Low-cost coherent receiver for long-reach optical access network using single-ended detection

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A low-cost coherent receiver using two 2 × 3 optical hybrids and single-ended detection is proposed for long-reach optical access network. This structure can detect the two polarization components of polarization division multiplexing (PDM) signals. Polarization de-multiplexing and signal-to-signal beat interference (SSBI) cancellation are realized by using only three photodiodes. Simulation results for 40 Gb/s PDM-OFDM transmissions indicate that the low-cost coherent receiver has 3.2 dB optical signal-to-noise ratio difference compared with the theoretical value. © 2014 Optical Society of America

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Cost-sensitive access networks are an indispensable part of the overall global optical networks [1]. To reduce the system costs, long-reach passive optical networks (LR-PONs) with a reach up to 100 km and large splitting ratio based on direct-detection or coherent-detection techniques [2,3] are being studied extensively. Direct-detection based LR-PONs have the advantage of low cost. However, limited sensitivity, signal-to-signal beat interference (SSBI) and chromatic dispersion induced power penalty are the key factors affecting the overall system performance. Coherent detection has the advantage of high sensitivity [4] and enables the use of advanced modulation formats such as quadrature amplitude modulation (QAM) and polarization division multiplexing (PDM) to increase system capacities [5,6]. Digital signal processing techniques are used in coherent detection systems to compensate transmission impairments of optical link in digital domain [7]. However, power consumption and the cost of a conventional coherent receiver consisting of four balanced photodiodes (B-PDs) and four analogy-to-digital converters (ADCs) restricts their adoptions in LR-PON [8]. Recently, a simplified optical coherent receiver is proposed for LR-PONs, in which four B-PDs are reduced to two B-PDs [3]. Alternatively, a 3 × 3 coupler and single-ended detection can be used as low-cost coherent receivers. However, this proposed simplified configuration with only three PDM signals is not designed for PDM systems [9].

In order to realize PDM transmissions to improve the capacity of LR-PONs, we propose a low-cost coherent receiver structure consisting of two 2 × 3 optical hybrids and only three PDM signals is based on single-ended detection in this Letter. Thus the cost of the proposed coherent receiver could be reduced greatly compared with the conventional coherent receiver. We demonstrate the proposed scheme in a 40 Gb/s PDM-OFDM transmission system with 16 quadrature amplitude modulation (16-QAM) signals, and simulation results show that the PDM signals can be appropriately recovered, thus making the proposed scheme a practical, low-cost solution for LR-PONs.

Figure 1 shows the basic configuration of the proposed low-cost coherent receiver that consists of two 2 × 3 optical hybrids, five polarization beam splitters/combiners (PBSs/PBCs), and 3 PDs. The optical signal and local oscillator (LO) are first split into x- and y-polarization components by using two PBSs and then go into the corresponding optical hybrids. The relative phase differences between the optical signal and LO of the six outputs are designed to be 0°, 0°, 180°, 0°, 180°, and 180°; and the power splitting ratio of each 2 × 3 optical hybrid are equal. The output optical signals of the hybrids are first grouped and recombined by using the PBCs, then fed into the corresponding PDs. A simple analog subtraction circuits are used to obtain x- and y-polarization components from three PDs.

To simplify the analysis, we first study the case without polarization crosstalks between the signals after the PDS. In principle, the joint transfer matrix of two 2 × 3 optical hybrids

Fig. 1. Configuration of the proposed low-cost coherent receiver.
where $a$ and $b$ are the coefficients of the two optical hybrids in the first stage. The six output signals from two optical hybrids can then be expressed as

$$
T_H = \begin{bmatrix}
a & b & 0 & 0 \\
b & a & 0 & 0 \\
a & -b & 0 & 0 \\
0 & 0 & a & b \\
0 & 0 & b & a \\
0 & 0 & a & -b
\end{bmatrix},
$$

