Experimental implementation of an all-optical OFDM system based on time lenses

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Experimental implementations of continuous optical time domain Fourier transformation based on time lenses and optical orthogonal frequency-division multiplexing (OFDM) system are carried out. Such a system is verified through 100-km transmission of 10-Gb/s non-return-to-zero (NRZ) intensity-modulated direct-detection (IM-DD) without any dispersion compensation. The system's bit error rate (BER) and power penalty are 10^{-12} and 4 dBm, respectively.

In recent years, optical orthogonal frequency-division multiplexing (OFDM) has gained popularity in the field of optical communication, especially in ultra-high-speed optical communication, owing to its large tolerance to chromatic dispersion, polarization mode dispersion, and timing jitter[1]. There are two kinds of optical OFDM systems: coherent optical OFDM (CO-OFDM) and optical OFDM (OOFDM) systems. CO-OFDM systems utilize radio frequency (RF) OFDM transmitters, which depend on electronic fast Fourier transform (FFT) circuits and complicated analog-to-digital converters (ADCs) to generate OFDM symbols. Thus, the transmission speed by electronic fast Fourier transform/inverse fast Fourier transform (FFT/IFFT), and analog/digital (A/D) and digital/analog (D/A) is limited as their sampling speed is lower than 10 GS/s under current circumstances[2]. On the other hand, OOFDM systems utilize all optical transmitters based on all optical Fourier transformations, such that the speed limitation of electronic circuits is eliminated fundamentally. Two kinds of physically feasible OOFDM systems are reported so far. One is the discrete optical Fourier transformation method[3], in which many phase shifters and time delay devices are used to make the system complicated and costly. The other is a kind of continuous optical Fourier transformation system based on time lens[4]. Kumar *et al.* put forward a new idea on all-optical implementation of OFDM using time lenses for optical inverse Fourier transformation (OIFT) or the optical Fourier transformation (OFT) system[4], which are simpler than discrete systems. The realization of time lens is based on the space-time duality of lightwave[5]. For a time lens, the time quadratic phase modulator is the key technology, but it is very difficult to realize. Kumar *et al.* also did not give any experimental realization scheme. Hirooka *et al.* used a sinusoidal clock signal to drive a LiNbO$_3$ phase modulator to replace the quadratics phase modulation, which caused a very narrow time window for Fourier transformation operation that could only be used for a single pulse[6]. Ng *et al.* used cross

phase modulation (XPM) effect to form a wider time window, but the system was also very complicated[7]. In this letter, we focus our research on the experimental realization of OFT for the OFDM symbol's realization, along with the realization of the electrical voltage t^2 wave, which result in a wider time window.

A schematic configuration diagram of our all-optical OFDM fiber system is shown in Fig. 1. In the transmitter, the initial optical pulses are divided into groups by a new clock, which is $1/N$ of the initial clock. The new clock functions as the system's synchronous clock beginning from the initial date, and then it drives the signal for the time lens in OIFT devices. A train of N pulses is operated by OIFT once a time, realizing the serial-to-parallel transaction and inverse Fourier transformation. As the input initial time domain signal is orthogonal, after OIFT, its spectral profile of output-transformed signal becomes the same as the input time domain signal, which is also orthogonal. Therefore, the output signal of OIFT is an OFDM signal, as shown in Fig. 1. The OFDM symbol's data rate is $1/N$ of the initial data
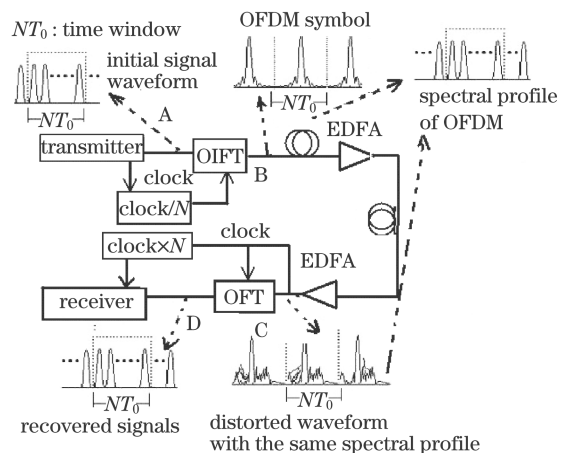

Fig. 1. Scheme of our OOFDM fiber transmission system. EDFA: erbium-doped fiber amplifier.

