All-optical orthogonal frequency multiplexing scheme with cyclic postfix based on fiber Bragg gratings

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Abstract. A novel all-optical orthogonal frequency division multiplexing (AO-OFDM) scheme is proposed and demonstrated. Ultrashort optical pulses are used as samples for optical discrete Fourier transform (DFT) and the inverse DFT process. Different subcarrier channels can be parallelly processed by fiber Bragg gratings. A 20-Gb/s two subcarrier AO-OFDM experiment is carried out with narrowband filtering and optical cyclic postfixes (CP) inserted. Experimental results show that this scheme has good spectral efficiency. Furthermore, the received signals have better eye diagrams and bit error rate performance with the help of CP. This scheme can be used in high-speed optical transmission systems.
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Subject terms: all-optical orthogonal frequency division multiplexing; optical samples; optical cyclic postfix; fiber Bragg grating.

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1 Introduction

An optical orthogonal frequency division multiplexing (OFDM) method recently arises as a potential technology for a future high-speed communication system.[1–4] It is considered to have large tolerance for different fiber transmission impairments, such as chromatic dispersion,[5–7] polarization mode dispersion,[8–10] and optical fiber nonlinearity.[11–13] Many existing optical OFDM systems use an electrical circuit to multiplex parallel data into multiple subcarriers (SCs) due to OFDM principle and modulate these signals in optical domain by a modulator. Thus, electrical OFDM modulation is limited by electronics process speed in a discrete Fourier transmission (DFT)–inverse DFT (IDFT) (DFT/IDFT) module and also the bandwidth of digital-to-analog/analog-to-digital converter. If the DFT process can be realized by optical method, then the OFDM signal process will be very fast and the transmission data rate will also increase greatly. All-optical DFT methods combining optical delays and phase shifters have been introduced recently. Continuous wave with data modulated is used for transmission, and the Mach–Zehnder interferometer is used as the IDFT module.[14,15] Also, a coherent wavelength-division multiplexing signal utilizing OFDM principle is proposed with either a coherent comb optical source[16] or coherent detection.[17] And a scheme using ultrashort optical pulses as samples for an optical DFT/IDFT process is proposed in Ref. 18, which has a complex structure of all-optical OFDM DFT/IDFT modules. Considering the good performance of fiber Bragg gratings (FBG) in optical code-division multiple-access (OCDMA) systems[19] it is promising to use FBGs as all-optical OFDM DFT/IDFT modules.

In this paper, we report a novel all-optical OFDM (AO-OFDM) scheme for AO-OFDM system applications. This scheme uses ultrashort optical pulses as sample pulses and can operate different SC channels multiplexing (MUX) and demultiplexing (DMUX) in parallel. Each AO-OFDM channel can be processed by a pair of FBGs as corresponding OFDM MUX/DMUX. And for the first time, optical cyclic postfixes are inserted to improve the quality of received eye diagrams and system performance.

2 Principle

Because of the mathematical definition of DFT/IDFT method, samples are considered to be phase shifted and time delayed for calculation. In optical domain, ultrashort pulses can also be used as samples for the all-optical DFT/IDFT process. In Ref. 18, optical DFT modules are combined by phase shifters and time-delay units, while these two parts are separated and complex for implementation. In fact, in one symbol period T, the samples S_T can be expressed as

$$S_T=\sum_{m=0}^{M-1} S_m=\frac{1}{N}\sum_{m=0}^{M-1}\sum_{k=0}^{N-1} X_m[A(m\Delta t)]\exp\left(-j2\pi\frac{m}{M}k\right)$$
$$=\frac{1}{N}\sum_{k=0}^{N-1} S_k, \tag{1}$$

where M is the number of samples in one symbol period, $A(t)$ is the profile of ultrashort optical pulse, Δt is the time interval of optical pulses and equals T/M, N is the number

