO component and the amplitude of the LO is $E_{L,x}=E_{L,y}=E_L$. Two input signals in the coupler are mixed and output, x and y represent the polarization direction, according to 3 × 3 The transmission matrix of the coupler can obtain three outputs:

$$\begin{pmatrix} E_{1,x} \\ E_{1,y} \\ E_{2,x} \\ E_{2,y} \\ E_{3,x} \\ E_{3,y} \end{pmatrix} = \begin{pmatrix} a & 0 & b & 0 & b & 0 \\ 0 & a & 0 & b & 0 & b \\ b & 0 & a & 0 & b & 0 \\ 0 & b & 0 & a & 0 & b \\ b & 0 & b & 0 & a & 0 \\ 0 & b & 0 & b & 0 & a \end{pmatrix} \begin{pmatrix} E_{S,x} \\ E_{S,y} \\ 0 \\ 0 \\ E_{L,x} \\ E_{L,y} \end{pmatrix} \tag{2}$$

Where a and b are:

$$a = \frac{2}{3}\exp\left(j\frac{2\pi}{9}\right) + \frac{1}{3}\exp\left(-j\frac{4\pi}{9}\right) \tag{3}$$

$$b = \frac{1}{3}\exp\left(-j\frac{4\pi}{9}\right) - \frac{1}{3}\exp\left(j\frac{2\pi}{9}\right) \tag{4}$$

Where j = sqrt {- 1}, without considering the bandwidth of single-ended photodetector, the three currents can be simply deduced $i_k = R\left(\left|E_x\right|^2 + \left|E_y\right|^2\right)$, where R is the response of the single-ended photodetector. With i_1 as an example, we can get:

$$i_1 = \frac{2}{3} R E_L A(t) \left[\cos\left(2\pi\Delta v t + \psi + \frac{2\pi}{3}\right)\sin(\varphi) + \cos\left(2\pi\Delta v t + \frac{2\pi}{3}\right)\cos(\varphi) \right] \tag{5}$$

By summing the sum of squares of the current, we obtain that the signal $S(t) = i_1^2 + i_2^2 + i_3^2$ is

$$S(t) = \frac{2}{3} R^2 E_L^2 A(t)^2 - \frac{2}{3} R^2 E_L^2 A(t)^2 * \left[\sin(2\varphi) \times \sin\left(-4\pi\Delta v t - \psi + \frac{\pi}{6}\right) \right] \tag{6}$$

The first item of the obtained *S(t)* contains the baseband signal components and their modulation information, and the second item is the polarization related beat frequency item. The baseband signal can be recovered after filtered by a low-pass filter. The baseband signal enters the digital signal processing module for peak extraction, normalized orthogonalization, polarization demultiplexing, frequency estimation, phase recovery, and period estimation to further obtain the sampling output. The simulation system is built according to the system structure in Fig.1, and the simulation output of the simplified coherent linear optical sampling system is obtained under ideal conditions.

C. Digital Signal Processing

The peak sequence *I(N)* and *Q(N)* corresponding to th *I* e and *Q* signals are identified and extracted by the collaborative peak extraction algorithm. The normalization process of the extracted two peak sequences is shown in (7) and (8):

