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Using White-light Optical Differential Phase Shift Keying for Bipolar Transmission in ECDM-PON

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Abstract. A novel scheme is demonstrated and experimentally performed for the transmission of bipolar code in electronic code division multiplexing-passive optical network (ECDM-PON) based on the analysis of the existing ECDM-PON technical solutions to solve the problem that optical fibers can only transmit unipolar code in ECDM-PON and implement random access in uplink channel without distance measurement. The traditional optical differential phase shift keying (DPSK) is improved in this scheme and used for the transmission of bipolar code. The frequency mismatch of traditional optical DPSK demodulator (delay line interferometer) is solved with low-coherence inference technology. Simulation and experimental results proved the stability and low bit error rate of our scheme.

Keywords: bipolar code transmission, ECDM-PON, frequency mismatch, low coherence interference, optical differential phase shift keying

1 Introduction

Code division multiple access (CDMA) is a mode of access in spread-spectrum radio communications. It has attracted a great deal of interest, due to its asynchronous multiple access, built-in addressing and simplicity of implementation. In passive optical network (PON), one technology using CDMA is optical CDMA (OCDMA) [1]. A major problem with OCDMA is the high cost of non-traditional optical devices, such as optical encoders/decoders and optical pulse sources. In order to solve this problem, researchers chose to implement the encoding and decoding process in the electrical domain instead. A newly arisen technology using CDMA in passive optical network is electrical code division multiplexing-PON (ECDM-PON) [2-4]. This technology can not only provide random access for multiple users, but also suppress optical beat noise [5]. In 2007, M. Kashima et al. proposed an electronic code division multiplexing (ECDM)-PON structure for spread spectrum coding and decoding in electrical domain. This system uses ECDM as a downlink multiplexing technology and its power reaches 42dB without amplifiers [6]. In the same year, Yasuhiro Kotani et al. introduced an ECDM-PON scheme using a charge-coupled device matched filter (CCD-MF) as the decoder in electrical domain, which can achieve the highest data transmission rate of 1.25Gbps and the chip rate of 10Gchip/s with the code length of 8 bits [7]. J.B. Rosas-Fernấndez proposed an electronic code division multiple (ECDM)-PON system using a transversal filter as the spread-spectrum encoder in electrical domain [8-9]. Using ECDM-PON encoding/decoding in electrical domain avoids the use of expensive optical devices, thereby reducing system cost. In addition, using existing electrical devices to encode/decode can reduce implementation complexity and improve system stability. However, current research on ECDM-PON is still at the

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experimental stage and has not been put into application. In addition, the application of ECDM as an access technology in the uplink channel of PON has serious multiple access interference problems that have not been solved yet.

Since the encoding and decoding of ECDM-PON are carried out in electrical domain, many bipolar code with excellent performance can be conveniently used as the address code. However, most ECDM-PON technologies use intensity modulation/direct detection (IM/DD) in optical transmission, which can only transmit unipolar code. At present, ECDM-PON technologies lack a fine performance scheme to transmit bipolar code. The unipolar spread-spectrum signal output after photoelectric detection includes a DC component. In order to eliminate the effect of inter-symbol interference caused by the DC component, Walsh orthogonal code was often chosen by many ECDM-PON schemes for it contains no DC component [9]. But Walsh orthogonal code requires synchronous transmission, so it is mainly used in downlink channel where synchronous transmission can be implemented. In order to use bipolar pseudo-random code to maximize the advantages of spread-spectrum technology, many schemes have carried out conversion from unipolar code to bipolar code at the receiving end. This conversion greatly increases the complexity of the system.

In this paper, we propose a novel scheme for the transmission of bipolar code in ECDM-PON based on the analysis of the existing ECDM-PON technical solutions to solve the problem that optical fibers can only transmit unipolar code in ECDM-PON and implement random access in uplink channel without distance measurement.

Optical DPSK technology can transmit bipolar code [10-11], so we used DPSK technology for optical modulation and demodulation. But the delay line interferometer (DLI) used for demodulating DPSK signal has the problems of frequency mismatch and instability [12]. So it can not be applied in optical access network. To solve this problem, in our scheme, low coherence light is used as the optical carrier signal of DPSK modulation to eliminate the instability. We passed low coherence light through the DLI both before and after DPSK modulation to counteract the optical path difference produced in the DLI. Low coherence light has broad spectral band, so we named it as “white light”. By this means, interference with an optical path difference of zero occurs in part of the white light signal. Therefore, the stability of DLI while demodulating low-frequency signal has been greatly improved.