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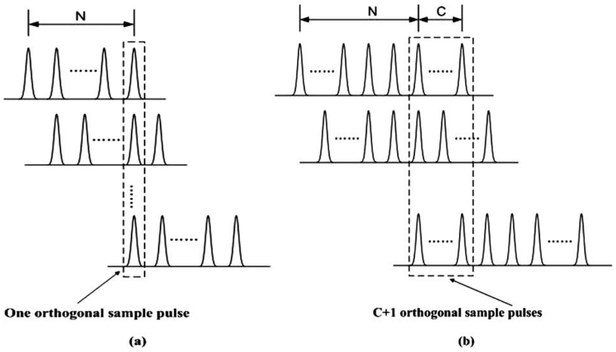

Fig. 1 Principle of optical OFDM modulation (a) without and (b) with CPs.

of SC, and X is the sample value. X keeps to constant in the whole symbol period. Thus, the samples in different subcarrier (S_k) can be processed in parallel as long as they are synchronous.

The k'th optical IDFT (OIDFT) module has the same structure of an optical DFT (ODFT). Thus, this signal after k'th OIDFT module can be demodulated as

$$P_k(t) = \sum_{m=0}^{N-1} S_k(t)\exp\left(-j2\pi k\frac{m}{N}\right) = \sum_{m=0}^{N-1}\sum_{n=0}^{N-1} A[t+(n+m)\Delta t]\exp\left[-j2\pi k\frac{1}{N}(n+m)\right] \tag{2}$$

This signal is the result of linear convolution; thus, the total sample number of one bit becomes $2N-1$. When $n+m=N-1$, that is at $t_s=(N-1)\Delta t$, there is a superposition of N samples, which can be expressed as

$$P_{(k,t_s)}(t) = N\cdot A(t)\exp\left(-j2\pi k\frac{N-1}{N}\right). \tag{3}$$

Figure 1(a) is the schematic of OFDM DMUX with MATLAB simulation. If the signal of the other SC channel passes through this OIDFT module, for example, f-th channel signal passes through k-th OIDFT module, then it will be

$$P_{(f,k)}(t) = \sum_{m=0}^{N-1} S_f(t)\exp\left(-j2\pi k\frac{m}{N}\right) = \sum_{m=0}^{N-1}\sum_{n=0}^{N-1} A[t+(n+m)\Delta t]\exp\left[-j2\pi\frac{1}{N}(fn+km)\right] \tag{4}$$

Thus, at $t_s=(N-1)\ \Delta t$, the signal superposition can be expressed as

$$\begin{aligned}P_{(f,k,t_s)}(t) &= A(t)\sum_{n=0}^{N-1}\exp\left[-j\frac{2\pi}{N}(nf+mk)\right] = A(t)\sum_{n=0}^{N-1}\exp\left\{-j\frac{2\pi}{N}[n(f-k)+(N-1)k]\right\} = A(t)\exp\left[-j\frac{2\pi}{N}(N-1)k\right]\sum_{n=0}^{N-1}\exp\left[-j\frac{2\pi}{N}n(f-k)\right]\\ &= A(t)\exp\left[-j\frac{2\pi}{N}(N-1)k\right]\frac{1-\exp[-j(2\pi/N)N(f-k)]}{1-\exp[-j(2\pi/N)(f-k)]}\\ &=0\quad[(f-k)\text{ is integer}].\end{aligned} \tag{5}$$

It is very clear that at t_s moment, orthogonality of different SC channel samples can be obtained, while it is not true at the other moments. This is because the optical DFT/IDFT process is based on linear convolution. In time slot T, only one demodulated sample can keep orthogonality, while other samples cannot.[18] Thus, at the receiver, the eye diagram has a very narrow decision width, and synchronous pulse carver modulation is needed to extract the correct sample.[18] In order to solve this problem, the optical samples can be partly cyclically extended, which can keep the SC orthogonal in the cyclic prefix or postfix samples. This ensures that the replicas of the OFDM symbol always have an integer number of cycles within the DFT interval, which has the same function in wireless OFDM systems.[20]

