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A New Adaptive Equalization Scheme for a 160-Gb/s Transmitted Signal Using Time-Domain Optical Fourier Transformation

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***Abstract*—We demonstrate a new adaptive equalization scheme at 160 Gb/s using time-domain optical Fourier transformation. In this technique, we take advantage of the fact that the spectral profile does not change even when the transmission fiber has linear perturbations such as jitter, polarization-mode dispersion, and higher order dispersions. The unchanged spectral profile is then converted into the time-domain waveform at the output, resulting in the reconstruction of the original undistorted waveform. With the present scheme, a 160-Gb/s optical time-division-multiplexing signal was successfully transmitted over 120 km by simultaneously equalizing both second- and third-order dispersions even when they varied with time.**

***Index Terms*—High-speed optical pulse transmission, optical Fourier transformation (OFT), optical phase modulation, transform-limited (TL) pulses, waveform distortion elimination.**

I. Introduction

ADAPTIVE dispersion equalization will become a key technique for ultrahigh-speed transmission systems, where we need to pay careful attention to the exact compensation of second-order and even higher order dispersion. The precise simultaneous compensation of second- and higher order dispersion, however, is very difficult. In addition, even a small variation in dispersion caused by environmental effects is critical to transmission performance for bit rates of 160 Gb/s and above. The equalization schemes proposed so far include the use of nonlinear chirped fiber Bragg gratings (FBGs) [1], [2] and a virtually imaged phased array [3]. Second-order dispersion [group-velocity dispersion (GVD)] was recently dynamically compensated at 160 Gb/s by using a chirped FBG [1], [2]; however, the adaptive equalization of both second- and higher order dispersion at 160 Gb/s is too complicated to achieve in a single device with these schemes. In addition, it is difficult to eliminate jitter and polarization-mode dispersion (PMD).

Recently, we proposed a new scheme for the elimination of any waveform distortion caused by linear perturbations in the transmission line by using time-domain optical Fourier transformation (OFT) [4], in which the unchanged spectral profile in the transmission is converted into the time domain. This scheme has been shown to eliminate PMD [5], timing jitter [6], [7], and third-order dispersion (TOD) [4]. Since there is no need to measure dispersion quantities when we use the time-domain OFT technique, the simple and high-quality transmission of an ultrahigh-speed signal becomes possible, which is a substantial benefit in terms of ultrahigh-speed optical time-division-multiplexing (OTDM) transmission. Furthermore, it is very important to note here, as we pointed out in [4], that waveform distortion due to perturbations that vary with time can also be eliminated, since such time-varying perturbations still maintain their spectral shape through the transmission. This means that time-domain OFT enables us to equalize any order of dispersion with only a single OFT circuit.

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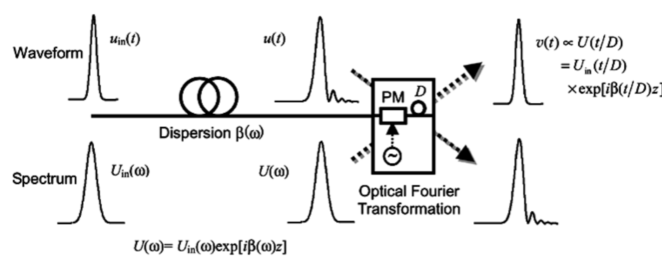

Fig. 1. Adaptive equalization using time-domain OFT.

In this letter, we demonstrate for the first time the adaptive equalization of both GVD and TOD for a 160-Gb/s OTDM signal by using time-domain OFT. We show that identical bit-error-rate (BER) characteristics can be achieved for various GVD (<1.7 ps/nm) and TOD (<1.7 ps/nm^2) values by using only a single OFT circuit. With the present scheme, a 160-Gb/s OTDM signal was successfully transmitted over 120 km even in the presence of residual GVD and TOD. We would like to emphasize that jitter and PMD are also eliminated simultaneously.

II. Principle of Adaptive Equalization Using Time-Domain OFT

Fig. 1 shows how time-domain OFT can recover the original pulse from a waveform distorted by linear perturbations such as higher order dispersion, jitter, or PMD. Time-domain OFT can be achieved by a linear chirp (with a chirp rate K) and an appropriate GVD medium (with a total GVD $D = k''L$, where k'' = second-order dispersion and L = length). This setup is similar to that of an optical regenerator based on soliton control [8]. In OFT, however, we do not use nonlinear optical effects. In addition, D and K have to satisfy a condition of $D = 1/K$.

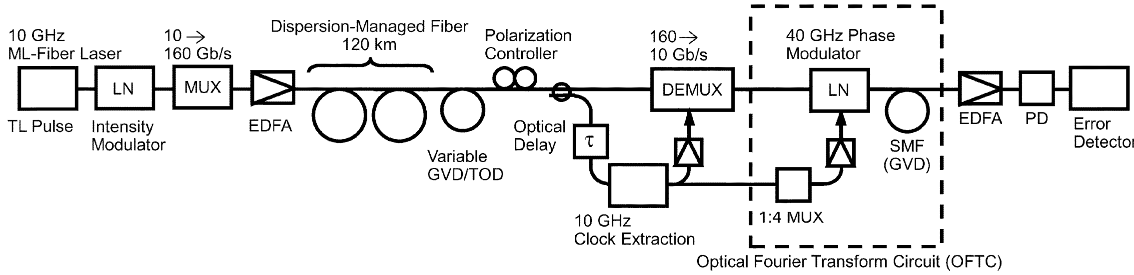

Fig. 2. Experimental setup.

