Phase pre-emphasis technique in real-time AOS-OFDM system

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A phase pre-emphasis technique used in an all-optical sampling orthogonal frequency division multiplexing (AOS-OFDM) system is proposed and demonstrated. With the application of this technique, 50-Gb/s AOS-OFDM data are successfully transmitted over 20-km uncompensated single-mode fiber (SMF) with real-time direct-detection. The constructive interference effect between symbols is decreased with this technique.

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Recently, many schemes are proposed for the future high speed optical communication systems. Optical orthogonal frequency division multiplexing (O-OFDM) technique is one of the promising techniques due to its advantages of high tolerance to chromatic dispersion, polarization mode dispersion, and optical nonlinearity[1−3]. In the conventional O-OFDM system, the symbols are typically generated in electrical domain and then converted into optical domain by a complex modulator. At the receiver end, high speed electrical counterparts are needed to convert the optical signal to digitial electrical signal[4−8]. These schemes are mainly limited by the sampling rate of digital-to-analog/analog-to-digital converter (DAC/ADC). Thus, most existing OFDM systems are off-line, while the highest bit rate of a real-time O-OFDM system is only 12.1 Gb/s[9]. Recently, all-optical realization methods of OFDM are introduced to overcome the electrical bottleneck, in which the discrete Fourier transform/inverse discrete Fourier transform (DFT/IDFT) transformation is realized by optical delay lines and phase shifters[10]. For the ultra-short optical pulse applied in many area, an all-optical sampling OFDM (AOS-OFDM) scheme with cyclic postfix (CP) was proposed theoretically and experimentally[11−13]. However, in the optical DFT/IDFT process, many optical samples combine together to cause constructive interference at the edge of each symbol. The high redundant interference pulses decrease the receiver sensitivity and cause error bits at the receiver. In this letter, a novel scheme with subcarrier phase pre-emphasis for AOS-OFDM is presented. With phase pre-emphasis technique, the demodulated signals are capable of better performance by suppressing the effect of constructive interference between neighbor symbols.

In an AOS-OFDM system, ultra-short optical pulses are applied as the sampling pulses. The number of optical sampling pulses in an OFDM symbol increases after the O-OFDM demultiplexer due to the linear convolution property of O-OFDM multiplexer/demultiplexer (MUX/DMUX)[9]. At the decision zone (area (a) in Fig. 1), pulses from different symbols and different channels keep orthogonal with each other. While, the sampling pulses between adjacent symbols in one channel (area (b) in Fig. 1) with different amplitudes and phases may perform constructive interference which generates very high peaks. Furthermore, those pulses from different channels overlap with each other, and complex effect may be introduced. The constructive interference degrades the receiving performance due to the optical power limitation of the photon detector.

In our proposed AOS-OFDM scheme, different initial phases are introduced instead of setting all of them the same. For simulation, the sample number in one symbol period is set to 20 (with four cyclic prefixes). We define the ratio between peak value and the top value of decision zone (PDR) after OFDM DMUX as the criterion of the AOS-OFDM system. Owing to initial phase difference, the optical interference between symbols (Fig. 1) will get

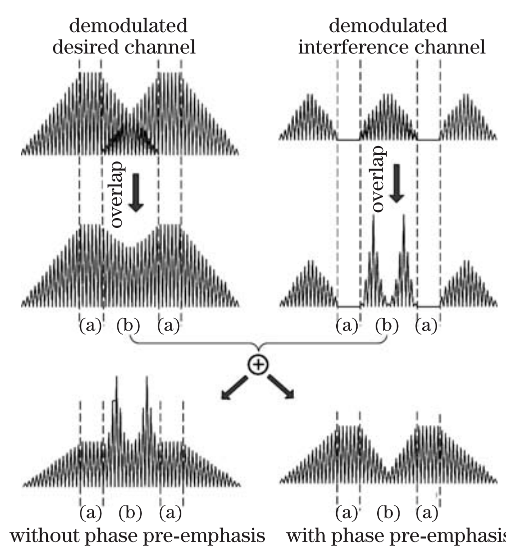

Fig. 1. Pulses overlapping between neighbor symbols.