In this paper, optical cyclic postfix samples are inserted in one symbol period, which can be easily fabricated by the FBG technique. The samples of SC k in one period can be expressed as

$$\begin{aligned}S_k &= \sum_{n=0}^{N-1} X_n\cdot A(n\Delta t)\exp\left(-j2\pi\cdot\frac{n}{N}k\right) + \sum_{c=0}^{C-1} X_n\cdot A[(N+c)\Delta t]\exp\left[-j2\pi\frac{c}{N}k\right]\\ &= \sum_{n=0}^{M-1} X_n\cdot A(n\Delta t)\exp\left[-j2\pi\frac{n}{N}k\right],\end{aligned} \tag{6}$$

where C is the number of cyclic postfixes, Δt equals $T/(N+C)$, and other symbols are same as in Eq. (1). Thus, the correct demodulated samples after the optical IDFT module increase to $C+1$. The comparison of signals with and without CP is shown in Fig. 1. With the increased orthogonal samples, the decision range in eye diagrams can be enlarged, and it may also give some benefits for dispersion walk-off as the electrical CP's function in a wireless multipath environment.

In order to realize our scheme, FBGs are used. The FBG is designed to have many sample subgratings along its length. With the scan-exposure technique, each subgrating can have the same refractive index modulation amplitude but different modulation phase shifts. For example the refractive index's spatial modulation function of the FBG has the following form:

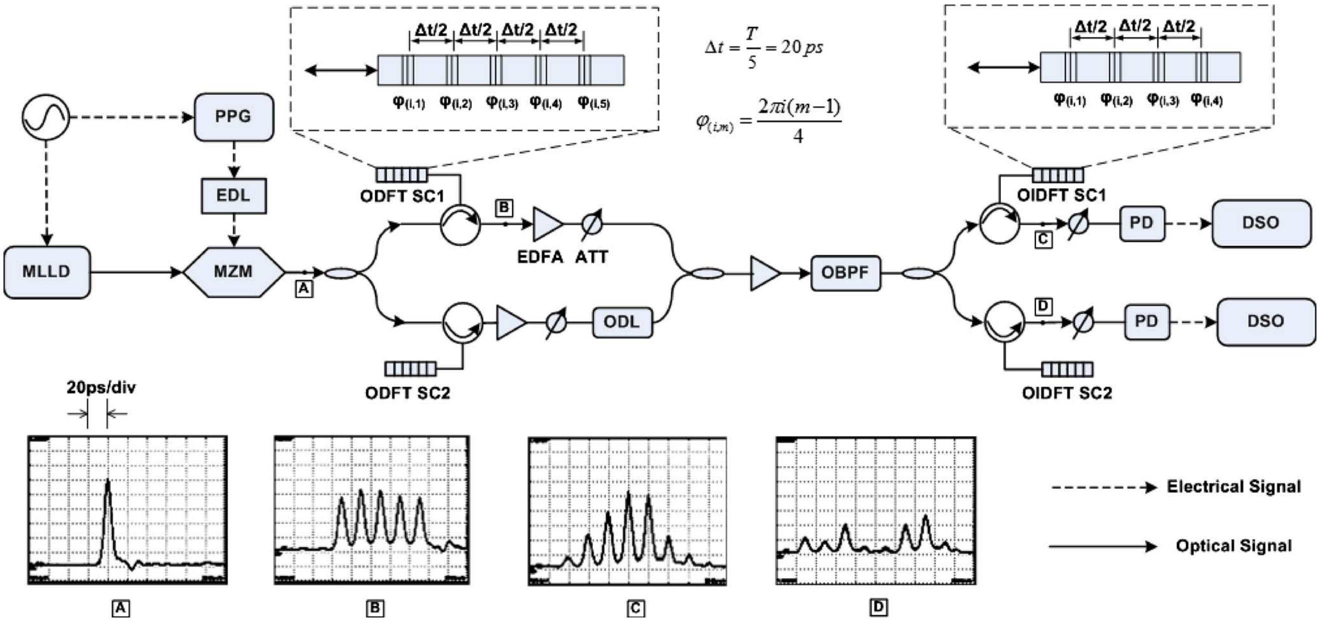

Fig. 2 Experimental setup. ATT-attenuator, DSO, EDFA, EDL, MLLD, OBPF, optical delay line ODL, PD, and PPG. (A) An original single input ultrashort pulse, (B) signal A after ODFT SC1, (C) signal B after OIDFT SC1, and (D) signal B after OIDFT SC2.

