All-optical sampling OFDM system performance analysis

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The performance of a novel all-optical sampling orthogonal frequency division multiplexing (OFDM) system is proposed and analyzed. Time delays and phase shifters are used to realize all optical forward/inverse discrete Fourier transform (DFT/IDFT). Different system configurations are tested and analyzed to optimize the performance, including the system capacity, modulation formats, DFT/IDFT constructions, and the width of the sample pulse. The 50- and 100-Gb/s real-time all-optical sampling (AOS) OFDM systems are investigated. All results are analyzed, and useful suggestions are offered for future high-speed applications.

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Orthogonal frequency division multiplexing (OFDM)[1,2] has attracted significant interest as a future high-speed communication system due to its high tolerance for optical fiber nonlinearity and its high spectral efficiency (SE)[3]. In traditional optical systems, discrete Fourier transform (DFT) and digital-to-analog/analog-to-digital conversion are realized in the electrical domain, which is limited by the electronics processing speed. To realize DFT and inverse DFT (IDFT) in the optical domain, an all-optical OFDM system based on time delay and phase shifters[4] as well as time lens[5] has been proposed and tested. Compared with traditional OFDM systems, the all-optical OFDM system has a faster signal processing speed. Obtaining a higher SE is an important goal during the development of all-optical OFDM technology, and great improvement has been achieved. In Ref. [6], inverse discrete cosine transform (IDCT) and DCT are utilized, replacing IDFT and DFT to achieve higher SE. Coherent prioritized demand multiplexing (PDM) OFDM scheme was proposed in Ref. [7], with SE reaching 7 (bit/s)/Hz. In Ref. [8], using joint 64-QAM and 16-QAM (QAM: quadrature amplitude modulation) modulation, the SE reached 7.2 (bit/s)/Hz.

Recently, an all-optical sampling (AOS) OFDM system using ultra-short pulses as optical samples introduced cyclic postfix (CP) to improve fiber dispersion tolerance[9]. However, different system configurations will influence the performance significantly, such as the number of channels, the data modulation format[10,11], and the sample pulse width. Hence, in this letter, different system configurations are simulated and analyzed to optimize the system performance.

In this letter, we utilize time delays and phase shifters to realize all-optical DFT/IDFT modules, as described in Refs. [4] and [9]. The structure is shown in Fig. 1.

Considering a single sample pulse of the kth sub-carrier after optical IDFT (OIDFT), the signal can be expressed as

$$S_k(t) = \sum_{n=0}^{M-1} X_n A(t + n\tau)\exp(\mathrm{j}2\pi nk/N), \qquad (1)$$

where X_n is the sample value, $A(t)$ is the shape of the optical sample pulse, N is the number of samples in one symbol period T_s, $\tau = T_\mathrm{s}/M$ is the time delay between each sample, and $\frac{2\pi nk}{N} = \Delta\varphi_n$. X_n does not usually change during one signal period, thus it is neglected in the formulas below.

At the receiver, optical DFT (ODFT) has a similar structure to OIDFT. The signal after the kth ODFT module can be expressed as

$$\begin{aligned} P_k(t) &= \sum_{m=0}^{N-1} S_k(t + m\tau)\exp\Big(\frac{\mathrm{j}2\pi km}{N}\Big) \\ &= \sum_{m=0}^{N-1}\sum_{n=0}^{M-1} A[t + (n+m)\tau]\exp\Big[\frac{\mathrm{j}2\pi k(n+m)}{N}\Big]. \end{aligned} \qquad (2)$$

A superposition of N samples is present in the orthogonal zone when the value of $n{+}m$ is from $N{-}1$ to $M{-}1$. If $C = M - N$ is the number of CPs, $C = M - N = 0$, the orthogonal zone becomes one pulse moment.

On the other hand, if the signal passes through non-corresponding ODFT modules, the output signal will be 0 in the time interval discussed above.