Table 1. Initial Phase of Different Cases

	Ch1	Ch2	Ch3	Ch4	Ch5
Case 1 (No Relative Phase Shift)	0	0	0	0	0
Case 2 (Max Ch3 PDR)	0	$-7\pi/4$	0	$-3\pi/8$	$-\pi/8$
Case 3 (For Experiment)	0	$-\pi/2$	$\pi/8$	$3\pi/8$	$5\pi/4$
Case 4 (Max Ch4 PDR)	0	$-\pi$	$-3\pi/4$	$-7\pi/4$	$-7\pi/4$
Case 5 (Min Ch3 PDR)	0	$-3\pi/4$	0	$-7\pi/8$	$-5\pi/4$
Case 6 (Min Mean PDR)	0	$-\pi$	0	$-\pi$	0

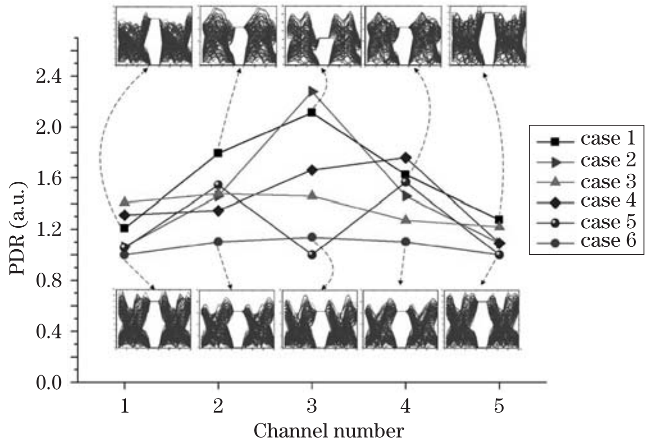

Fig. 2. Simulation results for six cases of initial phases, the eye diagrams are inserted.