$$\delta n(z) = \sum_{m=0}^{M-1} A(z - mZ_0)\varphi_{km} \exp\left(j\frac{2\pi}{\Lambda}z\right) + c.c., \tag{7}$$

where Λ is the period of the grating, Z_0 is the chip period, $A(z)$ is the profile of each chip's amplitude, and φ_{km} is each chip's phase shift. If $A(z)$ is very small, then the FBG's impulse response can be approximately given by $h(t) = K\delta n(ct/2n)$, where K is a constant coefficient, n is the effective refractive index, and c is speed of light. Thus, the input optical pulse $x(t)$ and the reflective signal have the relation

$$y(t) = x(t) \otimes h(t) = \sum_{m=0}^{M-1} B\left(t + m\frac{2n}{c}Z_0\right)\varphi_{km}, \tag{8}$$

where $B(t) = 2Kx(t) \otimes [A(ct/2n)\cos(2\pi/\Lambda)(ct/2n)]$. If we let $Z_0 = (cT/2nM)\varphi_{km} = \exp[-j2\pi(m/M)k]$, then $y(t)$ has the same structure as $S_k(t)$ in Eq.(1). Thus, it is reasonable to use FBGs as ODFT and OIDFT modules in AO-OFDM systems.

3 Experiment and Results

A two-SC AO-OFDM experiment is carried out and shown in Fig. 2 An optical pulse train with a pulse width of $\sim$2 ps is generated by a mode-locked laser diode (MLLD). The center wavelength is 1554.9 nm, and the repetition rate is 10 GHz. The non–return-to-zero (NRZ) on-off keying modulation pulse train from a pulse pattern generator is a $2^{31}-1$ pseudo-random bit sequence (PRBS) at 10 Gb/s. An electrical delay line (EDL) is used to confirm the synchronization. Then, the signal is fed into a coupler and reflected by two ODFT FBGs for different SC channels (SC1 and SC2). An optical delay line (ODL) is used in one arm to keep the synchronization. Erbium-doped fiber amplifiers (EDFA) and optical attenuators are used to confirm that they have the same power entering into another coupler. Then, the combined AO-OFDM signals are amplified and pass through a Gaussian-shape optical bandpass filter (OBPF) with a 3-dB bandwidth of 0.3 nm. The signal can be demodulated with corresponding OIDFT FBG and then detected by a 12.5-GHz photon detector (PD).

In experiment, FBGs are used as optical DFT/IDFT modules for $N=4$, $C=1$ case, which means the sample number in one symbol period is 5 and the CP length is 25%. The ODFT FBG for the i'th $(i=1,2)$ SC is designed to have five reflection subgratings as shown in Fig. 2. The time delay between each subgrating Δt is 10 ps and the phase shift of m'th $(m=1,2,3,4,5)$ subgrating $\varphi(i,m)$ is $2\pi i(m-1)/4$. And the corresponding OIDFT FBG for the i'th SC is designed to have four reflection subgratings, as shown in Fig. 2. The time delay is the same as ODFT FBG, and the phase shift is still $2\pi i(m-1)/4$ (here $m=1,2,3,4$). In order to test the ODFT/OIDFT performance, single bit transmission with one ODFT FBG (SC1) used is carried out without the OBPF. Figure 2 also shows optical samples in different position. There are five samples after ODFT-SC1 FBG [Fig. 2(b)]. After corresponding OIDFT-SC1, there are two highest pulses in the middle [Fig. 2(c)]. While after noncorresponding OIDFT-SC2, there are no pulses at the same position [Fig. 2(d)], which means the there are two samples with orthogonal characteristic. In PRBS case, two ODFT FBGs are both used; the eye diagrams of received signals without the OBPF are shown in Fig. 3 to show the difference between the signals with and without CP. The signals are directly detected by a digital sampling oscillator [(DSO), Tektronix TDS8200] with a detection bandwidth of 65 GHz. It is clear that the orthogonal samples increase with the help of CP.