The system setup is shown in Fig. 2. The ultra-short pulse generated from the mode-locked laser diode (MLLD) is split into k parts. Each part is modulated with independent data, such as non-return-to-zero (NRZ), differential phase shift keying (DPSK), or differential quadrature phase shift keying (DQPSK) formats,

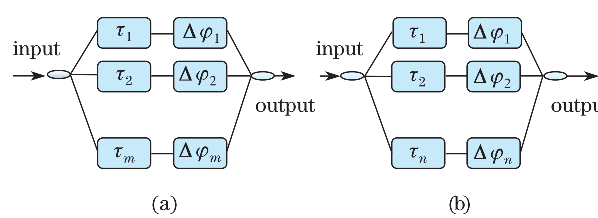

Fig. 1. Structure of the kth (a) OIDFT and (b) ODFT modules, they have the same structure and parameters except for the number of branches. $\tau_m = m \times T_\mathrm{s}/M$ is the time delay and $\Delta\varphi_n = 2\pi nk/N$ is the phase shift.

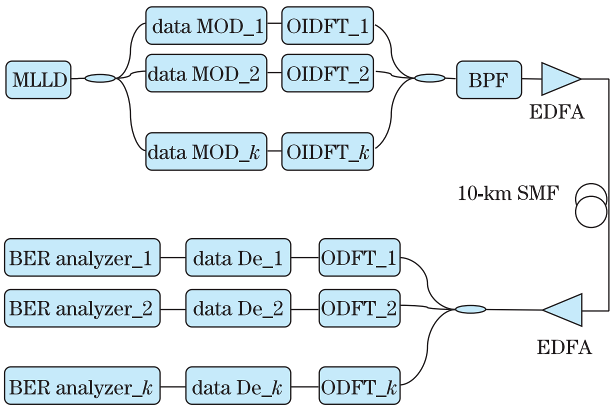

Fig. 2. Basic structure of AOS-OFDM system. MOD: modulator; EDFA: erbium-doped fiber amplifier; SMF: single-mode fiber; De: demodulator; BER: bit error rate.

and passes through an OIDFT module. The k channels combine and pass through a Gaussian band-pass filter (BPF) to achieve better SE. At the receiver, the signal is split into k parts and passes through corresponding optical ODFT modules and demodulators.

To optimize the system configuration, observing the performance and analyzing the result are necessary. Three important parameters were chosen for this purpose, which are listed in Table 1. The simulations and analysis focus on the relationship among the three parameters and the system bit error rate (BER) performance. The other parameters used in the simulation are listed in Table 2.

Table 1. System Configuration

Number of Channels	Data Modulation Type	Pulse Width (ps)
2, 5, 10	NRZ, DPSK, DQPSK	1, 2, 5, 10, 15

Table 2. Parameters Used in Simulation

Parameter	Value
Pulse Shape	Gaussian
Signal Period	100 ps
BPF Shape	Second-Order Gaussian
Symbol Rate of a Single Channel	10 G/s
Dispersion of SMF	17 ps/(nm·km)
Loss of SMF	0.2 dB/km
Fiber Length	10 km
Detector Responsivity	1 A/W
Dark Current	10 nA
Thermal Noise	1×10^{-24} W/Hz
Signal Power Before Detection	Around 0 dBm
Resolution Bandwidth of the Spectrum Analyzer	0.0001 nm

To test the influence of the number of sub-carrier channels, it was changed (2, 5, and 10, respectively) to observe the BER and eye diagrams. The DFT construction is "16 + 4", whereas the modulation format is DPSK with 2-ps-wide sample pulse. The 16 + 4 construction means that $N = 16$ and $M = N + C = 16 + 4 = 20$, as mentioned above.

If the optical signal-to-noise ratio (OSNR) is set as the scanning parameter to observe the performance of each channel, we achieve the results shown in Figs. 3 and 4. The eye diagram is obtained when the OSNR reaches about 15 dB. In the two-channel system, little disparity is observed in the BER performance between the two channels. However, the maximum OSNR penalty of BER = 1×10^{-6} rises along with the increase in the number of channels, which is about 3.5 and 5 dB in systems with 5 and 10 channels, respectively. Comparing the systems with 2 and 10 channels, the best and worst OSNR penalties of BER = 1×10^{-6} are about 2 and 6.5 dB, respectively. As a result, the performance degrades with the increase in the number of channels.