Simulation using *Optisystem* was performed to prove the feasibility of our scheme. Experiment demonstrated the advantage of our scheme in stability compared with traditional narrow-band light modulation.

2 Theoretical Model of Bipolar Signal Transmission in ECDM-PON

Before analyzing the bipolar optical transmission ECDM-PON system proposed in this paper, we firstly analyzed the traditional ECDM-PON scheme and the limitations of the existing unipolar optical transmission scheme.

2.1 Analysis of Unipolar Signal in ECDM-PON

The basic scheme of various ECDM-PON proposed before is shown in Fig. 1(a). In an optical network unit (ONU) accessed by a customer, user information is spread-spectrum-modulated by an address code. Both the user information and the address code are bipolar, and the modulated spread spectrum signal is also a bipolar sequence. Since the spread spectrum signal is bipolar, a bias must be added to it to make it a unipolar signal, and then the laser diode is modulated by this unipolar signal. The modulated optical signal passes through the single-mode fiber (SMF), and the signal after photoelectric detection is also a unipolar signal. At optical line terminal (OLT), a transverse filter (FIR filter) or a matched filter of charge-coupled devices is used for de-spreading. When de-spreading, each tap of the FIR filter is a local address code and the local address code is also bipolar. In the scheme of Fig. 1(a), the coding and decoding of spread spectrum modulation adopts the same method as that in traditional electrical domain, so it is more flexible and cost less than OCDMA that encodes and decodes in optical domain. However, different from the application of CDMA technology in electrical domain, the intensity modulation/direct detection (IM/DD) technique in optical fiber communication can only transmit positive signal. Therefore, a DC signal must be added to bipolar electrical signal to make it a unipolar signal, so that the photodetected signal at the OLT end is also a unipolar signal containing different DC biases. The following analysis is focused on how this requirement affects the performance of ECDM-PON.

For the ECDM-PON scheme in Fig. 1(a), we supposed the transmitted bipolar information $D_j\left(t\right)$ is modulated by the address code $Code_j$, and the modulated spreading sequence is $D_j\left(t\right)\cdot Code_j$. We assumed that the amplitude of the modulation signal after spreading is $\pm A_j$. During light intensity modulation, a DC bias need to be added to the bipolar spreading sequence to make it a unipolar sequence, which is expressed as $D_j\left(t\right)\cdot Code_j + A_j$. Not considering the fiber transmission loss, all the spreading sequences (with a number of N) at the receiving end after electro-optical detection are expressed as $\sum_{j=1}^{N}\left(D_j\left(t\right)\cdot Code_j + A_j\right)$. Then, the address code $Code_j$ is used to perform de-spreading on $\sum_{j=1}^{N}\left(D_j\left(t\right)\cdot Code_j + A_j\right)$, and the obtained value R_i is expressed as:

$$\begin{aligned} R_i &= Code_i \otimes \sum_{j=1}^{N}(A_j D_j(t)\cdot Code_j + A_j) \\ &= A_j Code_i \otimes \sum_{j=1}^{N} D_j(t)\cdot Code_j + Code_j \otimes \sum_{j=1}^{N} A_j \\ &= A_j D_i(t)\cdot Code_i \otimes Code_j + A_j \sum_{j=1, j\neq 1}^{N} Code_i \otimes Code_j + Code_i \otimes \sum_{j=1}^{N} A_j \end{aligned} \tag{1}$$

In Equation (1), term $A_j D_i\left(t\right)\cdot Code_i \otimes Code_i$ is the information term after de-spreading. Assuming the length of the address code is *w*, then the information term after de-spreading is $A_j D_i\left(t\right)w$. Term $A_j \sum_{j=1, j\neq i}^{N} Code_i \otimes Code_j$ is the inter-symbol interference term. Term $Code_i \otimes \sum_{j=1}^{N} A_j$ is the DC interference caused by the introduction of DC signal. The existence of term $Code_i \otimes \sum_{j=1}^{N} A_j$ is also the difference between ECDM-PON and electrical CDMA. Both orthogonal code and pseudo-random (PN) code can be chosen as the address code. In the next paragraph, we used orthogonal code as an example to analyze Equation (1).