(1)

where $E_{x,y}(g)$ and $E_{L,xy}(g)$ are optical signal and LO components on $x$- ($y$-) polarization, respectively. These six output signals are then divided into three groups—$E_1$, $E_2$, and $E_5$, and $E_3$, $E_4$, and $E_6$; they are recombined using three PBCs to form three new PDM signals that can be written as

$$
E_{o1} = \begin{bmatrix}
E_1 \\
E_2 \\
E_3 \\
E_4 \\
E_5 \\
E_6
\end{bmatrix} = \begin{bmatrix}
aE_{x,xy} + bE_{L,xy} \\
bE_{x,xy} + aE_{L,xy} \\
aE_{y,xy} - bE_{L,xy} \\
bE_{y,xy} - aE_{L,xy} \\
aE_{y,xy} + bE_{L,xy} \\
bE_{y,xy} + aE_{L,xy}
\end{bmatrix},
$$

(2)

$$
E_{o2} = \begin{bmatrix}
E_1 \\
E_2 \\
E_3 \\
E_4 \\
E_5 \\
E_6
\end{bmatrix} = \begin{bmatrix}
bE_{x,xy} + aE_{L,xy} \\
E_{x,xy} - bE_{L,xy} \\
aE_{y,xy} - bE_{L,xy} \\
E_{y,xy} - aE_{L,xy} \\
aE_{y,xy} + bE_{L,xy} \\
bE_{y,xy} + aE_{L,xy}
\end{bmatrix},
$$

(3)

$$
E_{o3} = \begin{bmatrix}
E_1 \\
E_2 \\
E_3 \\
E_4 \\
E_5 \\
E_6
\end{bmatrix} = \begin{bmatrix}
aE_{x,xy} - bE_{L,xy} \\
aE_{y,xy} - aE_{L,xy} \\
bE_{y,xy} + aE_{L,xy} \\
bE_{y,xy} - aE_{L,xy} \\
bE_{y,xy} - aE_{L,xy} \\
bE_{y,xy} - aE_{L,xy}
\end{bmatrix},
$$

(4)

where $E_{o1}$, $E_{o2}$, and $E_{o3}$ are recombined dual-polarization optical signals. As there are no polarization crosstalks, photo currents of the three PDM signals are

$$
I_1 \propto |aE_{x,xy} + bE_{L,xy}|^2 + |aE_{y,xy} + bE_{L,xy}|^2
= |a|^2|E_{x,xy}|^2 + |b|^2|E_{L,xy}|^2
+ 2 \text{Re}\{ab^* [E_{x,xy}E_{L,xy}^* + E_{y,xy}E_{L,xy}^*]\},
$$

(5)

$$
I_2 \propto |bE_{x,xy} + aE_{L,xy}|^2 + |bE_{y,xy} - aE_{L,xy}|^2
= |b|^2|E_{x,xy}|^2 + |a|^2|E_{L,xy}|^2
+ 2 \text{Re}\{ba^* [E_{x,xy}E_{L,xy}^* - E_{y,xy}E_{L,xy}^*]\},
$$

(6)

$$
I_3 \propto |aE_{x,xy} - bE_{L,xy}|^2 + |aE_{y,xy} - bE_{L,xy}|^2
= |a|^2|E_{x,xy}|^2 + |b|^2|E_{L,xy}|^2
- 2 \text{Re}\{ab^* [E_{x,xy}E_{L,xy}^* + E_{y,xy}E_{L,xy}^*]\}.
$$

(7)

In the above equations, the first term represents the SSBI caused by the PDM signal, which needs to be compensated. The second term is the direct current (DC) originated from the LO that can be ignored. The last term is the desired signal to be recovered.

In conventional coherent receivers, SSBI can be cancelled by using B-PDs directly. To fully compensate SSBI in our proposed low-cost coherent receiver, we can choose the parameters of the hybrids to be

$$
|b| = |a|, \quad \text{and} \quad b = a \quad \text{or} \quad b = ja,
$$

(8)

and based on the Eqs. (6)-(9), the photo-currents of $x$- and $y$-polarization components of reconstructed signals without SSBI can be expressed as

$$
\begin{bmatrix}
I_x \\
I_y
\end{bmatrix} = \begin{bmatrix}
I_2 - I_3 \\
I_1 - I_2
\end{bmatrix} = \begin{bmatrix}
\text{Re}\{E_{x,xy}E_{L,xy}^*\} \\
\text{Re}\{E_{y,xy}E_{L,xy}^*\}
\end{bmatrix}
$$

or

$$
\begin{bmatrix}
I_x \\
I_y
\end{bmatrix} = \begin{bmatrix}
-\text{Im}\{E_{x,xy}E_{L,xy}^*\} \\
-\text{Im}\{E_{y,xy}E_{L,xy}^*\}
\end{bmatrix}.
$$

(9)

One can deduce from Eq. (10) that this receiver configuration can adequately detect real-valued signals but not the in-phase component ($I$) and quadrature component ($Q$) of complex signals. However, heterodyne detection can be used to extend the proposed receiver structure to incorporate complex-valued signaling like QAM [5].