In addition, with the increase in the number of channels, the overlapping of spectra and the crosstalk between the two neighbor channels become more significant. Each channel is influenced by the crosstalk effect, with the different channels variably affected. Consequently, the system performance deteriorates and a disparity in BER performance among the channels is observed. Considering the $N + C$ system, the function of the OIDFT module

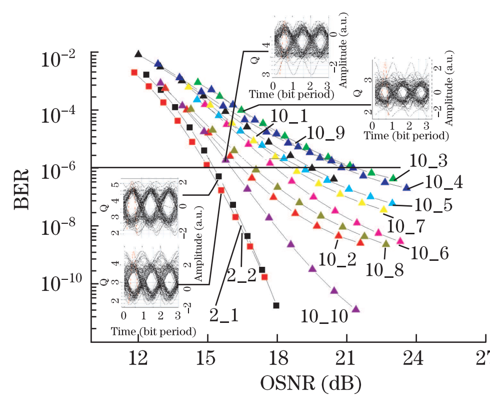

Fig. 3. Performances of systems with 2 and 10 channels (DPSK, 16+4, 2-ps pulse). 2_1 indicates the first channel of 2 channels, 10_1 indicates the first channels of 10 channels, and so on.

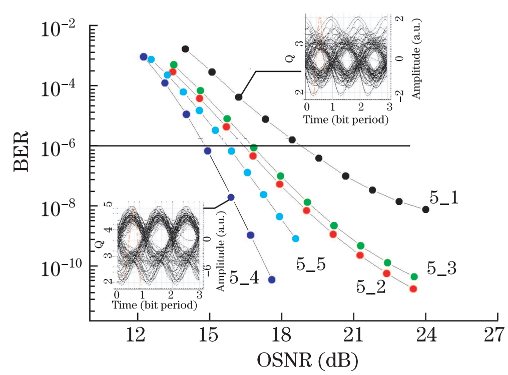

Fig. 4. Performance of system with five channels (DPSK,16+4, 2-ps pulse).

can be seen as a filter, and the system function of the kth OIDFT module can be expressed as

$$S(f)=\sum_{n=0}^{M-1}\exp(\mathrm{j}2\pi fn\tau)\exp\Big(\frac{\mathrm{j}2\pi nk}{N}\Big). \qquad (3)$$

Remarkably, if the channel index k is substituted with 1 and $N+1$ in Eq. (3), the two system functions become identical. Hence, the maximum number of channels of the $N+C$ system is clearly N.

To analyze the performances of different modulation methods, three typical modulation types were selected. In the simulation, the system contains five channels of 16 + 4 ODFT/OIDFT construction with 2-ps-wide sample pulses. The result shows the performances of the best and worst channels of each system.

As shown in Fig. 5, the DPSK system performs well both at high OSNR and low OSNR, whereas the performance of the NRZ system, the worst channel, deteriorates rapidly. The performance of the DQPSK system is not as good as the other two systems. The best OSNR penalty of BER $=1\times10^{-6}$ is about 3.5 dB compared with those of the NRZ and DPSK systems. The phase interval of the DQPSK constellation point is smaller than that of DPSK, indicating that it has a smaller decision interval. After transmitting over the fiber, the phase noise superimposes on the signal, thus the performance naturally degrades. However, the SE of the DQPSK

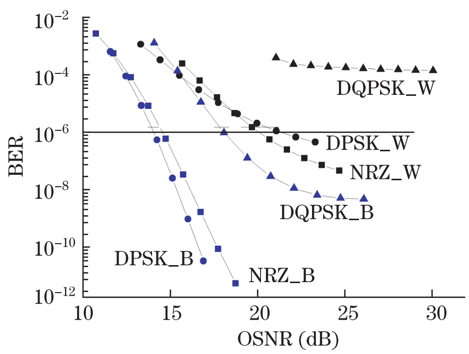

Fig. 5. Performances of the best channels (B) and the worst (W) channel of different modulation formats.

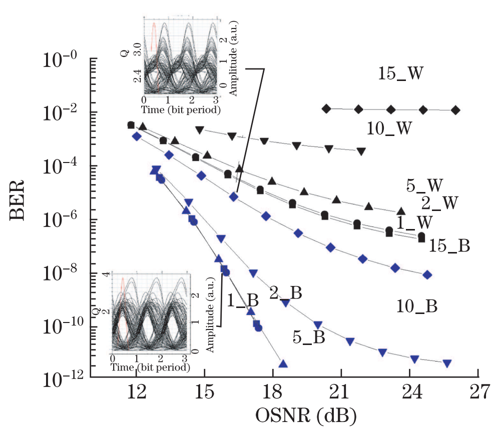

Fig. 6. Performances of the systems with 1/2/5/10/15-ps pulse (five channel, 16+4, DPSK). 1_B represents the best channels for 1-ps pulse, 1_W represents the worst channel for 1-ps pulse, and so on.

