Analog PAM4 modulation technique enabled by a polarization multiplexing modulator

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***Abstract*—In this paper, we propose a new method to generate radio-frequency (RF) pulse-amplitude-modulation with four amplitude levels (PAM4) signals. This method is a cost-effective one without the use of expensive digital to analog converters (DACs). By using a polarization multiplexing modulator that integrates two polarization orthogonal intensity modulators, the two polarization orthogonal intensity modulators are driven by two levels of RF signals, respectively. Then, by cascading a polarization controller (PC) and a polarizer, RF PAM4 optical signals can be generated. Based on our proposed scheme, we experimentally demonstrate the generation of RF PAM4 signal at 9.07GHz. Our experimental results show that the RF PAM4 signals have no obvious deterioration after transmission over 80km single mode fiber (SMF).**

Keywords-PAM4 modulation; polarization multiplexing modulator; radio-over-fiber system; radio-frequency signal; cost-effective

INTRODUCTION

Radio-over-fiber (ROF) technology has the characteristics of high bandwidth and high flexibility, so it is very suitable for building mobile wireless networks [1-6]. For the practical implementation of ROF technology, it is important to generate optical radio frequency (RF) signals with properties of high performance, low cost and high stability [4].

In the demonstrated ROF systems, the on-off-keying (OOK) modulation format is usually selected because of its easy generation [1-3]. But the spectral efficiency of OOK signals is very low. To use higher level modulation format such as PAM4 signals we can get higher spectral efficiency [4].

Pulse Amplitude Modulation with four amplitude levels (PAM4) modulation format does not require up-conversion and down-conversion, and the demodulation method is simple. From this perspective, PAM4 signals are more suitable for ROF systems [5]. It can be used to reduce the bandwidth requirements of optical and electrical components. It can also be used to extend the transmission distance in optical fiber communication system. On this modulation format, ones have conducted many studies on increasing the transmission rate, enhancing the anti-interference ability and extending the transmission distance

Digital-to-analog converters (DAC) is a flexible and efficient device. It can be used for high-order PAM signals generation. But in a ROF system, the RF signal usually has a high frequency. DAC with high-bandwidth is very expensive, and its power consumption is also high. Because of its low cost operation, DAC is not a suitable device for ROF system with low modulation format, such as PAM4.

In order to reduce the system cost, we propose a new scheme, which uses polarization multiplexing modulator (PM MOD) and polarizer to generate PAM4 ROF signal instead of DAC.

PRINCIPLE AND EXPERIMENT

Figure 1 is a schematic diagram of the PAM4 generation method in ROF system using polarization multiplexing modulator. A local-oscillator (LO) generate a sinusoidal electrical as optical carrier with frequency at f_c. The generated OOK format RF signal and LO signal are mixed and then divided into two parts, as data 1 and data 2.

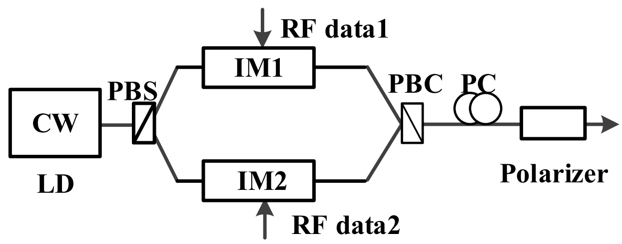

Figure 1. The module of PAM4 generation by proposed method.

After, data 1 and data 2 are modulated onto two beams of light with different polarization states by two IMs in PM.

Assuming that, the two input signals of IM_1 and IM_2 are $D_1(t)$ and $D_2(t)$, the output of IM_1 and IM_2 can be expressed as:

$$\mathrm{E}_{out_1} = \mathrm{A}_1\mathrm{D}_1\mathrm{E}\{J_0(\frac{\pi V_{RF}}{2V_\pi})\cos(2\pi f_c t) - J_1(\frac{\pi V_{RF}}{2V_\pi}) [\cos(2\pi(f_c - f_{RF})t) + \cos(2\pi(f_c + f_{RF})t)]\} \quad (1)$$

$$\mathrm{E}_{out_2} = \mathrm{A}_2\mathrm{D}_2\mathrm{E}\{J_0(\frac{\pi V_{RF}}{2V_\pi})\cos(2\pi f_c t) - J_1(\frac{\pi V_{RF}}{2V_\pi}) [\cos(2\pi(f_c - f_{RF})t) + \cos(2\pi(f_c + f_{RF})t)]\} \quad (2)$$

where A_1 and A_2 are the insertion loss of IM_1 and IM_2 respectively, E is the amplitude of the binary electrical signal, V_π is the half-wave voltage of IMs, V_{RF} is the RF modulation voltage, f_c is the optical carrier frequency and J_n is the first kind of Bessel function of order n.