With this condition, the output waveform after OFT $v(t)$ becomes proportional to the spectrum $U(\omega)$, where $\omega = t/D$ [4]

$$v(t) = \sqrt{\frac{i}{2\pi D}} \exp\left(-i\frac{1}{2}Kt^2\right) U(z, t/D). \tag{1}$$

When a transform-limited (TL) pulse is transmitted through a fiber, the spectral profile is maintained throughout the transmission even if the waveform is distorted in the time domain. Linear perturbations change only the phase of the input spectrum, that is $U(\omega) = U_{\rm in}(\omega)\exp[i\beta(\omega)z]$, where $\beta(\omega)$ is the dispersion in the transmission line. The transmitted spectrum is then transformed into the time domain at the output in the form

$$v(t) = \sqrt{\frac{1}{2\pi i D}} U_{\rm in}(t/D) \exp\left[-i\frac{1}{2}Kt^2 + i\beta(t/D)z\right]. \tag{2}$$

This enables us to reconstruct the original pulse waveform. It is important to note that the D or K value is independent of perturbations throughout the transmission.

For a Gaussian pulse of $u_{\rm in}(t) = A\exp(-t^2/2T_0^2)$, for example, a condition of $|D| = T_0^2$ gives us the output waveform as follows:

$$v(t) = \sqrt{\frac{i}{\mathrm{sign}(k'')}} A \times \exp\left(-\frac{t^2}{2T_0^2}\right) \exp\left[-i\frac{1}{2}Kt^2 + i\beta(t/D)z\right]. \tag{3}$$

Here, the output waveform $|v(t)|^2$ becomes exactly the same as the input waveform $|u_{\rm in}(t)|^2$. As there is no need to measure the exact dispersion values in advance, OFT works even when the perturbation varies with time, as long as the distorted waveform remains within the curvature of the phase modulation. Adaptive equalization is, therefore, possible. A distorted waveform in the time domain is converted to a spectrum, and hence, the output spectrum through the optical Fourier transform circuit (OFTC) becomes distorted instead. Time-variant elements such as a demultiplexer have no influence on OFT as long as the spectral shape is maintained although the phase of the longitudinal modes is modified.

III. Experimental Results at 160-Gb/s Transmission

To demonstrate the effectiveness of the present scheme, we carried out an adaptive equalization experiment for a 160-Gb/s OTDM system. The experimental setup is shown in Fig. 2. To obtain a 160-Gb/s OTDM signal, a 10-GHz pulse train was generated from a mode-locked fiber laser [9], which was modulated at 10 Gb/s with pseudorandom binary sequence $2^{23} - 1$ using an lithium-niobate (LN) intensity modulator and optically multiplexed to 160 Gb/s. The pulsewidth was 2.0 ps and the time bandwidth product was 0.43, indicating that the generated pulse had a TL Gaussian shape. The 160-Gb/s OTDM signal was transmitted through a 120-km transmission fiber, in which the GVD was compensated completely and the average TOD was 0.01 ps/km/nm^2. After the transmission, the transmitted signal was demultiplexed to 10 Gb/s by using a two-stage electroabsorption modulator with a switching window of 5.8 ps. The demultiplexed 10-Gb/s signal was coupled to the OFTC and then the BER was measured at the OFTC output. In the OFTC, the signal was first sinusoidally phase-modulated by a 40-GHz LN phase modulator with a chirp rate of approximately $K = -0.35$ ps^{-2}. An extracted 10-GHz clock was up-converted to 40 GHz to drive the phase modulator so that a 16 times larger chirp was applied, which enabled us to obtain a better OFT condition. The phase modulation function, which ideally should be parabolic, was approximated with a sinusoidal function. The chirped signal then passed through a GVD medium with $D = -2.93$ ps^2, satisfying the condition $D = 1/K$.

We investigated in detail the way in which the BER changes for various GVD and TOD values, with and without the OFTC. In the back-to-back case, the 160-Gb/s OTDM signal was directly injected to the demultiplexer without transmission over the fiber link, and the demultiplexed 10-Gb/s signal was led to a photodetector without passing through the OFTC. We first examined the deterioration in the transmission quality when the GVD value was varied, and investigated the improvement with OFT. For a precise evaluation of the GVD-induced penalties alone, we completely compensated for the TOD by adding an 18-km-long slope-compensating fiber, which was then followed by a single-mode fiber of a different length so that we could vary the GVD value while maintaining zero TOD. Fig. 3(a) shows BER curves versus received power for GVD values of 0.85, 1.39, and 1.70 ps/nm. When we increased the GVD to 1.7 ps/nm, the BER curve started to have an error floor as shown by filled squares. When we installed the OFTC without changing other setup, however, the error floor was effectively suppressed, and the BER almost recovered to the original back-to-back curve. The very small residual penalty shown by open squares was due to the approximation of the parabolic phase modulation in the OFTC with a sinusoidal function. The parabolic curvature was limited to near the top of the modulation in the sinusoidal approximation. Since the OFTC did not contain any bandwidth-limiting elements such as narrow-band optical filters, the improvement of power penalty is a consequence of the recovery of the undistorted waveform by OFT rather than the signal-to-noise ratio improvement due to filtering effects.