Walsh code is a common orthogonal code. According to the nature of Walsh code, the cross correlation $A_j \sum_{j=1, j\neq i}^{N} Code_i \otimes Code_j$ equals to zero. Moreover, not considering the No. 0 bipolar Walsh code, the DC component of the bipolar Walsh code is zero, so term $Code_i \otimes \sum_{j=1}^{N} A_j$ is also zero. Therefore, only the information term $A_j D_i\left(t\right)w$ remains in the result of Equation (1). From this result, we can know that bipolar Walsh code can be easily applied in ECDM-PON system and the interference introduced by the unipolar signal is eliminated. However, good autocorrelation and cross-correlation of Walsh codes need the synchronization of signals. In ECDM-PON system, only the downlink signal can be synchronized, so most of the current ECDM-PON systems are used in downlink channel with bipolar Walsh code used as the address code. Other orthogonal codes, such as orthogonal Gold codes, can also be used as address codes and also need to be applied in downlink channel.

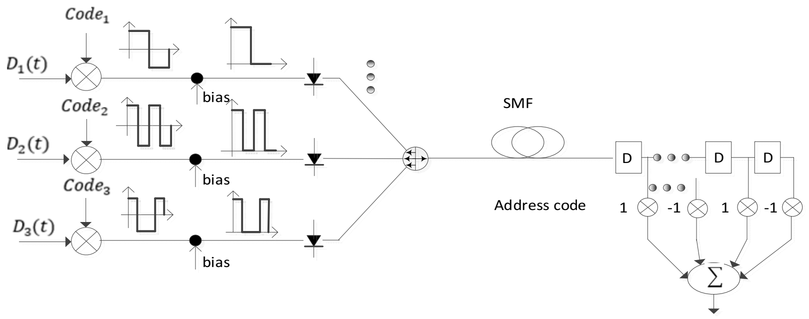
An important purpose of combining CDMA technology with PON technology is to achieve random access, thereby solving the problem that data transmission in uplink channel in traditional PON requires distance measurement. Since random access cannot guarantee synchronization, the orthogonal code mentioned above cannot be used for random access. In this case, address code $Code_j$ should be a PN code. Gold code has good correlation property, so it is an ideal address code. Gold codes include balanced Gold codes and unbalanced Gold codes. In a balanced Gold code, the number of "1" is only one more than the number of “-1” in a period. While in an unbalanced Gold code, the difference between the number of “1” and “-1” is more than 1 in a period, which means that the difference between the number of “1” and “-1” in a period is more than 1. In the DC interference term $Code_i \otimes \sum_{j=1}^{N} A_j$, assuming that $Code_i$ is a balanced Gold code and A_j is a constant with the value of A, then we have $Code_i \otimes \sum_{j=1}^{N} A_j = NA$. if $Code_i$ is an unbalanced code, the DC interference term will be larger. Because of random access, N is a random variable and the pulse amplitude A_j at the receiving end is also a variable. Therefore, DC interference term $Code_i \otimes \sum_{j=1}^{N} A_j$ will introduce large inter-symbol interference. Therefore, if Gold code is directly used as the address code for uplink data transmission, the performance of ECDM-PON will be greatly affected. The de-spreaded information $A_j D_i(t) \cdot Code_i \otimes Code_i$ determined by the auto-correlation performance of Gold code and the inter-symbol interference $A_j \sum_{j=1, j \neq i}^{N} Code_i \otimes Code_j$ determined by the cross-correlation performance of Gold code are completely same as those in electrical CDMA system.

If the DC component $\sum_{j=1}^{N} A_j$ can be removed from the received signal $\sum_{j=1}^{N} \left(A_j D_j \cdot Code_j + A_j \right)$, only $A_j Code_i \otimes \sum_{j=1}^{N} D_j(t) \cdot Code_j$ is left in Equation (1), which is exactly the same as the received signal in electrical domain. However, if we remove the DC component $\sum_{j=1}^{N} A_j$, because the number of “1” and “-1” in address code $Code_j$ are often unequal, removing DC component will also cause distortion to term $A_j Code_i \otimes \sum_{j=1}^{N} D_j(t) \cdot Code_j$.. The received signal is a broadband signal. To remove the DC component from a broadband signal, a band-stop filter or notch filter must be added. A band-stop filter with good performance generally uses the structure of a FIR filter [13]. In summary, the operation of removing the DC signal will not only increase the complexity of signal processing but also cause signal distortion. There are some other technical solutions to achieve the conversion from unipolar code to bipolar code, like subtracting the complement from the address code to achieve bipolar, which is used in OTDR ranging [11]. All these solutions have greatly increased the system complexity.

