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Peak-to-average power ratio reduction of transmission signal of all-optical orthogonal time/frequency domain multiplexing using fractional Fourier transform

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A R T I C L E I N F O

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A B S T R A C T

We examine a peak-to-average power ratio (PAPR) reduction effect in an optical fiber link using a fractional Fourier transform (FrFT). Fractional OFDM (FrOFDM) based on FrFT in place of discrete Fourier transform is a multiplexing approach that can balance the pros and cons of subcarriers in the time and frequency domains while keeping its orthogonal condition. A careful investigation of the PAPR behavior of a FrOFDM signal confirms that its PAPR can be minimized at a point where a Nyquist pulse train is formed by a time-lens effect. With emphasis on this low-PAPR characteristic of a Nyquist pulse train, the signal quality degradation owing to fiber nonlinearity can be mitigated. A 1.0-dB signal quality improvement after propagation in a dispersion-compensated fiber link is demonstrated in a simulation for a 12×10-Gbaud/s 16 QAM FrOFDM signal in comparison with that of a conventional OFDM.

1. Introduction

To deal with exponentially growing network traffic, the effective utilization of optical spectral resources and the reduction of energy consumption and costs for entire optical networks are strongly required [1]. Although many efforts such as quadrature amplitude modulation (QAM), polarization multiplexing, and wavelength division multiplexing enlarge network capacity, network growth is limited owing to signal distortions caused by the nonlinearity of fiber links. Many research studies on spatial division multiplexing (SDM) and phase conjugator based nonlinear compensation have been conducted to overcome this limitation [2,3]. To maximize the capacity of all fiber in cooperation with such an SDM approach and effective use of established fiber links, a single core should transmit as much data as possible.

Multiplexing approaches using an orthogonal basis such as orthogonal frequency division multiplexing (OFDM) and Nyquist optical time division multiplexing (N-OTDM) were proposed for achieving high spectral efficiency [4–7]. OFDM has further advantages of tolerances of residual dispersion and receiver bandwidth mismatch with a cyclic prefix [8]. All-optical OFDM can avoid the electrical speed limitations of digital signal processing and digital to analog conversion, and can reduce energy consumption and system costs [9–15].

However, OFDM has the disadvantage of a very high peak-to-average power ratio (PAPR) owing to the coherent superposition of many subcarriers in the time domain [16]. Since a high-PAPR signal may induce serious nonlinear effects in fiber links, the signal quality can be degraded and the launchable power can be limited. On the other hand, a transmit signal of N-OTDM has a low-PAPR characteristic because the signal energy is spread in the time domain. Nevertheless, this technique demands an ultrashort time gate on the receiver side. Undesired coherent superposition also occurs owing to fiber dispersion.

The most feasible approach should be selected for multiplexing in accordance with the performance of receivers and the characteristics of fiber link. Fractional OFDM (FrOFDM) based on a fractional Fourier transform (FrFT) in place of discrete Fourier transform has been proposed to increase system flexibility in the time and frequency domains

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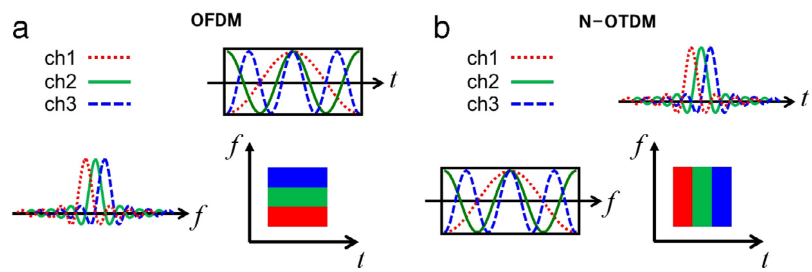

Fig. 1. Diagrams of (a) OFDM and (b) N-OTDM.

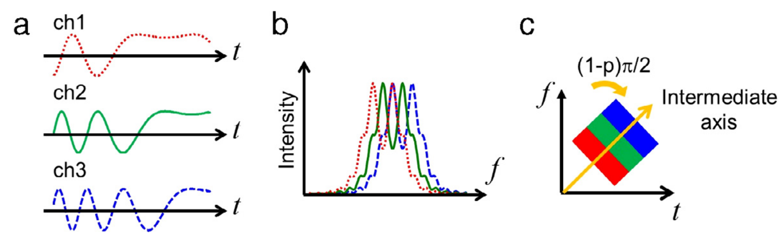

Fig. 2. (a) Waveform of FrOFDM subcarriers. (b) Intensity of spectra of FrOFDM subcarriers. (c) Spectrogram of FrOFDM signal.

while maintaining the orthogonal condition [17]. In our previous work, we demonstrated fundamental processes of transmit and receive for all-optical FrOFDM, and the generation of a Nyquist pulse train using a FrOFDM signal and a fiber dispersion [18–21]. Since the Nyquist pulse train has a low-PAPR characteristic; it is expected to be used to mitigate fiber nonlinearity [22].