In order to test the spectral efficiency of this scheme, an

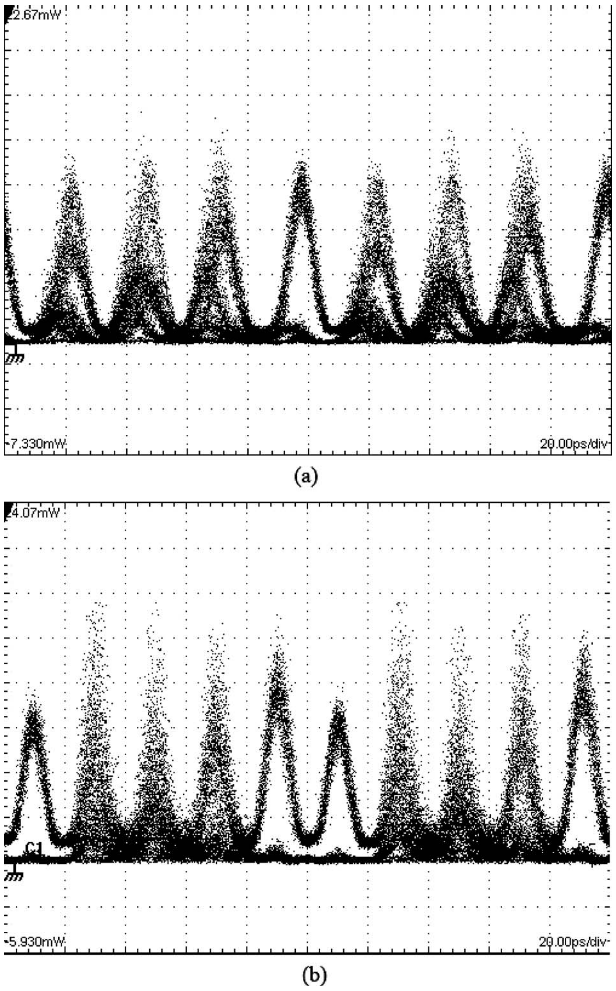

Fig. 3 Eye diagrams without OBPF of (a) without CP and (b) with CP.

OBPF mentioned previously is used. Figure 4 shows optical spectra of AO-OFDM signals after OBPF and without CP. The combined OFDM signal has a bandwidth of 0.218 nm (interval of first null point), which equals 27.25 GHz, and the spectral efficiency is 0.74. Figure 5 shows optical spectra of AO-OFDM signals with CP. The combined OFDM signal has a bandwidth of 0.254 nm, which equals 31.75 GHz, and the spectral efficiency is 0.63. The blue and red lines in Figs. 4 and 5 are spectra of demodulated SC1 and SC2 channel, respectively. Compared to a traditional 20-Gb/s NRZ signal (0.32-nm interval of first null point), this AO-OFDM signal has better spectral efficiency. The bit error rate (BER) curves and eye diagrams of different cases are shown in Fig. 6. In 2-SC channel cases, the system without CP has an obvious BER floor at 10^{-4} for the narrow decision width of the eye diagram. However, the system with CP has no BER floor with good eye-diagram quality. Furthormore, there is less power penalty between the cases with and without OBPF, which means the system can work at high spectral efficiency with the help of CP. In order to test the transmission performance of our scheme, the AO-OFDM signal is fed into a 20-km single-mode fiber link, which has chromatic dispersion of 17 ps/nm/km at 1550-nm. Figure 7 shows the BER curves of B2B and after 20-km transmission. The power penalties of both SC1 and SC2 are <0.5 dBm.

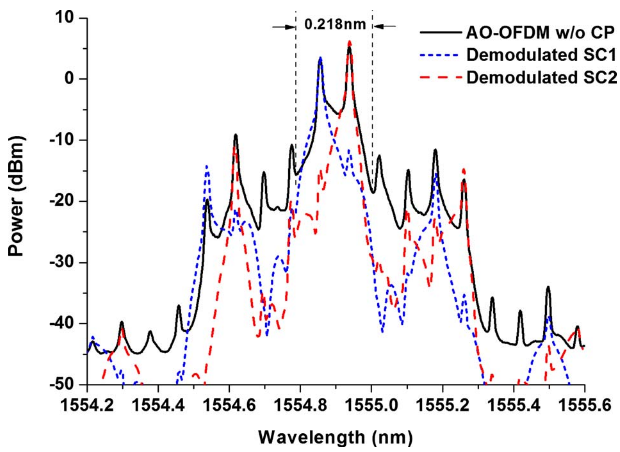

Fig. 4 Optical spectra of AO-OFDM signals without CP and demodulated SC1 and SC2 channels.

