# A PMD-supported 100-Gb/s optical frequency-domain IM-DD transmission system

**Wei Li (李 蔚)[1*], Yaojun Qiao (乔耀军)[2], Qingsheng Han (韩庆生)[1], and Huan Zhang (张 欢)[1]**

[1] *Wuhan National Lab for Optoelectronic, Huazhong University of Science and Technology,*
*Wuhan 430074, China*
[2] *Key Laboratory of Information Photonics and Optical Communications, Ministry of Education,*
*Beijing University of Posts and Telecommunications, Beijing 100876, China*
[*] *E-mail: weilee@hust.edu.cn*

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A novel method for distortion-free optical pulse transmission is theoretically proposed and simulated, in which two time lenses formed by dispersion fibers and quadratic phase modulations are utilized. One is used as an optical inverse Fourier transformation (OIFT) device to transform the initial time-domain data to frequency-domain one at the transmitter and the other as an optical Fourier transformation (OFT) device to recover the data at the receiver. By using the unchanged spectral envelope in linear optical fiber communication, the initial data can be recovered. Through simulations, a 10×100 Gb/s intensity-modulated direct-detection (IM-DD) dense wavelength division multiplexing (DWDM) system over 2000-km transmission without the compensation for polarization mode dispersion (PMD) and dispersion slope is achieved, which can be used to upgrade the current 10-Gb/s IM-DD system to a 100-Gb/s one directly.

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Recently, with the bit rate increasing to 100 Gb/s and beyond, the current intensity-modulated direct-detection (IM-DD) formats are not applicable any more because of their low tolerance for optical distortions including chromatic dispersion, dispersion slope, polarization mode dispersion (PMD), time jitter, etc. In order to realize ultra high-speed optical transmission over 100 Gb/s, various advanced modulation formats and transmission schemes have been developed[1]. However, these new technologies are complex and costly. The temporal optical Fourier transformation (OFT) based on time lenses is a promising technique for the ultra short pulse distortion-free transmission[2−5]. The principle is that the spectral envelope of an optical pulse is kept unchanged during transmission in optical fiber by using OFT to swap the spectral and temporal envelope, and the unchanged spectral envelope can be used to recover the original undistorted input pulse waveform. Wang *et al*. used a single time lens at the receiver to convert the distorted time domain signals into frequency domain to reconstruct the input pulses[2,3]. Because the ultra short optical pulse period leads to the very limited regeneration time for OFT, this technique can only be used in an optical time division multiplexing (OTDM) system. By using cross-phase modulation with parabolic pulses as a time lens, Hirooka *et al*. formed a wider regeneration window[4]. But a more complex system is needed to form such parabolic pulses.

In this letter, we propose a simple OFT-based system, which is much different from above schemes. In our scheme, two time lenses are added into a conventional 10-Gb/s IM-DD system to achieve a 100-Gb/s one. One time lens is put at the transmitter as an optical inverse Fourier transformation (OIFT) device. At the receiver after transmission, the other time lens is used as an OFT device to convert the transmitted signals back into time-domain for direct detection. A sequence of $N$ pulses is launched into the OIFT to form one signal. So the transmission speed is reduced to $1/N$ of its initial speed. Moreover, the regeneration time window is $N$ times longer than the initial data period, much longer than those in Refs. [2−4]. Potentially, it has a much better tolerance for linear perturbations. The simulations show a 10×100 Gb/s IM-DD DWDM system over 2000-km transmission without using PMD compensation.

The system configuration of our OFT-based IM-DD system is shown in Fig. 1, where $NT$ is the time window corresponding to the regeneration time[5], $N$ is the number of the initial optical pulses in one time window, $T$ is the initial data period, which is 10 ps in a 100-Gb/s system. In our system, the initial intensity-modulated pulses are divided into different continuous sequences by a new time clock, which is $N$ times longer than the initial data clock. $N$ initial pulses in each sequence are converted into one special frequency-domain signal by the OIFT device. It is a continuous real-time process. So the OFT and OIFT should be continuous with a period of $NT$. Each OFT and OIFT device has two phase modulators and a dispersion medium.

After the OIFT, the new signals are lunched into fiber. During transmission on link, we still use dispersion compensation modules (DCMs) to compensate the chromatic dispersion as those had been used in a conventional 10-Gb/s system. DCMs can also ensure the spectral signals to be confined in the time window during very long distance transmission.