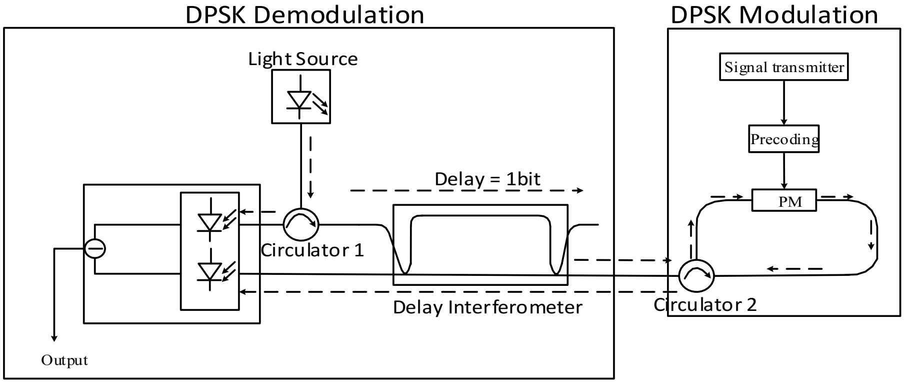
If we can realize bipolar transmission with optical signal, it will enable ECDM-PON to adopt the same codec scheme as that of electrical CDMA. In the next part, we will introduce a novel scheme to realize the transmission of bipolar code with optical signal in ECDM-PON.

2.2 Theoretical Model of White-light DPSK

Fig. 1(b) is the diagram of our scheme, in which white light is used for DPSK modulation and demodulation with delay line interferometer. The white light signal is transmitted in the direction of dotted arrows. After sent out from the light source, the white-light signal passes through the delay line interferometer for preprocessing. Then the pre-processed optical signal passes through circulator 2, and then it is phase modulated by the pre-coded unipolar code. After that, the modulated signal passes through circulator 2 again, returning to the delay line interferometer, and the delay line interferometer demodulates the coherent DPSK-modulated signal. Finally, the demodulated signal is converted into electric signal in the balanced detector for outputs.



(a) The basic scheme of various ECDM-PON proposed before



(b) The scheme we proposed for bipolar signal transmission proposed in ECDM-PON

Fig. 1. The diagrams of traditional ECDM-PON scheme and the ECDM-PON scheme wo propose

Fig. 2 shows the optical pre-processing procedure mentioned above. The white-light carrier signal enters the delay line interferometer and delays by 1 bit, and the delay line interferometer outputs a mixed optical carrier signal. Coupler 1 and 2 are both directional couplers with coupling coefficient of 0.5. We named the optical signal passing through the short arm *signal a* and the optical signal passing through the long arm *signal b*. Their corresponding intensities are $E_1(z)$ and $E_2(z)$. The output signal of coupler 1 could be expressed as follows:

$$\begin{bmatrix} E_1(z) \\ E_2(z) \end{bmatrix} = G_c \begin{bmatrix} E_1(0) \\ E_2(0) \end{bmatrix} \tag{2}$$

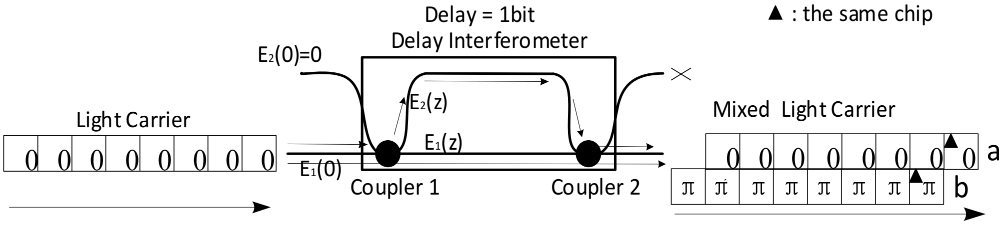


Fig. 2. Phase before and after the optical signal passes through the delay line interferometer

Here, $E_1(0)$ and $E_2(0)$ are the input signals of the two arms. As shown in Fig. 2, $E_2(0)$ equals to 0. G_c is the Jones matrix of coupler. It could be expressed by:

$$G_c = \frac{\sqrt{2}}{2} \begin{bmatrix} 1 & -j \\ -j & 1 \end{bmatrix} \tag{3}$$

Equation (3) also applies to coupler 2. According to Equation (2) and (3), the phase of *signal b* has a change of π/2 each time it passes through a coupler, so its total phase change passing through the interferometer is π if we ignore the phase change caused by interferometer unequal arms. *Signal a*, on the other hand, does not have any phase change. Since the coherence length of white light is 0, the optical path difference between *signal a* and *signal b* is much longer than the coherence length of white light. So two outgoing optical signals do not interfere with each other, and their intensities are both half of the original.