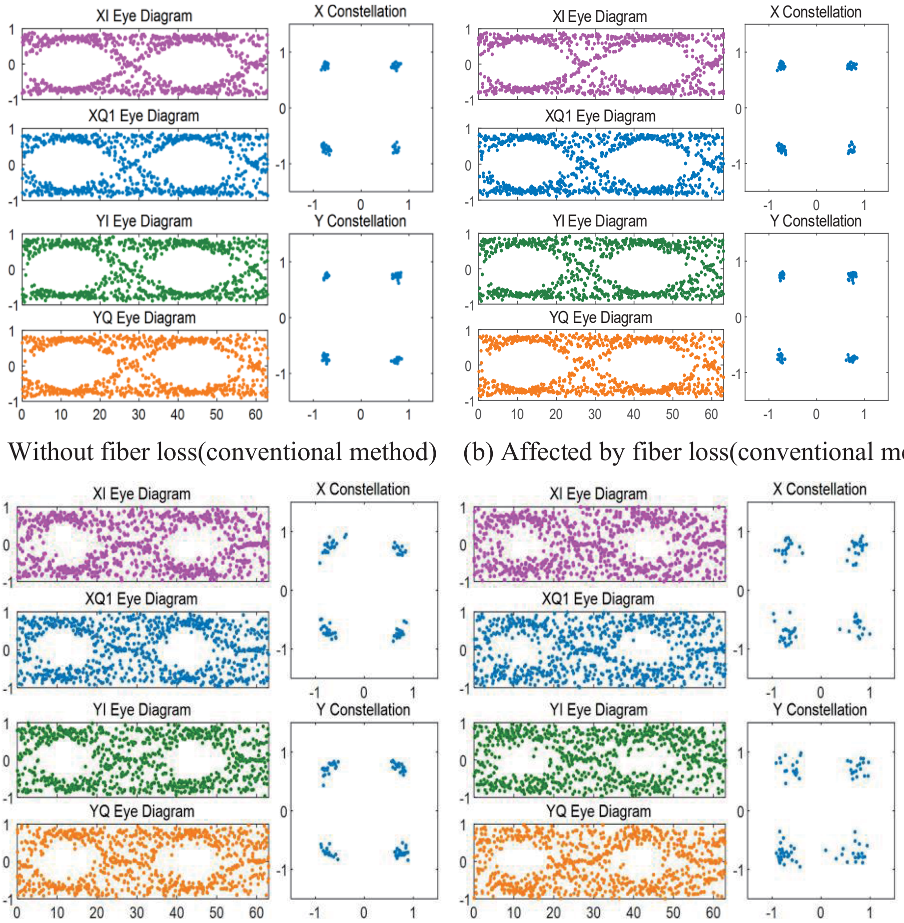
$$I'(N) = I(N) / \max I(N) \tag{7}$$

$$Q'(N) = Q(N) / \max Q(N) \tag{8}$$

After normalization, $I''(N)$ and $Q''(N)$ are obtained by orthogonalizing the sequence through Schmidt orthogonalization algorithm to eliminate intersymbol interference. Then, the signal distortion caused by birefringence effect is balanced and eliminated by constant modulus algorithm. The polarization demultiplexing process is shown in (9) and (10):

$$\begin{bmatrix} I''(N_x) \\ I''(N_y) \end{bmatrix} = p \begin{bmatrix} I'(N_x) \\ I'(N_y) \end{bmatrix} \tag{9}$$

$$\begin{bmatrix} Q''(N_x) \\ Q''(N_y) \end{bmatrix} = p \begin{bmatrix} Q'(N_x) \\ Q'(N_y) \end{bmatrix} \tag{10}$$



(a) Without fiber loss(conventional method) (b) Affected by fiber loss(conventional method)

(c) Without fiber loss(simplified method) (d) Affected by fiber loss(simplified method)

Fig.2. Constellations and eye diagrams obtained by the conventional method & the simplified method

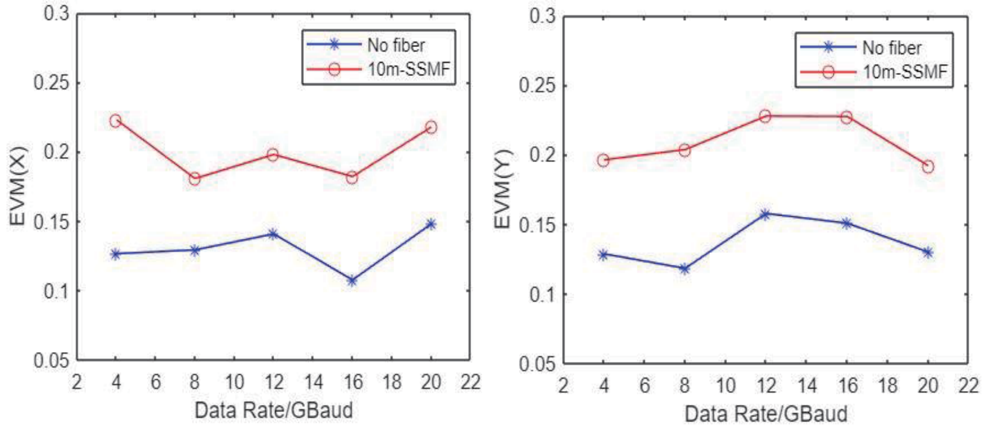
After that, frequency offset estimation and phase estimation are carried out by Viterbi-Viterbi algorithm to achieve carrier recovery and phase recovery; the software synchronization algorithm based on chirp z transform is used to accurately estimate the signal period of the peak sequence to eliminate the timing error caused by the linear optical sampling system; the processed pulse sequences $I''(N_x)$, $I''(N_y)$, $Q''(N_x)$ and $Q''(N_y)$ are integrated to portray accurate eye diagrams and calculate the EVMs.

