56 Gb/s direct-detection polarization multiplexing multi-band CAP transmission

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Carrierless amplitude and phase (CAP) modulation is generating increasing interest for short-reach optical communications. Polarization multiplexing (PolMux) is a good way to improve the CAP system's data rate further with the limited bandwidth of electrical devices. In this Letter, we experimentally demonstrate a 56 Gb/s direct-detection PolMux CAP system over a 15 km fiber link for the first time, to our best knowledge. Two-band CAP modulation with different modulated orders for each band is employed. An optical filter at the receiver is utilized to realize the polarization separation. No extra digital signal processing for polarization-dependent distortion is required.

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The development of multi-media services and cloud computing has driven the speed of short-reach data communication links to higher and higher data rates. Carrierless amplitude and phase (CAP) modulation, a variant of quadrature amplitude modulation (QAM), is generating increasing interest[1–11]. The digital or analog implementation of shaping and matched filters considerably reduce system complexity and component requirements, and hence enable a relatively high data rate to be transmitted using low-cost optical components. Many CAP-based systems have been reported recently. Research towards 100 Gb/s multi-subband CAP system over a 100 m multi-mode fiber (MMF) is shown in Ref. [2] using an 850 nm vertical cavity surface emitting laser (VCSEL). An $11\times 5\times 9.3$ Gb/s wavelength-division multiplexing (WDM) CAP16 system is demonstrated in Ref. [3]. A 400 Gb/s O-band CAP system over a 40 km standard single-mode fiber (SSMF) is demonstrated in Ref. [4], and a 10 Gb/s CAP signal with high-order coding up to seven and eight levels are proposed in Ref. [5]. A high-order CAP system with direct detection (DD) can increase the link capacity at a fixed bandwidth and serve as a feasible choice for future high-capacity emerging optical interconnects for consumer electronics.

An alterative way to increase the capacity is polarization multiplexing (PolMux), which is considered an excellent scheme to improve the data rate further and has been widely used in coherent systems. With the help of coherent detection and advanced digital signal processing (DSP), the polarization-dependent distortion can be compensated easily. However, the phase information is lost in DD systems, so conventional DSP algorithms cannot be used directly. To solve this problem, many DD–PolMux systems have been demonstrated. A post-detection DSP is proposed for orthogonal frequency-division multiplexing (OFDM) in Ref. [8], and a low-complexity photonic integrated optical front-end and an adaptive 3×2 multi-input multi-output (MIMO) DSP is shown in Ref. [12]. Reference [13] shows an optical filtering scheme without DSP for the OFDM signal. The first two schemes are challenging and not suitable for the DD–PolMux CAP system, because they require either specified training patterns in the frequency domain or a photonic-integrated optical front-end.

In this Letter, an optical filtering technique is introduced to realize a DD–PolMux CAP system. Unlike Ref. [13], there is no low-frequency guard band, so higher potential spectral efficiency (SE) is obtained. Two-band CAP modulation with different modulated orders for each band is employed. Compared with ordinary high-order DD solution with the same data capacity, 5.1 bit/s/Hz SE is obtained in our system using single side-band modulation, which is higher than ordinary CAP32 (4.5 bit/s/Hz) but lower than ordinary CAP64 (5.5 bit/s/Hz). However, we simply use CAP32 and CAP4 in this system to achieve the SE. When a double sideband is considered, the SE is 2.0 bit/s/Hz, lower than ordinary CAP32 (2.3 bit/s/Hz). The minimum device electrical bandwidth required for ordinary CAP32 is 12.3 GHz, whereas the device electrical bandwidth we used is only 10 GHz, which means a lower cost. With the help of an optical filter and a modified two-band CAP receiver, we experimentally demonstrate a 56 Gb/s DD–PolMux CAP system over a 15 km fiber link for the first time, to our knowledge.