At the receiver, the transmitted signals constricted in the time window can be converted back into initial pulse sequences by an OFT device. The whole system does not need the compensation for PMD and dispersion slope. If the time window is wide enough, the whole system may not need DCMs anymore. Unfortunately, for a 100-Gb/s

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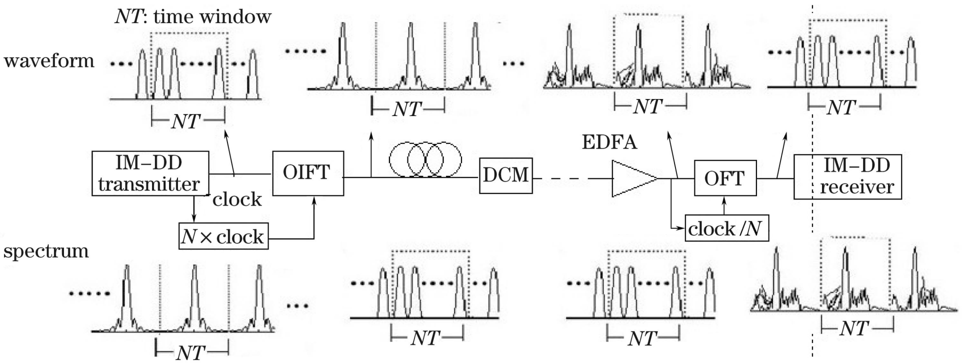

Fig. 1. Schematic diagram of OFT-based IM-DD system. EDFA: erbium-doped fiber amplifier.

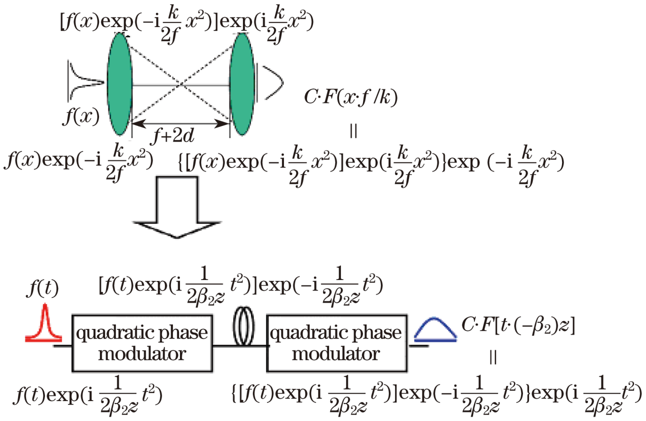

Fig. 2. Structure and principle of time lens in our system.

system over a long distance transmission, the chromatic dispersion is very sensitive and large, especially in normal fibers.

The behavior of the temporal optical pulses in a dispersion medium can be described by the analogy of a spatial imaging system as the space-time duality of the lightwave[4]. A spatial quadratic phase shift is applied by a lens to create a linear spatial chirp. The waveform then diffracts in space to take the Fourier transformed profile of its aperture shape at the focal length. The structure and principle of the time lens in our system are shown in Fig. 2, where $f(t)$ is the input time domain waveform, $F(t)$ is the Fourier transformation form of $f(t)$, $z$ is the length of high dispersion fiber, $\beta_2$ is the dispersion parameter of the dispersion fiber representing the diffusivity in time domain as in space, $C$ is a constant, and $\beta_2 Z$ decides the width of time window.

When $\beta_2 < 0$, Fig. 2 can realize an OFT as

$$\begin{aligned}&CF[(-\beta_2)t]\\&=\{[f(t)\exp(\mathrm{i}\frac{1}{2\beta_2 z})t^2]\exp(-\mathrm{i}\frac{1}{2\beta_2 z}t^2)\}\\&\exp(\mathrm{i}\frac{1}{2\beta_2 z}t).\end{aligned}\tag{1}$$

If $\beta_2 > 0$, the corresponding structure can realize an OIFT as

$$\begin{aligned}&Cf(t)=\\&\left\{\left[F(\beta_2 zt)\exp(\mathrm{i}\frac{1}{2\beta_2 z}t^2)\right]\exp(-\mathrm{i}\frac{1}{2\beta_2 z}t^2)\right\}\\&\exp(\mathrm{i}\frac{1}{2\beta_2 z}t^2).\end{aligned}\tag{2}$$