In this work, we investigated the optimization of a transmission signal of an orthogonal multiplexing approach in accordance with the characteristics of the fiber link, focusing on the reduction of PAPR. From the numerical simulation results of the changes of PAPR under propagation in a dispersive fiber, we confirmed that the PAPR of a FrOFDM signal can be minimized at a point where a Nyquist pulse train is formed by the time-lens effect. Moreover, through a simulation, we demonstrated the fiber nonlinearity mitigation effect by evaluating the transmission performance of the FrOFDM signal in the dispersion-compensated fiber link.

2. All-optical orthogonal time/frequency-domain multiplexing using fractional Fourier transform

OFDM systems transmit complex data s_n of high-order constellations in parallel using N complex frequency subcarriers. The OFDM symbols overlap the time interval T and satisfy the orthogonality condition in the frequency domain, as shown in Fig. 1(a).

$$x^1(t) = \sum_{n=0}^{N-1} \phi_n^1(t) \tag{1}$$

$$\phi_n^1(t) = s_n rect\left(\frac{t}{T}\right) e^{-j2\pi\frac{n}{T}t} \tag{2}$$

$$X^1(f) = \sum_{n=0}^{N-1} s_n \sin c\,(fT) \otimes \delta\left(f - \frac{n}{T}\right). \tag{3}$$

where $\phi_n^1(t)$ is the subcarrier waveform, $x^1(t)$ is the OFDM symbol, and $X^1(f)$ is the Fourier transform of $x^1(t)$. The OFDM symbol has the advantages of a high tolerance for residual dispersion and an ability of assist to receiver bandwidth. However, its high PAPR owing to the overlap of many subcarriers in the time domain induces a nonlinear distortion in the fiber links.

The N-OTDM symbol is a series of sinc pulses, delayed by $\Delta t = T/N$, that satisfy the orthogonality condition on the time axis, as shown in Fig. 1(b).

$$x^0(t) = \sum_{n=0}^{N-1} s_n \sin c\left(\frac{t}{\Delta t}\right) \otimes \delta(t - n\Delta t) \tag{4}$$

$$X^0(f) = \sum_{n=0}^{N-1} s_n rect(f\Delta t) \cdot e^{-j2\pi n\Delta t f} \tag{5}$$

where $x^0(t)$ is the N-OTDM symbol, and $X^0(f)$ is the Fourier transform of $x^0(t)$. Although the N-OTDM symbol has a low PAPR, an ultrashort time gate is required for demultiplexing. Furthermore, the growth of PAPR along propagation in a fiber link is expected owing to fiber dispersion.

OFDM and N-OTDM are complementary approaches for time and frequency multiplexing. In an actual system, a more feasible approach should be selected according to the performances of receivers and the characteristics of fiber links. It is possible to generalize these multiplexing approaches by introducing a new set of subcarriers. These subcarriers correspond to fractional Fourier transform (FrFT) kernels that are orthogonal over a symbol duration T.

$$x^p(t) = \sum_{n=0}^{N-1} \phi_n^p(t) \tag{6}$$

$$\phi_n^p(t) = s_n rect\left(\frac{t}{T}\right) \cdot e^{j\pi\left\{\left[n^2\sin^2\left(p\frac{\pi}{2}\right)+\frac{t^2}{T^2}\right]\cot\left(p\frac{\pi}{2}\right)-2\frac{n}{T}t\right\}} \tag{7}$$

where $\phi_n^p(t)$ is the subcarrier waveform, and $x^p(t)$ is the FrOFDM symbol. Nonessential constants have been neglected. p is a fractional parameter. For $p = 1$, FrFT is a conventional Fourier transform, and the signal is an OFDM symbol. Fig. 2(a), (b) show the waveforms and spectra of FrOFDM subcarriers corresponding to $p = 0.1$. The FrOFDM symbol is rotated at an angle of $(1-p)\pi/2$ from the OFDM symbol onto an intermediate axis between the time and frequency, as shown in Fig. 2(c). The FrOFDM symbol can be demultiplexed by applying a complementary FrFT such as $-p$ at the receiver. Just like the conventional Fourier transform, the FrFT could be performed in the optical domain with passive optical components such as arrayed waveguide gratings and wavelength selective switches [21].

3. PAPR reduction using FrOFDM symbol

3.1. Generation of Nyquist pulse train using FrOFDM symbol

The equation for an FrOFDM subcarrier can be written as

$$\phi_n^p(t) = e^{j\pi n^2\sin^2\left(p\frac{\pi}{2}\right)\cot\left(p\frac{\pi}{2}\right)}\phi_n^1(t) \cdot e^{j\pi\frac{\cot\left(p\frac{\pi}{2}\right)}{T^2}\cdot t^2}. \tag{8}$$