In conventional PolMux systems, x- and y-polarizations are separated using a polarization beam splitter (PBS). The polarization rotation and dispersion in the transmission links can be recovered with the help of coherent detection and advanced DSP. However, these algorithms are not suitable on account of the square-law detection in DD

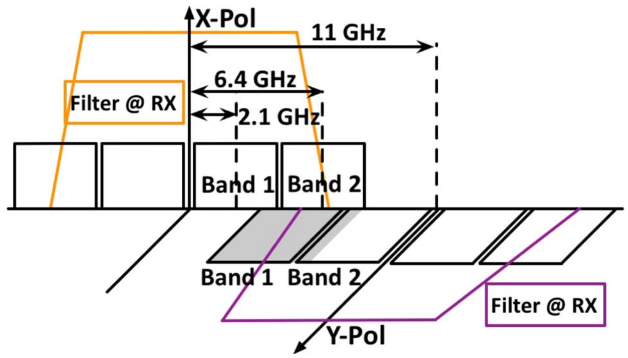

Fig. 1. Illustration of the proposed DD–PolMux multi-band CAP system.

systems. To realize a DD–PolMux system, two optical carriers with a frequency offset are utilized, as shown in Fig. 1. They are in x- and y-polarizations and modulated, respectively. An optical bandpass filter is used at the receiver side to filter out the optical carrier and signal in x- or y-polarization. Carrier-signal mixing only occurs between photons with the same polarization, so the power of the signal in alternative polarization is suppressed because of the corresponding removal optical carrier. Note that the side band on the left of the x-polarization carrier or the right of the y-polarization carrier can be filtered out to improve the spectrum efficiency further to 5.1 bit/s/Hz. Consequently, the center wavelength of the filter is fixed to the carrier wavelength in our work to ensure that the target signal bands are between the carriers.

The main tradeoff is from the optical filter. The filter bandwidth should be smaller enough to suppress the carrier in an alternative polarization. On the other hand, the narrow filter will introduce distortion at the high-frequency components. Therefore, a two-band CAP modulation format is utilized. The entire signal band is divided into two parts. High-order modulation such as CAP32 is applied on the low-frequency components (Band 1). For the high-frequency components (Band 2), CAP4 is used since larger power attenuation is found after the filter at the receiver. Also, some frequency guard band is set to help suppress the unwanted optical carrier. The shaded area in Fig. 1 is occupied commonly by the signals in x- and y-polarizations. Our PolMux–DD CAP system is realized with a relatively high SE.

Figure 2 shows the experimental setup of the DD–PolMux 2-band CAP system. At the transmitter side, two original bit sequences with a $2^9 - 1$ pseudo-random bit sequence (PRBS) are generated and mapped into five and two levels for Bands 1 and 2, respectively. In order to match the operating rate of the shaping filters that follows, the coded sequences are up-sampled by a factor of 6. The generation procedure of the CAP signal in each band is the same as in Ref. [7] and combined at the output. The roll-off coefficient of the baseband impulse response is $\alpha = 0.1$. The baud rate for each band is set to 4 Gbaud. The center frequency f_c for Bands 1 and 2 is set to 2.1 and 6.4 GHz, respectively, as shown in Fig. 1. An arbitrary waveform generator (AWG; Tektronix 7122C) is used to produce a two-band CAP RF signal at a rate of 24 GSa/s. The RF signal D and its negative $\bar{D}$ after a 100 GHz electrical amplifier (EA) are used to drive the 10 GHz $LiNbO_3$ Mach–Zehnder amplitude modulators (AMs). The two branches are uncorrelated with different time delays. Although the AMs and EAs in the two branches are the same model, the diversity of the devices leads to different results. As the driving voltage of signals in the x- and y-polarizations must be the same, we found 0.78 V peak–peak driving voltage from the AWG must be picked up. Optical carriers are from two tunable external cavity lasers (ECLs) with a fixed frequency offset of 11 GHz. The x- and y-polarizations are hold by the polarization controllers (PCs) after the AMs and combined at the polarization beam combiner (PBC). The optical signal launched into fiber is about 5 dBm.