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$$\exp\left(\mathrm{i}\frac{1}{2\beta_2 z}t^2\right)$$

input → dispersive medium → quadratic phase modulator → dispersive medium → IFT or FT of input

$$*\exp\left(-\mathrm{i}\frac{1}{2\beta_2 z}t^2\right) \qquad\qquad *\exp\left(-\mathrm{i}\frac{1}{2\beta_2 z}t^2\right)$$
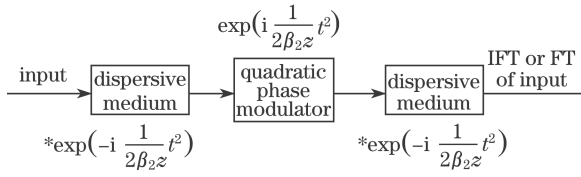
Fig. 2. Schematic diagram of the time lens.

rate. After transmission, at the receiver, the transmitted symbol is launched into another time lens parallel to the serial one in order to operate the OFT and parallel to the serial one. In the OFT of the receiver, the synchronous clock of the driving signal becomes the initial time clock. Therefore, after the OFT, the initial time domain signal can be recovered.

The key devices in Fig. 1 are the all-optical OIFT and OFT. Here, we use time lenses, as shown in Fig. 2, wherein two high dispersion media formed by the fiber Bragg grating (FBG) groups are used, as well as a quadratic phase modulator[5].

At the transmitter, the signs of the second-order dispersion coefficients should be positive. The phase modulator multiplies the optical field envelope by a function

$$h(t) = \exp(\mathrm{i}\alpha t^2), \qquad (1)$$

and the chirp α and accumulated second-order dispersion S ($S = \beta_2 L$) of each dispersive element are related by

$$\alpha = \frac{1}{2S}. \qquad (2)$$

As we know, the function of the phase modulator (PM) is

$$h(t) = \exp\left(\mathrm{i}\pi\frac{V(t)}{V_\pi}\right), \qquad (3)$$

where $V(t)$ is the electrical signal that drives PM, and V_π is a half-wave voltage. Comparing Eq. (1) with Eq. (3), the electrical driving signal for a PM should be

$$V(t) = \alpha\frac{V_\pi}{\pi}t^2. \qquad (4)$$

We should make sure that the aperture of the time lenses is finite. In this case, $V(t)$ should be modified as

$$V(t) = \sum_{n=-\infty}^{\infty} V_0(t - nT_{\mathrm{OFDM}}), \qquad (5)$$

$$V_0(t) = \alpha\frac{V_\pi}{\pi}t^2, \qquad (6)$$

where T_{OFDM} is the total width of an OFDM signal in the transmitter in Fig. 1

If it is very difficult to achieve the t^2 wave, then we use a cosine wave to approximate the t^2 wave[6], such that the frequency f_m of the cosine wave should satisfy $f_\mathrm{m} = 1/T_{\mathrm{OFDM}}$. We suppose that f_m and the input signal width T_{block} in the block n allow $f_\mathrm{m}T_{\mathrm{block}}$ to be small. In this case, we can write