After preprocessing, the mixed optical carrier signal passes through circulator 2 and enters the CDMA+DPSK modulation section. The digital signal b_n, which is emitted from the bit sequence generator, is differential pre-coded at first. Differential precoding adopts the method of delayed XOR. The pre-coded signal d_n is expressed by:

$$d_n = d_{n-1} \oplus b_n \tag{4}$$

Then, the pre-coded digital signal d_n phase modulates optical *signals a* and *b* in the mixed carrier signal. The modulation process is shown in Fig. 3. When dn is 1, both signal a and signal b have a phase change of π. When d_n is 0, they have no phase change. After that, the modulated optical signal is transmitted back into the delay line interferometer.

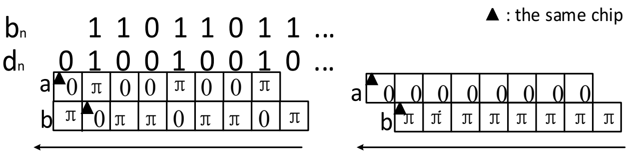
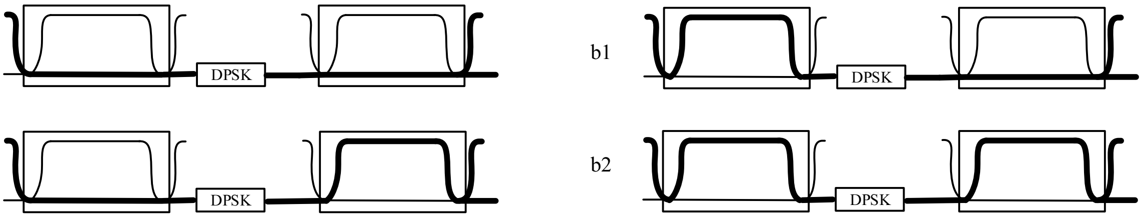
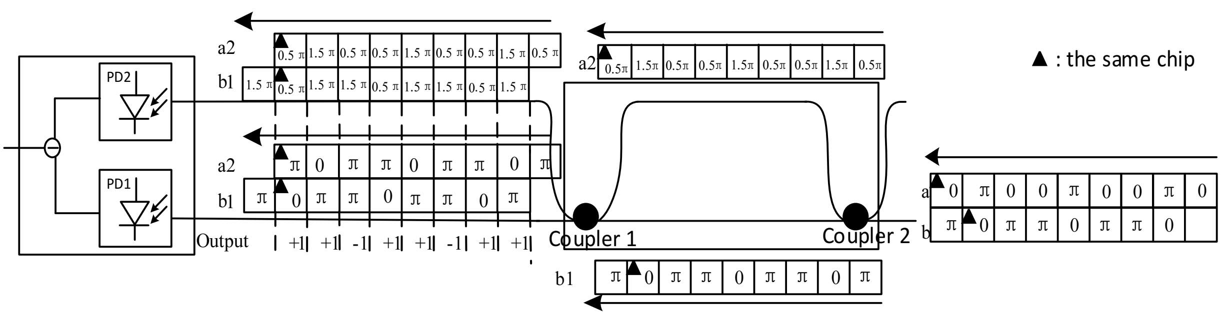


Fig. 3. DPSK modulation of *signal a and b*

Fig. 4(a) shows four different paths of the optical signal in the delay line interferometer after it passes through the delay line interferometer again. We name them *signals a1, a2, b1* and *b2*. *Optical signals a1* and *b2* are non-coherent light due to their unequal optical path length. They will be offset by the photoelectric balanced detector.



(a) The paths taken by *optical signals a1, a2, b1, b2*



(b) The phase change of the optical signal as it passes through the delay interferometer

Fig. 4. The optical paths and phase change of *optical signals a1, a2, b1, b2*

Since *signals b1* and *a2* pass along light paths of substantially the same length, the mixed optical signal of them is coherent light. So we can ignore the phase changes caused by unequal arms while demodulating *signals b1* and *a2*. The process of coherent demodulation is shown in Fig. 4(b). The input signal $\boldsymbol{E_{in}(\omega)}$ could be expressed by

$$E_{in}(\omega) = Ae^{j\Phi} \tag{5}$$

where A and Φ are the amplitude and the phase of the input optical signal respectively.