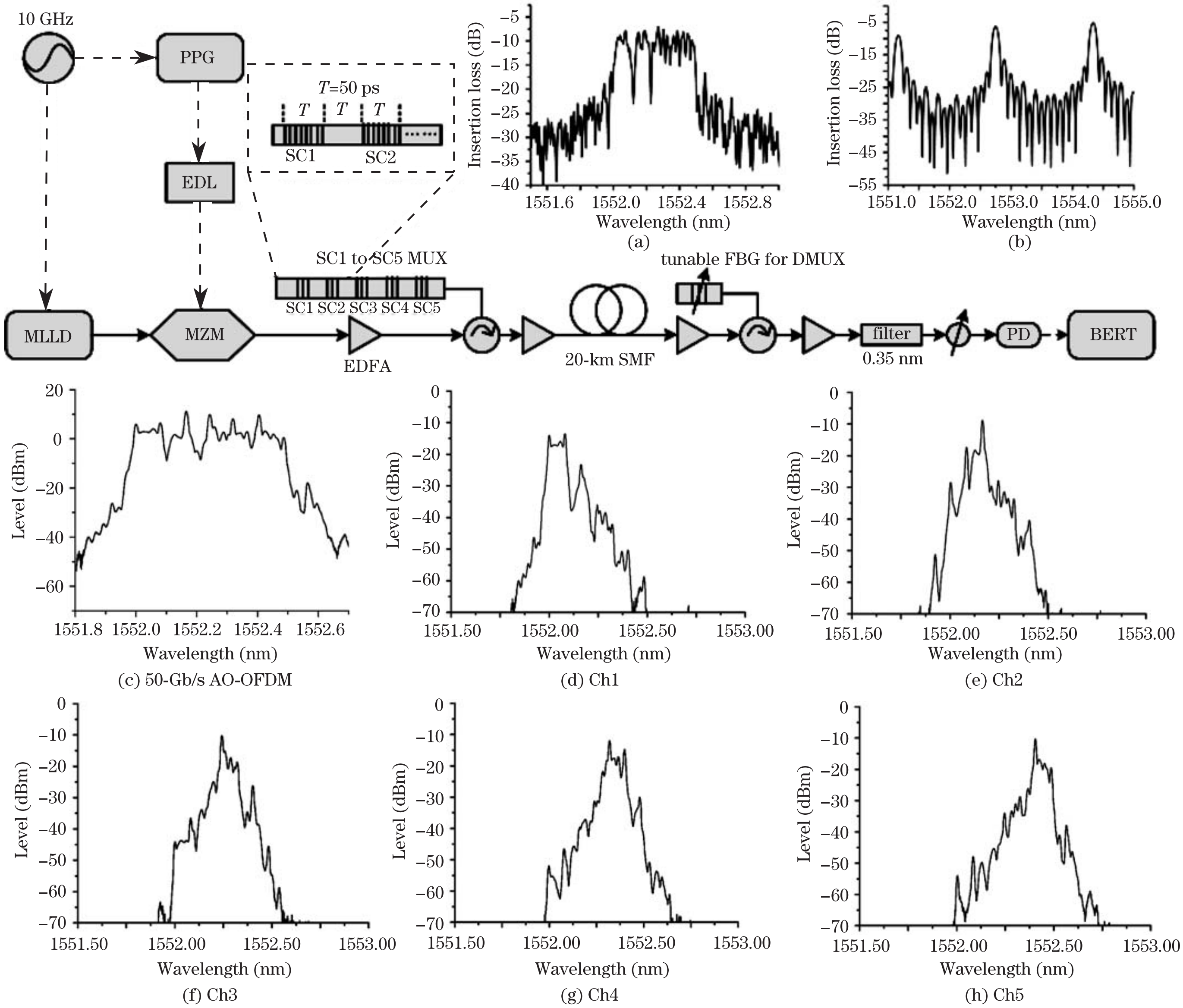

Fig. 3. Experimental setup. (a) Spectrum of AOS-OFDM MUX; (b) Spectrum of AOS-OFDM DMUX; (c) Spectrum of AOS-OFDM signal; (d)–(f) spectra of five channel demodulated signals. EDL: erbium-doped laser, EDFA: erbium-doped fiber amplifier, PD: photon detector.

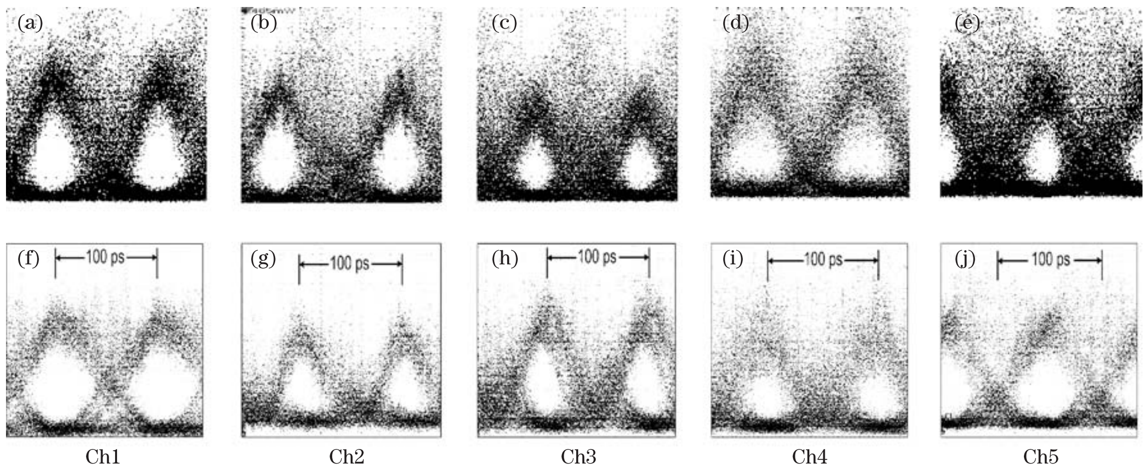

Fig. 4. Eye diagrams after transmission (with same time unit).