$$\cos(2\pi f_\mathrm{m}t) = 1 - \frac{(2\pi f_\mathrm{m}t)^2}{2}. \qquad (7)$$

From Eqs. (5)–(7), the electrical signal driving PM should be rewritten as

$$V(t) = a\frac{V_\pi}{\pi}\frac{2[1 - \cos(2\pi f_\mathrm{m}t)]}{(2\pi f_\mathrm{m})^2}. \qquad (8)$$
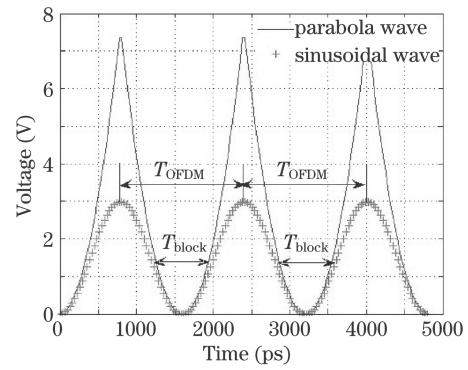

Fig. 3. Computation results of parabola wave and its approximate sinusoidal wave.
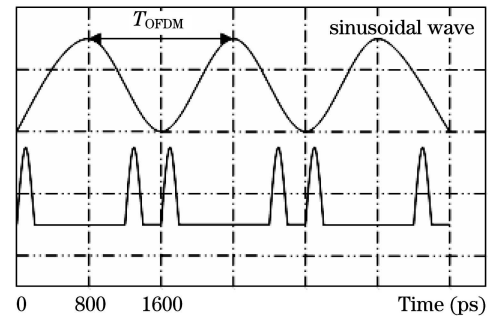

Fig. 4. Driving voltage and arbitrary input signal's position.
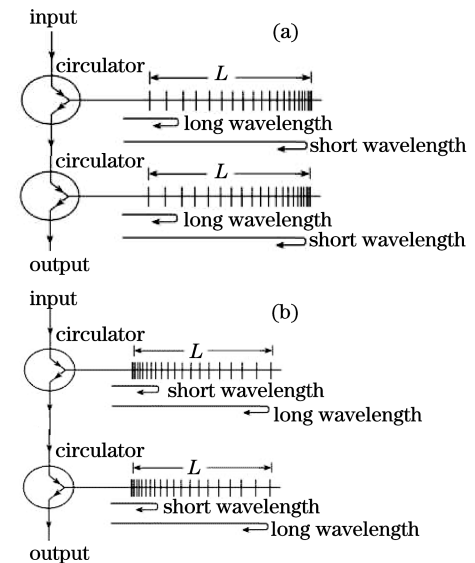

Fig. 5. Realizations of the high dispersion medium with (a) $\beta_2 < 0$ and (b) $\beta_2 > 0$.

For experimental implementation, firstly, the sinusoidal wave should have a 180° phase-shift. Then we amplify the amplitude of the sinusoidal wave and add a constant direct-current (DC) bias. Consequently, we obtain the driving voltage, as described in Eq. (8). Figure 3 shows the computation result of the parabola wave (Eqs. (5) and (6)) and its approximate sinusoidal wave (Eq. (8)) when $T_{\mathrm{OFDM}} = 1600$ ps. Thus, $f_\mathrm{m} = 625$ MHz, or the accumulated dispersion of the dispersive elements is 3400 ps/nm at 1550.12 nm, and $V_\pi = 6$ V. From Fig. 3, we can find that there is only a constraint time window during the whole width of each
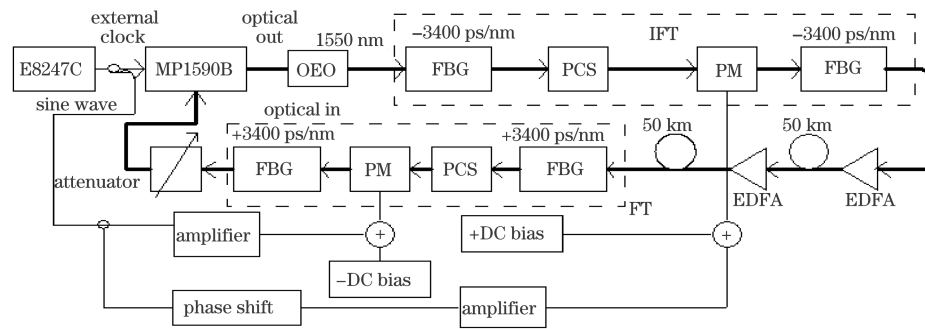
Fig. 6. Experimental setup for a 10-Gb/s OFDM system using time lenses. OEO: optical-electro-optical converter; PCS: polarization control setup.
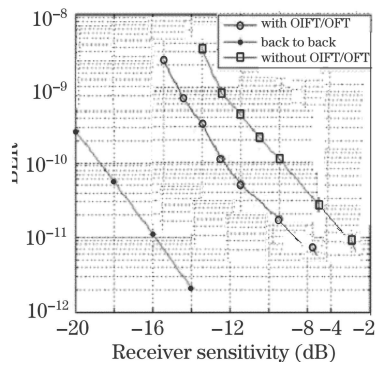