Suppose the input optical pulses are Gaussian pulses. For $N$ pulses in the time window $NT$, the initial input optical signal sequences into the OIFT can be written as

$$g\,(t)=\exp\left[-\frac{1}{2}\left(\frac{t}{T_{\mathrm{FWHM}}}\right)^2\right]\sum_{k=1}^{N}\delta\,(t-kT),\tag{3}$$

where $T_{\mathrm{FWHM}}=2(\ln 2)^{1/2}T_0$, $T_0$ is the half width at 1/e intensity point. Then after the OIFT, the transformed signal is

$$\begin{aligned}g'(t)&=g(t)CF^{-1}(t)\\&=\exp\left[-\frac{1}{2}\left(\frac{t}{T_{\mathrm{FWHM}}}\right)^2\right]F\left[\sum_{k=0}^{N-1}\delta\,(f-kF)\right]\\&=\exp\left[-\frac{1}{2}\left(\frac{t}{T_{\mathrm{FWHM}}}\right)^2\right]\left[\frac{\sin\,(\pi FNT)}{\sin\,(\pi FT)}\right].\end{aligned}\tag{4}$$

And the Fourier transformation of $g'(t)$ is

$$G\,(f)=\exp\left[-\frac{1}{2}\left(\frac{f}{NT_0}\right)^2\right]\left[\sum_{k=0}^{N-1}\delta\,(f-kF)\right],\tag{5}$$

where $G(f)$ denotes the Fourier transformation of $g'(t)$ which is the converted signal spectral envelope. Equation (5) has the same form as Eq. (3). As we know, in a linear optical fiber link without much nonlinear and narrow filter,

$$F(z,\omega)=F(0,\omega)\exp(\mathrm{i}\sum\nolimits_n D\omega^n z).\tag{6}$$

It is very important to note that

$$|F(z,\omega)|^2=|F(0,\omega)|^2\,,\tag{7}$$

where $F(z,w)$ is the spectral profile of the transmission signal.

So, after transmission, although the waveform is distorted, its spectral profile is unchanged. Then an OFT

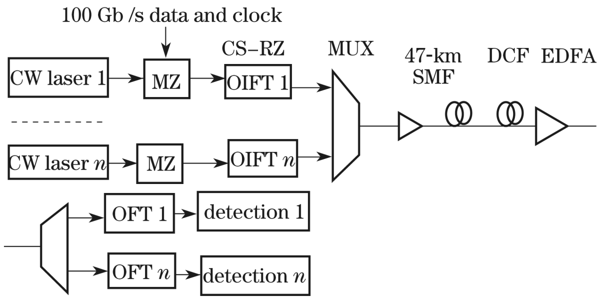

Fig. 3. Configuration of 10×100 Gb/s OFT DWDM system. CW: continuous wave; MZ: Mach-Zehnder modulator; MUX, multiplexer.

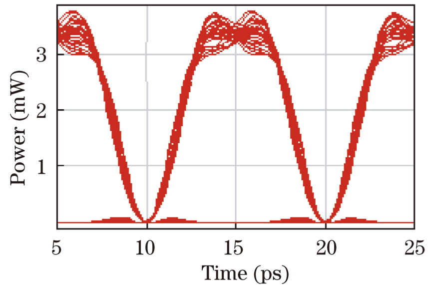

Fig. 4. Eye diagram of initial pulses at the transmitter.

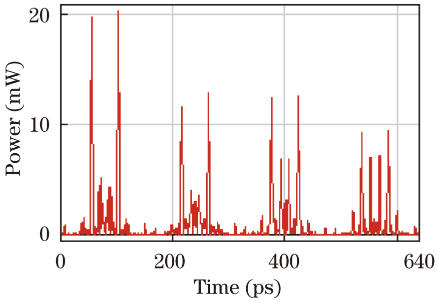

Fig. 5. Transformed time domain waveform of the signals after OIFT.