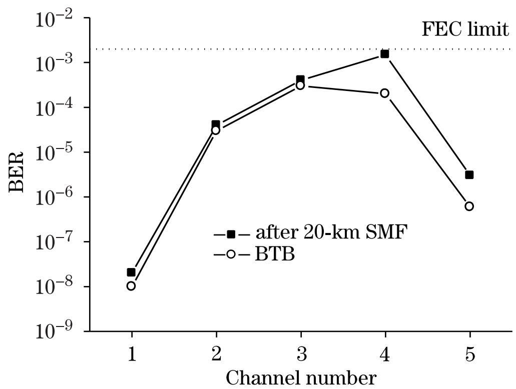

Fig. 5. BER performance before and after SMF link. FEC: forward error correction.

constructive or deconstructive. Furthermore, as there are many channels in the AOS-OFDM system, the interference results are quite complex. The minimum phase shift is $\pi/8$ in the range $[0, 2\pi]$ and all the possible cases are simulated. From the results, six typical cases with different sub-carrier (SC) initial phases are chosen as listed in Table 1. The results are shown in Fig. 2 with eye diagrams inserted. In case 1, all the SC channels have no relative initial phase shift. In case 3 (with initial phase $[0, -\pi/2, \pi/8, 3\pi/8, 5\pi/4]$) and case 6 (with initial phase $[0, -\pi, 0, -\pi, 0]$), all the channels have uniform performance. It can be seen that with appropriate phase design, the constructive interference effect between symbols is decreased.

The AOS-OFDM experimantal setup is shown in Fig. 3. An ultra-short optical pulse train with pulse width of about 2 ps is generated by a mode-locked laser diode (MLLD) with the repetition rate of 10 GHz. The pulse train from pulse pattern generator (PPG) is a 2^7–1 pseudo-random bit sequence (PRBS) at 10 Gb/s. After synchronously modulated with a Mach-Zehnder modulator (MZM), the signal is reflected by the MUX fiber Bragg grating (FBG) and is boosted into a 20-km single-mode fiber (SMF). Five MUX sub-FBGs for each SC channel are manufactured in a FBG whose structure is shown in Fig. 3(a). The single-way time interval between each sub-FBG is set to be 50 ps (Fig. 3), which equals half of OFDM symbol period (100 ps), to keep five channels synchronous. The MUX sub-FBG for ith SC is designed to have 20 reflection sub-gratings including four CPs sub-gratings; the single-way time delay and phase shift of nth sub-grating are $(n–1)/2\times5$ ps and $(i–3)(n–1)\pi/8$, respectively. The DMUX has a similar structure as the sub-FBG in MUX but without the CP added. The spectrum of DMUX is shown in Fig. 3(b). The DMUX FBG can be tuned to filter out the corresponding AOS-OFDM SC channels.

The initial relative phase shifts are the same as case 3. The DMUX FBG is designed to have 16 reflection sub-gratings corresponding to the MUXs. After a 10-Gb/s traditional direct-detection optical receiver, the signals are analyzed by a bit error rate tester (BERT). The spectra of AOS-OFDM signal and demultiplexed SC channels are shown in Fig. 3 inset. The –20-dB bandwidth of the OFDM signal is about 0.5 nm corresponding to the spectral efficiency of 0.8 bps/Hz.

We also compare the received eye diagrams of cases 1 and 3 in the experiment. Figures 4(a)–(e) are the demodulated eye diagrams for channels 1 to 5 for case 1 after transmission over a 20-km SMF, Figs. 4(f)–(j) are the eye diagrams for case 3 after transmission over a 20-km SMF. In Figs. 4(f)–(j), it is shown that the middle of the eye diagram can be clearly observed opening and the constructive interference between adjacent eyes is suppressed. The bit error rate (BER) performance of case 3 is shown in Fig. 5. The BER is measured with optimal received power. The performances for different SC channels are not uniform because of the non-ideal frequency response of the lab-made FBGs. However, it is clear that after 20-km SMF transmission, the system performance keeps almost the same as that of the back-to-back (BTB) case.

In conclusion, a novel scheme with SC phase pre-emphasis for AOS-OFDM is proposed and demonstrated. Different intitial phases are added on each SC channel, thus the demodulated signal has good performance as the effect of constructive interference between neighbor symbols is weakened. 50-Gb/s AOS-OFDM signals are generated and successfully transmitted over a 20-km uncompensated SMF link with real-time direct-detection. With this method, the constructive interference effect between symbols is greatly decreased.

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