Fig. 7. BER measurement results.

OFDM signal that is used. That is, only T_{block} (Fig. 3) is available, So we need to insert a bit "0" during the guard time $T_{\text{OFDM}} - T_{\text{block}}$ and put the arbitrary input signal during T_{block}. Figure 4 shows the driving voltage (sinusoidal wave) and arbitrary input signal's position.

We use more than two conjoint FBGs to form ± 3400 ps/nm dispersive elements, as shown in Fig. 5 ($\beta_2 < 0$). For $\beta_2 > 0$, we use the same scheme, by which the input wavelength is identified as the short wavelength. At the receiver, the signs of the second-order dispersion coefficients should be negative, and the voltage driving PM should be inversed. That is, the additional constant DC bias to the sinusoidal wave should be negative.

We performed experiments to demonstrate the real-world implementation of OFDM using time lenses with the setup shown in Fig. 6, where the dispersive elements are FBGs, and the PM is LiNbO$_3$. The transmission fiber is G.655 fiber. At the transmitter, the generator E8247C generates a 625-MHz sinusoidal wave, which is used to drive the analyzer MP1590B. Thus, $T_{\text{OFDM}} = 1600$ ps. MP1590B could generate pseudo-random binary sequence (PRBS) consisting of an optical pulse at 10 Gb/s when there is an optical pulse at bit "1" and no signal at bit "0", respectively. We could also define each pulse group independently to make sure that there are arbitrary input signals during T_{block} and the bit "0" during the guard time $T_{\text{OFDM}} - T_{\text{block}}$.

Each of the 16 pulses generated by MP1590B are operated in IFT and are transformed into an OFDM symbol by the first time lens, which consists of two FBGs and a PM. This PM is driven by 625-MHz sinusoidal wave, which has a 180° phase shift, and amplified and added to a positive DC bias. The accumulated dispersion of each FBG is -3400 ps/nm. If the half-wave voltage V_π

of PM is 6 V, then the peak-to-peak value V_{pp} of the driving voltage is 5.6893 V, and the DC bias is 2.8446 V. After transmission through a 240-km fiber link without any dispersion compensation, the initial pulses could be recovered by OFT, in which the accumulated dispersion of FBG is 3400 ps/nm, no phase shift to the sinusoidal wave is identified, and the DC bias is -2.8446 V.

Figure 7 shows the bit error rate (BER) measurement of the systems under the conditions of back to back, with OIFT/OFT, and without OFT/OIFT, respectively. The transmission distance is 100 km, and the signal is a non-return-to-zero (NRZ) intensity-modulated direct-detection (IM-DD) one. The power penalty is 4 dBm for OOFDM.

In conclusion, we have experimentally shown an optical OFDM scheme that offers a large tolerance of dispersion in a high-speed optical communication system. A time domain OFT method based on time lens is used in this scheme. We have experimentally shown a successful 10-Gb/s NRZ IM-DD 100-km transmission without compensations and with a power penalty of 4 dBm and a BER of 10^{-12}.

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