The two polarized signals are mixed together by a polarization beam coupler (PBC). The combined signal can be expressed as:

$$E_{out1} = A_1 D_1(t)\hat{X} E\{J_0(\frac{\pi V_{RF}}{2V_\pi})\cos(2\pi f_c t) - J_1(\frac{\pi V_{RF}}{2V_\pi})[\cos(2\pi(f_c - f_{RF})t) + \cos(2\pi(f_c + f_{RF})t)]\} \quad (3)$$

and

$$E_{out2} = A_2 D_2(t)\hat{Y} E\{J_0(\frac{\pi V_{RF}}{2V_\pi})\cos(2\pi f_c t) - J_1(\frac{\pi V_{RF}}{2V_\pi})[\cos(2\pi(f_c - f_{RF})t) + \cos(2\pi(f_c + f_{RF})t)]\} \quad (4)$$

where $\hat{X}$ and $\hat{Y}$ represent the polarization directions.

Through a polarizer, the optical signal can be expressed as:

$$E_{out} = (A_1 D_1(t)\cos(\theta) + A_2 D_2(t)\sin(\theta)) E\{J_0(\frac{\pi V_{RF}}{2V_\pi})\cos(2\pi f_c t) - J_1(\frac{\pi V_{RF}}{2V_\pi})[\cos(2\pi(f_c - f_{RF})t) + \cos(2\pi(f_c + f_{RF})t)]\} \quad (5)$$

where θ is the angle between E_{out1} direction and X polarization direction, and it is also the angle between the E_{out2} direction and Y polarization direction.

After single mode fiber (SMF) transmission and Erbium-doped fiber amplifier amplification, the photodetector (PD) gets the received signal. The received signal is given by:

$$E_{res} = (A_1 D_1(t)\cos(\theta) + A_2 D_2(t)\sin(\theta)) G E \{J_0(\frac{\pi V_{RF}}{2V_\pi})\cos(2\pi f_c t + \varphi_0) - J_1(\frac{\pi V_{RF}}{2V_\pi})[\cos(2\pi(f_c - f_{RF})t + \varphi_1) + \cos(2\pi(f_c + f_{RF})t + \varphi_2)]\} \quad (6)$$

where, φ_0 , φ_1 and φ_2 are phase delay of the optical carrier, lower sideband and upper sideband, respectively.

At PD, the amplitude of the electrical signal is given by:

$$I(t) = R\langle |E_{res}|^2 \rangle \quad (7)$$

where R is the gain of PD. When Eqs (6) is substituted into Eqs (7), The amplitude of the received signal can be expressed as:

$$I(t) \propto (A_1^2 D_1^2(t)\cos^2(\theta) + A_2^2 D_2^2(t)\sin^2(\theta)) G^2 E^2 \frac{1}{2} J_1^2(\frac{\pi V_{RF}}{2V_\pi})\cos(4\pi f_{RF} t + \varphi_2 - \varphi_1) \quad (8)$$

Because of the same model of IM_1 and IM_2, the insertion loss in IM_1 and IM_2 are equal. It means that $A_1 = A_2$. Besides, the phase of the electrical signals on IM_1 and IM_2 can be synchronized by adjusting the phase shifter. When the phase is synchronized, $\varphi_2 - \varphi_1 = 0$.

So the signal can be expressed as:

$$I(t) \propto D_1^2(t)\cos^2(\theta) + D_2^2(t)\sin^2(\theta) \quad (9)$$

If both D_1 and D_2 represent an OOK signal with an amplitude of 1, the 4 levels of output signal from the polarizer can be expressed as 0, $D_1^2(t)\cos^2(\theta)$, $D_2^2(t)\sin^2(\theta)$, and $D_1^2(t)\cos^2(\theta) + D_2^2(t)\sin^2(\theta)$.