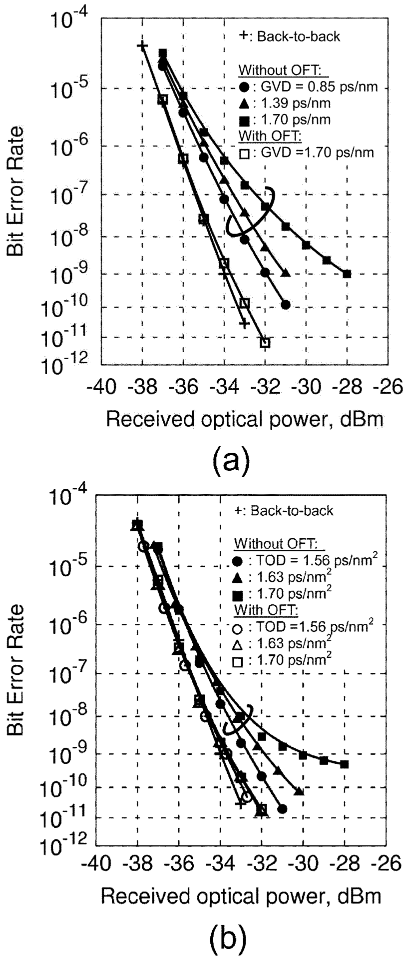

Fig. 3. BER characteristics of demultiplexed 10-Gb/s data for various values of (a) GVD and (b) TOD.

Next we evaluated the change in the BER by varying the TOD under zero GVD and examined the improvement with the use of OFT. We varied the TOD value by adding a dispersion-shifted fiber of a different length after the 120-km transmission line, in which the GVD was completely compensated. Fig. 3(b) shows the measured BER curves for TOD values of 1.56, 1.63, and 1.70 ps/nm^2. Regardless of the change in the TOD values, the penalties in the BER curves without OFT (filled symbols) were successfully removed by OFT. In particular, the error floor for TOD $= 1.70$ ps/nm^2 was suppressed by OFT. The small residual penalty after OFT is again due to the sinusoidal approximation of the phase modulation in the OFTC. Fig. 4 shows the waveform and spectrum of the demultiplexed 10-Gb/s signal without and with OFT when TOD $= 1.63$ ps/nm^2. The waveform and spectrum were measured with an optical sampling scope and an optical spectrum analyzer, respectively. The pulse broadening observed in the demultiplexed waveform in Fig. 4(a) without OFT is shortened by the OFTC to that seen in Fig. 4(b), and at the same time, pulse broadening in the time domain is converted to spectral broadening on the right side by OFT as shown in Fig. 1.

IV. Conclusion

We reported a new adaptive equalization scheme using time-domain OFT that enables us to equalize both GVD and TOD simultaneously for ultrahigh-speed transmitted signals. OFT enables us to construct ultrahigh-speed transmission systems without the careful management of fiber dispersion, and hence, high-speed signal transmission through already installed fiber cables can be easily achieved.

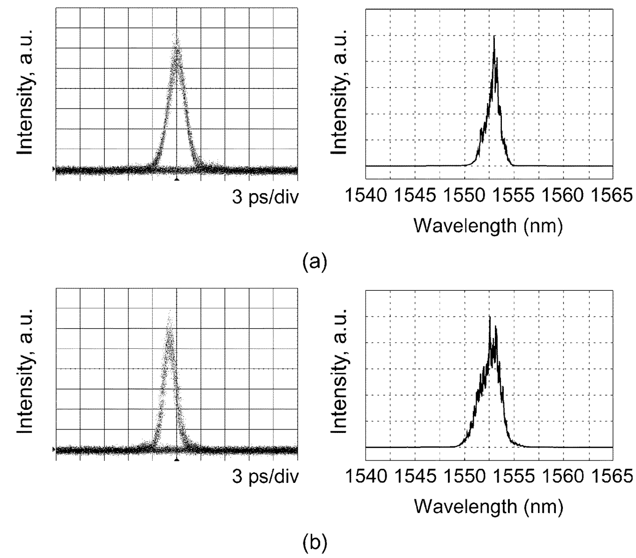

Fig. 4. Waveform (left) and spectrum (right) of demultiplexed 10-Gb/s signal when TOD $= 1.63$ ps/nm^2. (a) 10 Gb/s, without OFT. (b) 10 Gb/s, with OFT.

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