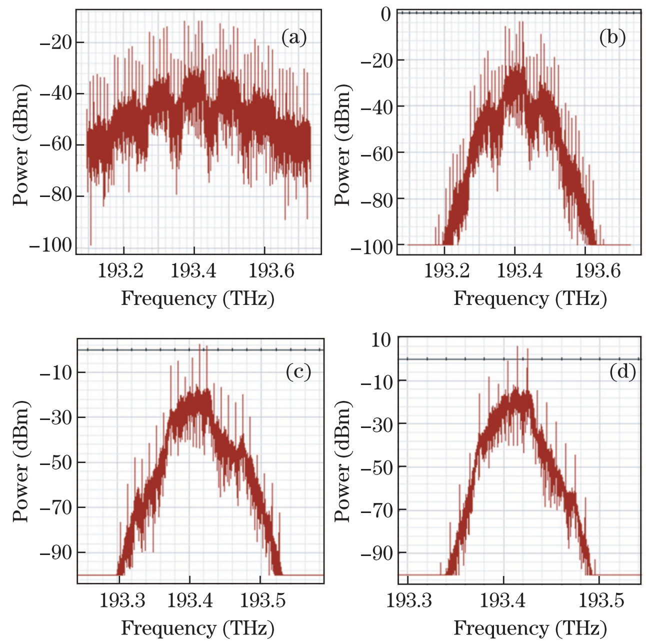

Fig. 7. Spectra after OIDFT of different sample pulses: (a) 2 ps; (b) 5 ps; (c) 10 ps; and (d) 15 ps.

system is 2 (bit/s)/Hz, whereas those of the DPSK and NRZ systems are only 1 (bit/s)/Hz. Therefore, a compromise has to be made between the BER performance and the SE in the real system.

The width of the sample pulse is another important parameter that determines the final performance. To evaluate its function, we changed the pulse width and observed the eye diagram and BER. In the simulation, the system contains five channels of DPSK signal with 16 + 4 ODFT/OIDFT construction. The BER performances and spectra are shown in Figs. 6 and 7, respectively.

The result shows that the BER performance of some channels deteriorates dramatically when the pulse width is greater than 5 ps. The increase in the width of the sample pulse indicates the decrease of its spectrum width. When the spectrum of the sample pulse is wide enough, the spectra of all channels reach their peaks. However, when the spectrum of the sample pulse becomes narrow, the spectra of some channels decrease to the falling edge of the Gaussian envelope after OIDFT, degrading its performance.

On the other hand, the performances of the systems with 1-, 2-, and 5-ps pulses are very similar. The Gaussian filter extends the pulse width before the pulse enters the fiber, which reduces the influence of fiber dispersion. Considering the system mentioned above, with a 70-GHz-bandwidth Gaussian filter, after the 10-km fiber transmission, the pulse width will extend to about 35-ps whether the original width is 1, 2, or 5 ps. As a result, their performances are similarly excellent. However, the dispersion effect will significantly degrade the performance if the Gaussian filter is removed because the pulse width is ultra short. If a 2-ps pulse is used, the pulse width is extended to more than 200 ps after the 10-km fiber transmission, indicating that the intersymbol interference will be much more significant.

In conclusion, simulations and analyses have been performed on the AOS-OFDM system. The analysis is focused on four areas: the total number of channels, CPs, the data modulation format, and the width of the sample pulse. To optimize the system, considering the problem comprehensively is necessary. By maintaining the same N, the total bit rate increases with the increase in the number of channels; however, the BER performance degrades at the same time. Among the three data modulation formats, the DPSK system has the best performance, although its bit rate is doubled. Thus, if the total bit rate is the most important consideration, DQPSK is the best choice. The requirement for the sample pulse width is not very strict as long as the spectrum of the signal is located at the peak of the Gaussian envelope. Different system configurations have been tested to optimize the system performance. Based on the simulation and analysis above, a 5- or 10-channel system using a DPSK or DQPSK signal with a 2-ps width sample pulse is acceptable.

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