So, if $\cos^2(\theta) = 2 * \sin^2(\theta)$ or $\sin^2(\theta) = 2 * \cos^2(\theta)$ as shown in Fig. 2, the ratio of the four levels would be 0:1:2:3 or 0:2:1:3. Then the final output is a 4 levels RF signal by this means.

Figure 2 shows the experimental setup for the generation of RF PAM4 signal at 9.07GHz and transmission over 80 km SMF fiber. At the transmitter side, a local-oscillator (LO) is used to generate a 9.07GHz sinusoidal electrical signal. And then, a power divider is used to divide the electrical signal into two parts. The binary data and LO signal are mixed by a double-balanced mixer to realize frequency up-conversion. After amplified by an electric amplifier (EA) amplifies with 3dB bandwidth of 40GHz and 30dB gain, the mixed signal will be divided into two parts: data 1 and data 2. Data 2 will pass through a phase shifter to synchronize data 1 for RF PAM4 signal generation. There is five-bit delay between Data 1 and Data 2 for decorrelation purposes.

The continuous-wave (CW) lightwave generated from a distributed-feedback laser has an operating wavelength of 1551.63nm and an output power of 10dBm. The CW lightwave is modulated by an integrated polarization multiplexing modulator (IM), composed of two polarization multiplexing modulators. The generated data1 and data2 individually drive the two modulators with orthogonal polarization directions. After, the two beams of modulated laser recombined using a PBC. The PC is used to adjust the polarization direction of the optical signals into the polarizer to generate RF PAM4 signals. The bandwidth of polarization multiplexing modulator is larger than 25GHz, the insertion loss is 6dB, and the polarization isolation exceeds 20dB. In this step, by adjustment of PC, the polarization direction would be corrected to get the suitable angle θ for RF PAM4 signal generation.

After 80km SMF-28 transmission and amplified by an Erbium-doped fiber amplifier (EDFA), the signal is detected by a photodiode with a 3dB bandwidth of 15GHz. The received signal is down-

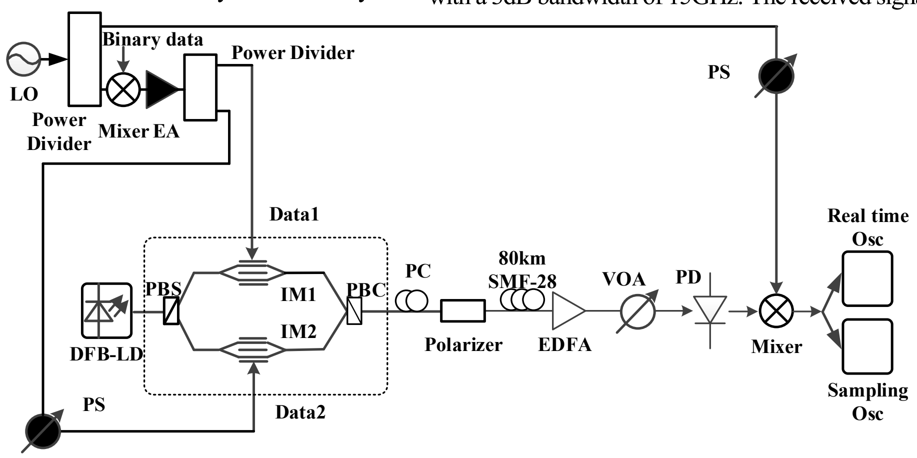

Figure. 2. Experimental setup for generation, transmission and detection of 9.07 RF GHz PAM4 signals.

converted to baseband by mixing with the LO signal generated from the transmitter side. The variable optical attenuator (VOA) before PD is used to adjust the input power into the PD to measure the bit-error-ratio (BER). Finally, the signal is captured by a sampling oscilloscope (OSC) with 20GHz bandwidth for eye diagram or captured by a 40GSa/s real time OSC with 13GHz bandwidth for data collection and BER calculation by offline processing with digital signal processing.