III. System Setup

The performance of the proposed method was evaluated by numerical simulation. In the numerical simulation, we set the signal source and pulse optical power to 5dBm. The signal source is set as a continuous wavelength laser with a central frequency of 1560nm The repetition frequency of pulse light source is 99.8652MHz. The responsivity of single-ended photodetectors is 0.64. In addition, we set the optical fiber parameters in the numerical simulation according to the actual single-mode optical fiber characteristics. Where the fiber length is $10m$, the dispersion coefficient and polarization mode dispersion coefficient corresponding to single-mode fiber are 17ps/nm/km and 1 $ps/\sqrt{km}$ respectively. The attenuation coefficient of optical fiber is 0.2dB/km, and the nonlinear coefficient is $2.6\times10^{-20}m^2/W$.

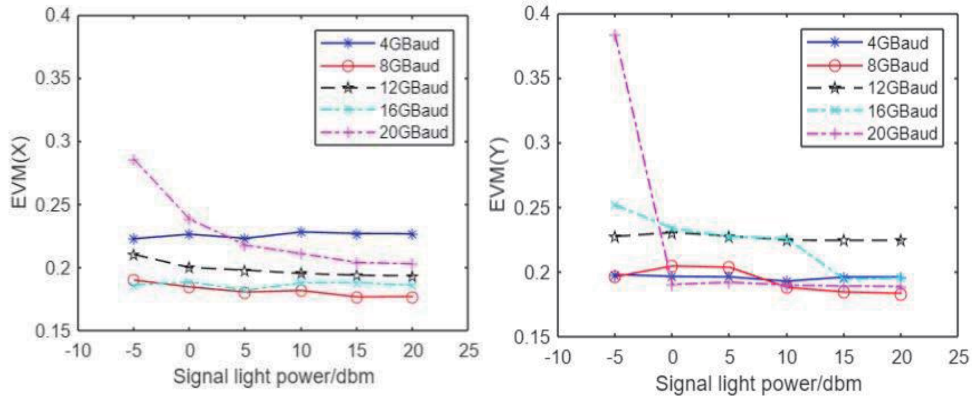
IV. Simulation Result And Dsicussion

Fig.2 (a) and Fig.2 (b) show the constellations and eye diagrams obtained by conventional methods without/with fiber loss at 8GBaud signal rate. Fig.2 (c) and Fig.2 (d) show the constellation and eye diagrams obtained by the simplified method. We can observe that under 5dBm signal optical power, optical fiber transmission reduces the sampling performance to a certain extent, but the eyes and constellations constructed by this simplified method are clear. From the sampling results obtained by the two methods, the simplified method has similar performance with the conventional method, but the hardware cost of the simplified method is about 28% less than that of the conventional method. In addition, we study the EVM performance of the simplified method at different signal rates. Fig.3 shows the EVM performance of two cases under different signal transmission rates. We can observe that optical fiber transmission leads to the degradation of the performance of the sampling method, with a decrease of about 58%. Fig.4 shows the EVM performance of the simplified method under different signal source powers. For PDM-QPSK signals with signal rate lower than 16GBaud, changing the signal source power has a weak impact on EVM performance; For signals with signal rate higher than 16GBaud, we can improve EVM performance by



(a)EVM(X) (b)EVM(Y)

Fig.3. The EVM performance of the two cases under different signal transmission rates



(a)EVM(X) (b)EVM(Y)

Fig.4. The EVM performance of the simplified method under different signal source powers

increasing signal source power. When the signal rate is 16GBaud, it can reach the EVM value of 0.1912. When the signal rate is 20GBaud, the EVM value of 0.1966 can be reached.

V. CONCLUSION

A linear optical sampling method which simplifies the coherent structure is proposed. Compared with conventional methods, it reduces the hardware cost and has similar performance. For PDM-QPSK signals with different signal rates, the proposed method can improve the performance of EVM by increasing the signal optical power, especially for PDM-BPSK signals with signal rates higher than 16GBaud, considering the signal damage caused by optical fiber transmission.

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