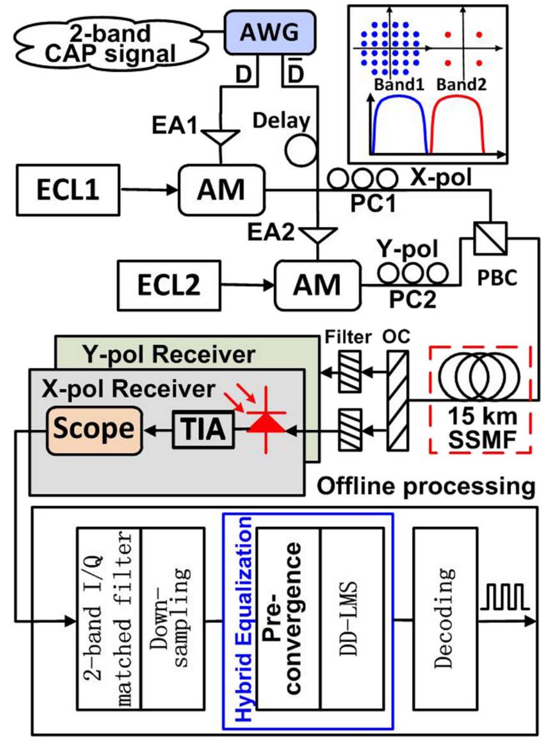

Fig. 2. Experimental setup of the 56 Gb/s DD–PolMux two-band CAP system. TIA, transimpedance amplifier.

After the 15 km fiber link, the received optical CAP signal is first sent into the optical filter and then detected by a photo detector (PD) with a responsivity of 0.9 A/W. Its sensitivity and bandwitdth are −19 dBm and 10.7 GHz, respectively. Then the signal is sampled by an oscilloscope at a sampling rate of 40 GSa/s and is processed offline. For the offline processing, the sampled signal is first resampled to six samples/symbol and sent into the two-band I/Q matched filters. After the equalization, the signal is decoded and followed by the bit error counting more than 2×10^5 bits. Note that the demodulated procedure and equalization are the same to the single band

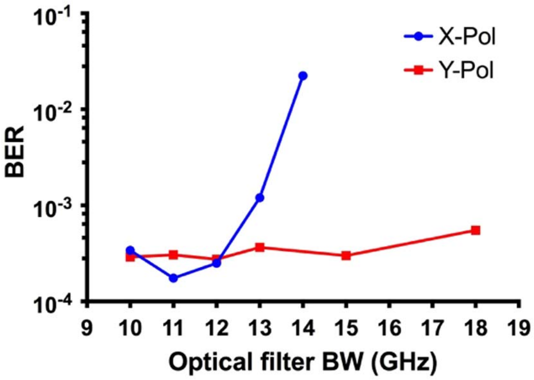

Fig. 3. Optimal bandwidth of the optical filter for x- and y-polarizations.

CAP signal[7], except that the two pairs matched filters with the center frequency 2.1 and 6.4 GHz are used to recover the two-band CAP signal.

Figure 3 indicates the performance investigation of the filter. A programmable filter (Finisar 4000S) in 1 GHz increments from 10 GHz up to the entire C + L band is employed as a bandpass filter. As aforementioned, the center wavelength of the filter is fixed to the carrier wavelength. Figure 3 indicates the optimal bandwidth of the optical filter for x- and y-polarizations. The curves are different because of the misalignment problems between the lasers and optical filters. As aforementioned, the carrier spacing is fixed at 11 GHz and the center wavelength of the filter is the same as the carrier wavelength. However, there may be a misalignment problem due to the frequency accuracy of the laser (±1.5 GHz) and filter (±1.0 GHz). As shown in Fig. 3, the main reason is that the center wavelength of the x-polarization filter is shifted to the right and close to the y-polarization carrier. With the increase of the x-polarization filter bandwidth, the y-polarization carrier component will be filtered into the x-polarization filter, leading to serious degradation of the bit error rate (BER) performance.

The measured spectra for the two-band CAP signal are shown in Fig. 4. Figure 4(a) shows the spectrum of an optical up-converted two-band CAP signal in the lower branch. After the PBC, the x- and y-signals are combined with the frequency offset of 11 GHz, as shown in Fig. 4(b). Figure 4(c) indicates the signal after a 15 km fiber link. After the filter at the receiver, the carrier in the upper branch is suppressed, as shown in Fig. 4(d). In this example, the resolution for the measured spectrum is set to 0.01 nm.