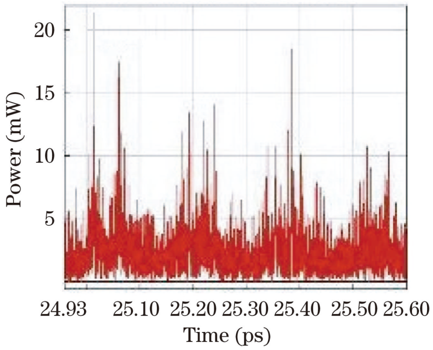

Fig. 6. Received time domain waveform after 2000 km before OFT.

will rebuild the initial signal.

For a 100-Gb/s OFT IM-DD system, we choose the carrier-suppressed return-to-zero (CS-RZ) code as the initial code whose pulse period is 6.5 ps. Ten pulses are chosen in one time window here. The phase modulation driving voltage period is 8.7729 cos $(2\pi\frac{100\times10^9}{10}t)$.

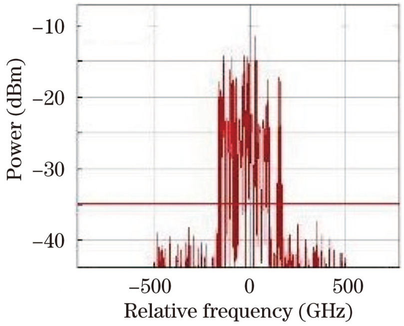

Fig. 7. Transformed spectral profile of signals after OIFT at the transmitter. The center frequency is 193.1 THz.

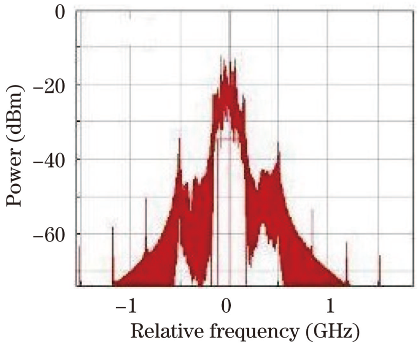

Fig. 8. Transmitted spectral profile of signals after 2000 km before the OFT at the receiver. The center frequency is 193.1 THz.

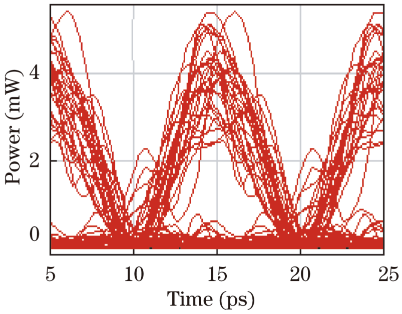

Fig. 9. Eye diagram of recovered pulses after OFT.

For the OIFT and the OFT, the length of dispersion fibers are both 800 m. The dispersion parameter $D$ is $\pm 74$ ps/(nm·km). The negative one is used in the OFT, while the positive one is for the OIFT.

A 10×100-Gb/s OFT DWDM system over 2000-km fiber shown in Fig. 3 is simulated by VPI Transmission Maker transmission software. The average power of each channel is 1 mW. Each OIFT converts one channel signal. Then they are multiplexed and transmitted over 40 spans of 50-km dispersion-controlled fiber link, which consists of standard single-mode fiber (SMF) and dispersion compensating fiber (DCF). The PMD coefficients of SMF and DCF are set at 0.5 ps/km$^{1/2}$. After transmission, each channel is separated by a demultiplexer, and then is lunched into an OFT before detection. Figures

4−9 show the simulation results. Compared with the transmitter's time domain waveforms shown in Figs. 4 and 5, the time domain waveforms after 2000-km transmission are badly distorted, as shown in Fig. 5. They could not be recovered in time domain. But the spectral profile is changed a little by the amplified spontaneous emission (ASE) noise, as shown in Figs. 7 and 8. After OFT, it is recovered successfully, as shown in Fig. 9. The system is proved to be efficient. The bit error rate (BER) is $10^{-12}$.

In conclusion, we show a high speed frequency-domain signal transmission method over 2000-km fiber without the compensation for PMD and dispersion slope to upgrade current 10-Gb/s systems directly to 100-Gb/s systems, in which the unchanged spectral envelope is used to carry the initial signals to tolerate PMD distortion. Two time lenses each formed by two phase modulators and a dispersion fiber are added in the traditional IM-DD DWDM system. This scheme is promising in the future high-speed long-haul transmission systems.

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