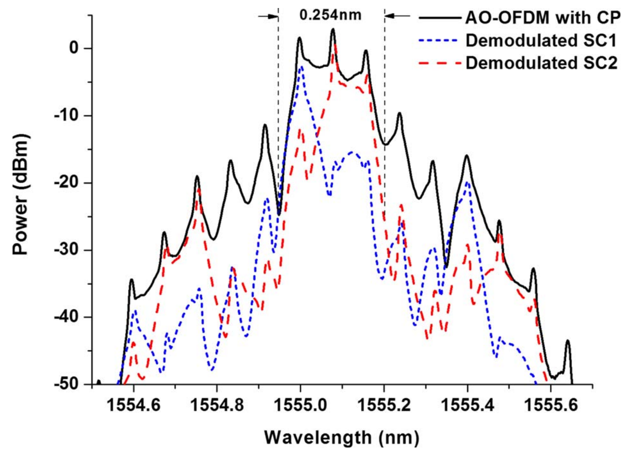

Fig. 5 Optical spectra of AO-OFDM signals with CP and demodulated SC1 and SC2 channels.

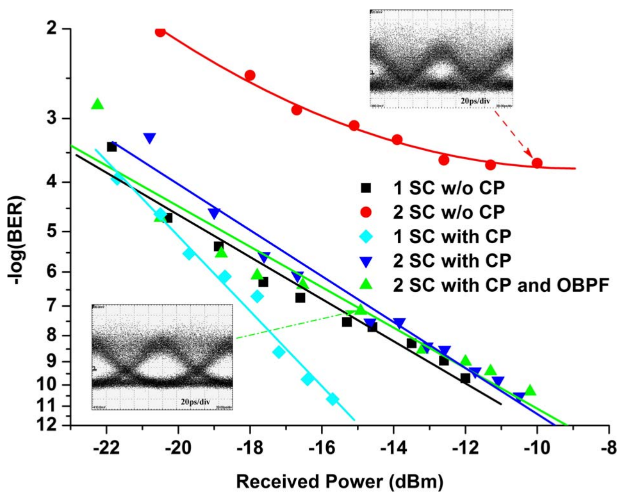

Fig. 6 BER curves with eye diagrams inserted.

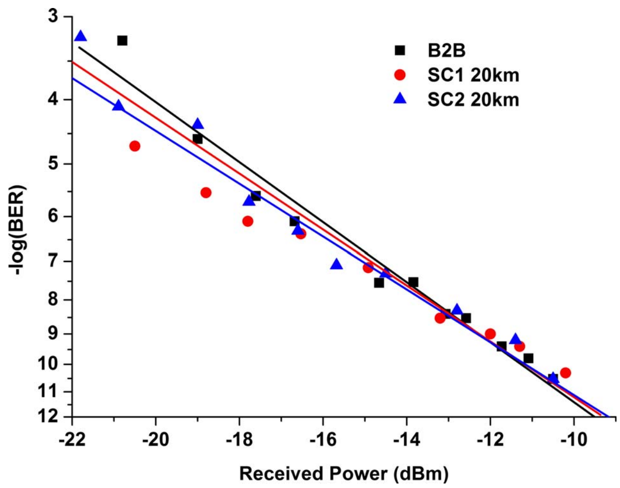

Fig. 7 BER curves of B2B and after 20-km SMF cases.

4 Conclusions

An AO-OFDM scheme with optical cyclic postfix is proposed and demonstrated. Ultrashort optical pulses are used for ODFT/OIDFT samples and different SC channels can be processed in parallel with the FBG technique. A 20-Gb/s two SC AO-OFDM experiment is carried out with narrowband filtering. Experimental results show that this scheme has good spectral efficiency and BER performance.

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