In the presence of a polarization crosstalk, the output signal with polarization crosstalk can be expressed as

$$
\begin{bmatrix}
E_{x,\text{out}} \\
E_{y,\text{out}}
\end{bmatrix} = \begin{bmatrix}
\cos(\alpha) & -\sin(\alpha) \\
\sin(\alpha) & \cos(\alpha)
\end{bmatrix} \begin{bmatrix}
E_{x,\text{in}} \\
E_{y,\text{in}}
\end{bmatrix},
$$

(10)

where $\alpha$ is the rotation angle of the signal relative to the principal axis of the PBS. In this case, the Jones matrix used to compensate such polarization crosstalks can be expressed as

$$
H_{\text{pol}} = \begin{bmatrix}
\cos(\alpha) & -\sin(\alpha) \\
\sin(\alpha) & \cos(\alpha)
\end{bmatrix}^{-1},
$$

(11)

and it can be implemented digitally at the receiver.

To verify the feasibility of our proposed low-cost coherent receiver for the PDM-OFDM system, a simulation of 40 Gb/s 16-QAM PDM-OFDM using heterodyne detection is conducted and the schematic diagram is shown in Fig. 2. The proposed rotation angle $\alpha$ in the simulation is set as 30 deg in the simulation. The FFT size is 256, in which 64 subcarriers are loaded with OFDM signals. The center one subcarrier is unloaded to avoid DC influence. The cyclic prefix is 1/8 of FFT size per OFDM symbol. As shown in Fig. 2, a laser with line-width 100 kHz is first split into two parts and then modulated by respective $I/Q$ modulators that are driven by OFDM signals generated by separate OFDM generators. A PBC is used to form the PDM OFDM signal [10]. After the erbium-doped optical fiber amplifier (EDFA), the transmitted signals are fed into the proposed low-cost coherent receiver structure followed by offline digital signal processing.

To show whether SSBI has been cancelled using the proposed low-cost coherent receiver, a 6.0 GHz guard
band has been set between the LO and OFDM signal. The spectrum of $I_x$ detected by PD and the spectrum of $I_y$ after subtraction are shown as insets (a) and (b) in Fig. 2, respectively. We can clearly see that the SSBI has been successfully mitigated. Thus, a 6.6 GHz guard band is not required in the simulation.

Then a simple B2B measurement is carried out to show the bit error rate (BER) performance versus optical signal-to-noise ratio (OSNR) using the proposed low-cost coherent receiver and simulation results are shown in Fig. 3. The theoretical value versus OSNR is also given for comparison. It can be found that the required OSNRs of $x$- and $y$-polarization components are 16.2 and 16.3 dB for BER $= 1 \times 10^{-3}$, respectively. Compared with the theoretical value, the simulation implementation penalty is around 3.2 dB, which is mainly caused by the heterodyne detection that contains the noise from the unwanted image band [5]. There should be no performance difference between the theoretical value and heterodyne detection, provided the optical filtering is used to eliminate the image-band ASE for heterodyne detection. However, considering the cost in the PON, we did not use the optical filter to eliminate the excess ASE from the unwanted image band. Therefore, there is ~3 dB OSNR degradation compared with the theoretical value.

The recovered 16-QAM constellations of the circled points are shown in insets respectively. Figures 3(a) and 3(d) are the constellations of $x$- and $y$-polarization signals without compensating for polarization crosstalks while Figs. 3(b) and 3(c) are the constellations using de-multiplexing algorithm processing.

In conclusion, we have demonstrated a low-cost coherent receiver for PDM LR-PON systems using two $2 \times 3$ optical hybrids and single-ended detection. The proposed structure only needs three PDs and two ADCs, and thus has low power consumption and low cost compared with the conventional coherent receiver. In addition, the proposed structure can realize PDM and SSBI cancellation. Simulation results demonstrated adequate transmission performance and are tolerant to polarization crosstalks through appropriate receiver signal processing.

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