Figure 5 denotes the BER performance of a 56 Gb/s DD–PolMux two-band CAP signal over a 15 km fiber link, which is the combination of CAP32 and CAP4 in each curve. A 1.8 dB power penalty is observed after the 15 km SSMF. As the bandwidth of the two-band CAP signal is more than 8 GHz, the penalty is mainly from the chromatic dispersion in the fiber link. The inserted constellations are Bands 1 and 2 of the y-polarization two-band CAP signal after the 15 km fiber link at a received

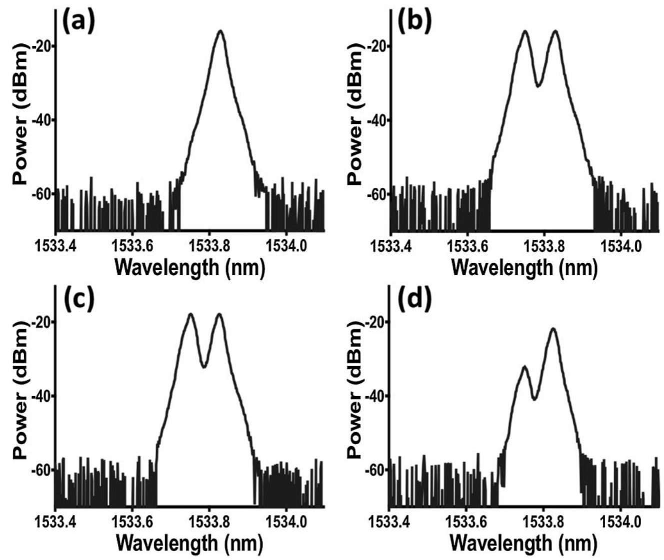

Fig. 4. Spectra of the following: (a) two-band CAP signal in the lower branch; (b) combined x- and y-signals after the PBC; (c) signals after the 15 km fiber link; (d) signal in the lower branch after the filter at the receiver.

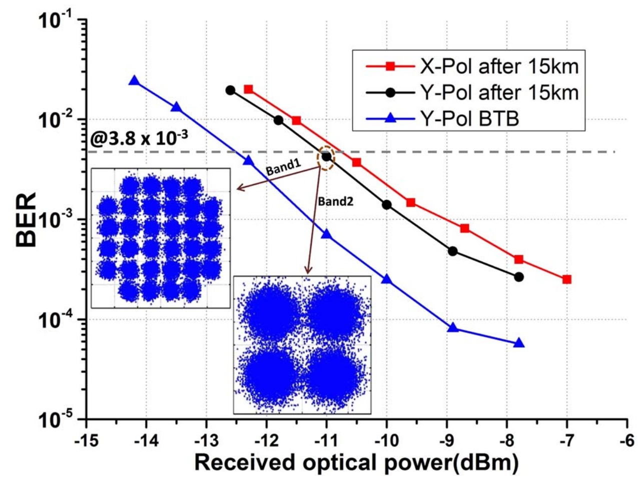

Fig. 5. BER curves of 56 Gb/s DD–PolMux two-band CAP system for back-to-back and 15 km SSMF transmission.

power of −11 dBm. Therefore, it can be concluded that the proposed DD–PolMux CAP system using our optical filtering technique is feasible for high-speed bandwidth limited short-reach transmission. The main data rate limitation is from the 6 GHz bandwidth of the AWG used in the transmitter.

In conclusion, we present an optical filtering technique to realize PolMux in a DD–CAP system. The polarization is separated after the optical filter without the PBS and polarization-dependent distortion compensation. No low-frequency guard band is required and two-band CAP modulation with different modulated orders for each band is employed, thus achieving a single-sideband SE of 5.1 bit/s/Hz and a lower device electrical bandwidth requirement. The optimal optical filter bandwidth is investigated and a 56 Gb/s DD–PolMux CAP system over a 15 km fiber link is experimentally demonstrated to prove the feasibility of this optical filtering technique and its potential in future high-speed short-reach transmission systems.

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