The input-output relationship of the delay line interferometer could be expressed by:

$$\begin{aligned} &(E_1(\omega)\ E_2(\omega)) \\ =\ &(E_1(\omega)\ \ 0\ \ )\begin{bmatrix} \sqrt{0.5} & j\sqrt{0.5} \\ j\sqrt{0.5} & \sqrt{0.5} \end{bmatrix}\begin{bmatrix} e^{-j\omega T} & 0 \\ 0 & 1 \end{bmatrix}\begin{bmatrix} \sqrt{0.5} & j\sqrt{0.5} \\ j\sqrt{0.5} & \sqrt{0.5} \end{bmatrix} \\ =\ &\left(\frac{1}{2}A[e^{j\Phi_n} - e^{j\Phi_{n+1}}]\ \ \frac{1}{2}A[e^{j\Phi_n} + e^{j\Phi_{n+1}}]\right) \end{aligned} \tag{6}$$

Here, $\boldsymbol{E_1(\omega)}$ and $\boldsymbol{E_2(\omega)}$ are the signal received by PD1 and PD2 in Fig. 4(b). T is the delay (1 bit).

From Equation (6), we can know that when Φ_{n+1} and Φ_n are equal, the amplitudes of the signals received by PD1 and PD2 are 0 and A, respectively, and the outgoing signal is +1. When Φ_{n+1} and Φ_n are not equal, the amplitudes of the signals received by PD1 and PD2 are A and 0, respectively, and the outgoing signal is -1. For example, when the input code is 11011011, as shown in Fig. 3, the output code will be +1 +1 -1 +1 +1 -1 +1 +1.

In this way, a bipolar code transmission scheme is proposed to simplify the electronic code division multiplexing-PON (ECDM-PON) system. Since this scheme can solve the frequency mismatch and instability of delay line interferometers, it has broad application prospects in multi-user random access systems.

3 Simulation and Stability Testing

3.1 Simulation

Fig. 5 is a simulation schematic diagram using *Optisystem*. We set the bit rate of the bit sequence generator to 100Mbps. The continuous wave (CW) laser, serving as the light source, produced an optical signal with a wavelength of 1550nm and a line width of 2.1752×10^6MHz. The phase deviation of the phase modulator is π. The output of the balanced detector is filtered by a band-pass filter and transmitted to the oscilloscope visualizer. The oscilloscope visualizer displays the output bipolar code. Fig. 6(a) shows the output with m sequence 1110010 as the input code. When the inputs are 1 and 0, the outputs are +1 and -1, respectively. This simulation result is consistent with theoretical analysis.

We have proven the feasibility of our scheme when transmitting signals with a frequency of 100Mbps. To test the feasibility of our scheme in higher frequency band, 1Gbps (Fig. 6(c)) and 2.5Gbps (Fig. 6(d)) are chosen as the bit rate of the bit sequence generator. The minimum BER when the bit rate is 1Gbps and 2.5Gbps is 5.881×10^{-10} bps and 5.41912×10^{-11} bps, respectively. Because a BER of 10^{-9} bps is often considered the maximum acceptable BER for telecommunication applications, our scheme can also work well in high frequency band.