RESULTS AND DISCUSSION

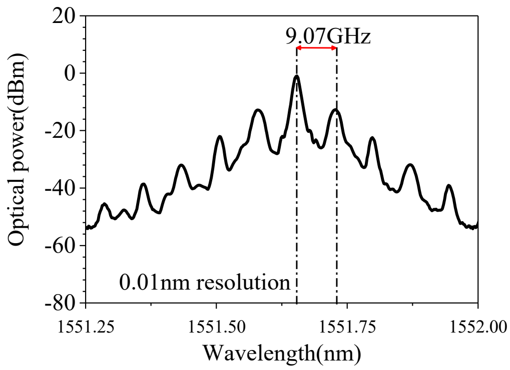

Figure. 3. Optical spectrum of the RF PAM4 signal after transmission over 80km SMF-28 and EDFA.

Figure 3 demonstrates the optical spectrum with the resolution of 0.01nm after transmission on 80km SMF-28. It can be seen that the received signal is a DSB optical signal. The frequency difference between the optical carrier and the sideband is 9.07GHz.

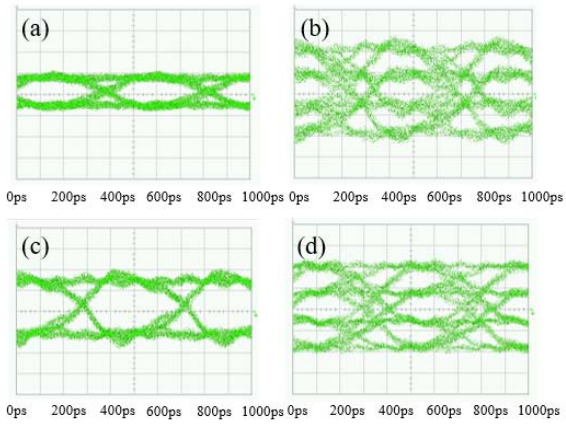

Figure. 4. Eye diagrams of (a) one polarization direction in case o fBtB; (b) PAM4 signal in case of BtB; (c) one polarization direction after 80 km transmission; (d) PAM4 signal after 80km transmission.

In Fig. 4, the eye diagrams of PAM4 signal and OOK signal are shown. By adjusting the PC before the polarizer, the polarization direction of the output optical signal can be easily selected. It can control the level of the output PAM signal. When only one IM in the PM modulator is driven, the PM modulator will only generate a single polarized light signal. The eye diagrams of the signal in the direction of polarization is shown as Fig. 4 (a) and (c). In this situation, the signal would be OOK form. But if the PC is adjusted to get a circularly polarized light, the output optical signal would have two polarization directions of the same intensity. In this way, the output signal will have four average levels, so the output signal is in the form of PAM4. The diagrams of PAM4 signal are shown as Fig. 4 (b) and (d). Besides, by comparing Fig. 4 (a) and Fig. 4 (b) or Fig. 4 (c) and Fig. 4 (d), the 80km transmission do not significantly reduce the quality of the eye diagram.

Figure 5 shows the measured BER performance versus the input optical power into PD for PAM4 signal generated by the proposed method with and without 80km SMF-28 transmission. Obviously, 80km transmission has almost no effect on the BER of the signal. And when the input power into the photodiode is larger than -8 dBm, the BER of PAM4 signal generated by proposed method would be less than hard forward error correction (HD-FEC). The result proves that this scheme is feasible and has good performance.

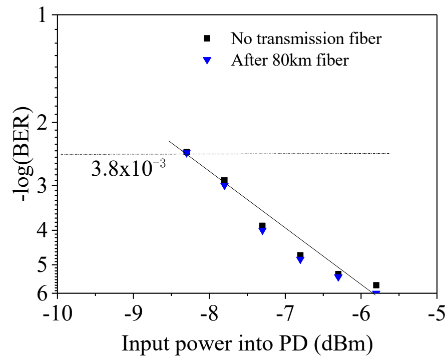

Figure. 5. Measured BER versus input power into PD for no transmission fiber and after 80km fiber.

As a conclusion, we proposed a new scheme to generate RF PAM4 optical signal at low cost. Instead of using an expensive DAC, the RF PAM4 signal is generated by combining two RF OOK signals with different polarization directions. In this way, the costs of the system decrease significantly. And we experimentally demonstrated the generation and 80km fiber transmission of RF PAM4 signal in this new method. The result of this experiment proved that, the proposed system has good performance.

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