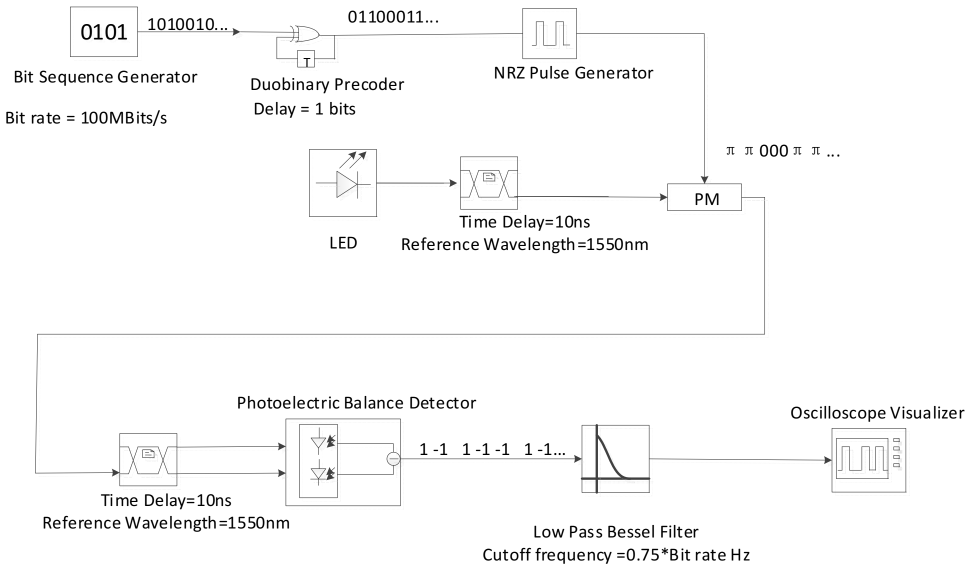
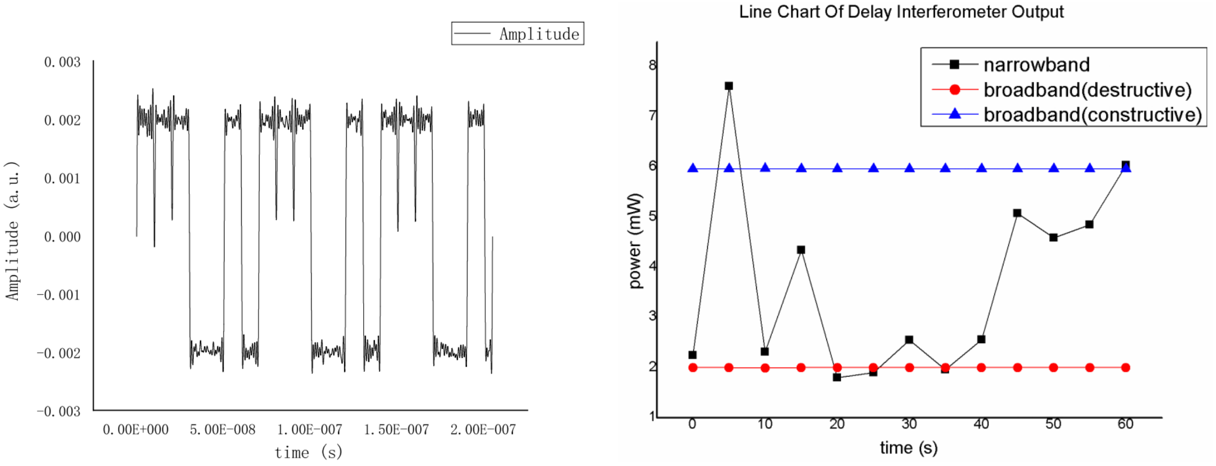
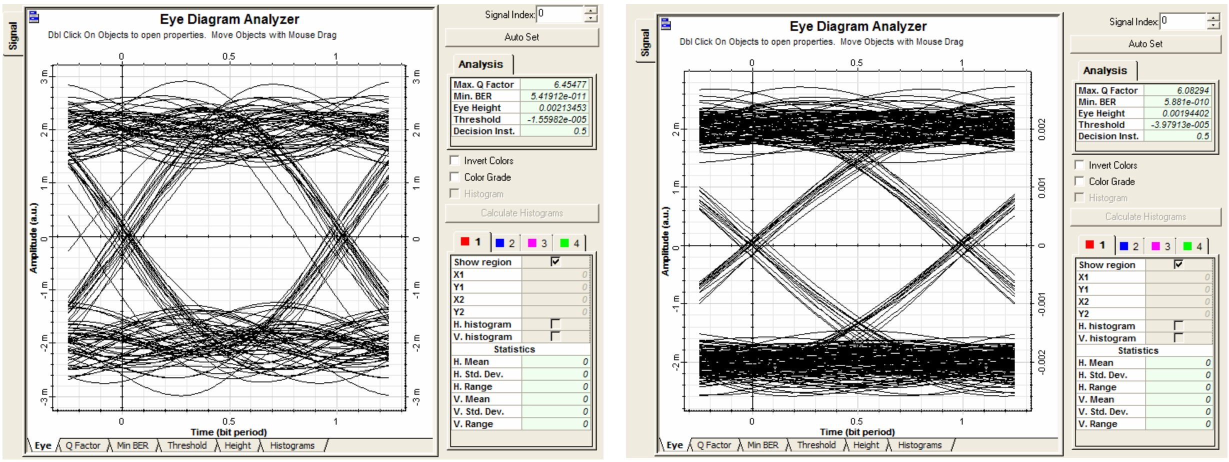


Fig. 5. Simulation schematic diagram



(a) The output with m sequence 1110010 as the input code

(b) Delay line interferometer output power



Max. Q Factor	6.45477
Min. BER	5.41912e-011
Eye Height	0.00213453
Threshold	-1.55982e-005
Decision Inst.	0.5

Show region	☑
X1	0
Y1	0
X2	0
Y2	0
H. histogram	☐
V. histogram	☐
Statistics	
H. Mean	0
H. Std. Dev.	0
H. Range	0
V. Mean	0
V. Std. Dev.	0
V. Range	0

Max. Q Factor	6.08294
Min. BER	5.881e-010
Eye Height	0.00194402
Threshold	-3.97913e-005
Decision Inst.	0.5

Show region	☑
X1	0
Y1	0
X2	0
Y2	0
H. histogram	☐
V. histogram	☐
Statistics	
H. Mean	0
H. Std. Dev.	0
H. Range	0
V. Mean	0
V. Std. Dev.	0
V. Range	0

(c) Eye diagram analysis for 1Gbps

(d) Eye diagram analysis for 2.5Gbps

Fig. 6. Simulation and experimental results

3.2 Stability Testing

We have also experimentally demonstrated the advantage of our scheme in stability, compared with the traditional narrow-band light modulation. Our experimental setup is shown in Fig. 1(b). The input power we set for narrow-band light modulation and white light modulation is 10mW and 20mW, respectively. We first set the line width of the light source to 10MHz and measured the output power of the delay line interferometer after the optical signal passes through it for the first time. Then we set the line width of the light source to 3.750×10^6 MHz (30nm) and measured the output power of the delay line interferometer after the optical signal passes through it for the second time. Since we set the bit rate of the bit sequence generator to 100Mbps and the refractive index of the optical fiber is 1.5, the length of each chip could be calculated as 2 meters, which is equal to the arm-length difference of delay line interferometer. The coherence length of the light L could be expressed as

$$L=\frac{\lambda^2}{\Delta\lambda} \tag{7}$$

Here, $\Delta\lambda$ is the spectral width of the input signal. λ is the frequency of the input signal.

For narrow-band light and white light, the frequency we set and coherent length we calculated from Equation (7) are shown in Table 1.

Table 1. The Frequency and Coherent Length of Narrow-band Light and White Light

	Frequency (MHz)	Coherent Length (meters)
Narrow-band Light	10	20
Broad-band Light	3.75×10^6	8.0×10^{-5}

We can see from table 1 that the coherence length of narrow-band light is greater than the optical path difference and that of white light is much smaller than the optical path difference. So only the narrow-band light remains coherent.

Fig. 6(b) shows the output power stability of the two different solutions. As shown in Fig. 6(b), while using narrow-band modulation, the stability of outputs can be barely guaranteed. While using the scheme supposed by us, the optical signal is broad-band, and the output power of the two arms is stabilized at 5.95mW (constructive arm) and 1.99mW (destructive arm). Due to the insertion loss, their sum is less than 10mW. In the power output from the constructive arm, the light intensity of non-coherent light is 1.99mW, and the light intensity of coherent light is 3.96mW, which is about twice that of incoherent light. This result is in line with the theoretical analysis and proves that our solution can significantly improve the output power stability of the delay line interferometer.

4 Conclusion

We have proposed and experimentally demonstrated a bipolar signal transmission scheme for the transmission of bipolar code in electronic code division multiplexing-passive optical network (ECDM-PON) based on the analysis of the existing ECDM-PON technical solutions to solve the problem that optical fibers can only transmit unipolar code in ECDM-PON and implement random access in uplink channel without distance measurement. In this scheme, we improved the traditional optical differential phase shift keying (DPSK) to make it available for the transmission of bipolar code. We used low-coherence inference technology to eliminate the frequency mismatch of traditional optical DPSK demodulator (delay line interferometer). The simulation results show that our scheme can work well in both low and high frequency and the experimental results show that the stability of the delay line interferometer in our scheme is significantly improved compared with that in traditional narrow-band light modulation. This scheme has broad application prospects in asynchronous multi-user system.

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