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Abstract: We demonstrate optical orthogonal time-frequency domain multiplexing (OTFDM), which inherits the advantages of high-speed OTDM and high-spectral-efficient OFDM. Single-Pol., 2-b/s/Hz, 160-Gb/s OTFDM-QPSK is achieved by optical time-domain processing.
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1. Introduction

Recently, orthogonal frequency-division multiplexing (OFDM) is gathering attention because of its great spectral efficiency [1][2]. A major difficulty in the OFDM technique is how to realize Fast Fourier Transform (FFT) or equivalent filtering functions for multiplexing and demultiplexing. In electrical approaches, the FFT functions need to be implemented in a high-speed digital signal processor (DSP), thus the data rate achievable is restricted by processing speed of the DSP [1]; in optical approaches, optical FFTs based on special optical filtering circuits are required for the orthogonal multiplexing and demultiplexing [2], which prevents high-degree and high-throughput multiplexing due to the complexity of the circuits.

In this paper, we propose and demonstrate another optical multiplexing technique called orthogonal time-frequency domain multiplexing (OTFDM), which inherits advantages of both conventional OTDM (temporal multiplexing) and OFDM (high spectral efficiency). In OTFDM, we easily achieve high-speed and high-capacity transmission beyond electrical bandwidth limitations. Unlike OFDM, the OTFDM simply adopts optical time-domain processing both in the transmitter and receiver sides without relying on either electrical or optical FFT circuits. Therefore, the data rate is not restricted by processing speed of the DSP or complexity of the optical filtering circuits. Moreover, OTFDM obtains spectral efficiencies as high as OFDM, which can reach 1 [Baud/Hz], twice of traditional unfiltered on-off keying, phase-shift keying (PSK) signals etc. OTFDM is a linear and orthogonal multiplexing technique; therefore, we can adopt multilevel signaling techniques like nPSK and nQAM together with the OTFDM, ultimately enhancing spectral efficiency up to log2(n) [b/s/Hz]. In this paper, we demonstrate 2-b/s/Hz, 160-Gb/s (Single-Pol. 8x20-Gb/s) OTFDM-QPSK by using novel modulation (multiplexing) and demodulation (demultiplexing) techniques processed in time domain.

2. Principles

2.1. Orthogonal time-frequency domain multiplexing

In OTFDM, tributary signals are optically multiplexed into time-frequency domain with minimum occupying bandwidth through time-domain processing. Figure 1 shows the principles of OTFDM. As shown in (a), the OTFDM transmitter has a multi-parallel modulator structure [3] that generates m sets of tributary signals to multiplex them. In the ith tributary arm, an optical rectangular comb with a frequency spacing of B [Hz] and bandwidth of mB [Hz] is data modulated at the symbol rate of B [Baud]; the outputs from the arms are superposed (multiplexed) with an m × 1 optical combiner after giving a delay of iB [sec] to the tributary. Therein, the frequency spacing of the comb is same as the data modulation speed and the number of comb lines is equal to the degree of multiplexing (number of tributaries). For the comb generation, in each arm of the transmitter, a Mach-Zehnder modulator based flat comb generator (MZ-FCG) is suitable because it can generate the comb having a rectangular spectral profile and stable fixed phase relationships between the frequency components [4]. As for the data modulation, an inphase- quadrature- (IQ) modulator can be used for signaling in nPSK, nAPSK, nQAM or any other linear modulation formats.

The modulation spectrum after multiplexing is rectangular and its bandwidth is mB [Hz]. The OTFDM signal at the bit rate of mB log2(n) [b/s] is transmitted within the bandwidth; therefore the spectral efficiency reaches as high as log2(n) [b/s], which is twice of those of typical modulation formats, like nPSK, at the same symbol rate.
2.2. Optical coherent matched detection for OTFDM demultiplexing and demodulation

The generated OTFDM signal is much faster than the response of photodiodes and its temporal waveform is far from conventional formats (ex. OTDM signals) because each tributary is strongly overlapped in the time domain. To demultiplex and demodulate the tributary channels from the OTFDM signal, we use a novel detection scheme called coherent matched detection, which is shown in the Fig. 1(b). In the scheme, the received OTFDM signal is homodyne mixed with a locally generated comb (local comb) [5], which has the same amplitude and phase characteristics as the comb generated in the transmitter side. By the coherent matched detection, only the target channel is orthogonal demultiplexed and demodulated from the ultrafast OTFDM signal when it temporally overlaps exactly with the local comb. This operation is assured without causing excess receiver penalty because the multiplexed signals are orthogonal to each other in the optical time frequency domain and the orthogonality is kept even after the homodyne mixing. From another perspective, after the homodyne mixing the target tributary channel synchronized to the local comb is down converted to DC frequencies; while other channels are converted to higher frequencies, which are subsequently filtered by a low-pass electrical filter applied to the homodyne mixed signals. After the coherent matching process, the carrier phase of the demultiplexed channel can be recovered with an aid of digital signal processing or any optical phase locking techniques.

Unlike other coherent demultiplexing techniques for OTDM systems [6][7], the coherent matched detection does not rely on temporal sampling with optical short pulses that requires adequate time separation between neighboring pulses. This is advantageous for demultiplexing of densely multiplexed signals like OTFDOM.

3. Experiments

Fig. 2 shows the experimental setup for back-to-back transmission of single-Pol. 160-Gb/s (8-ch × 20-Gb/s) OTFDM-QPSK. In the transmitter side, an 8×10 GHz rectangular comb was generated from a CW light by using an MZ-FCG followed by an optical band-pass filter for spectral shaping. The comb was QPSK modulated at the symbol rate of 10 Gbaud by using an IQ modulator. For multiplexing eight channels, we used a delay-line based OTDM multiplexer with eight arms each with the delay of 12.5/i/100k [ps], where i and k are integers.

The OTFDM-QPSK signal was received with the OTFDM receiver based on the coherent matched detection. The receiver consists of an optical 90-degree hybrid coupler followed by balanced detectors and the local comb was launched through the local oscillator port. For simplicity, in this experiment, the rectangular comb for the local comb was shared with the comb generated in the transmitter side. By the coherent matched detection, only the target tributary channel was recovered by digital signal processor (DSP) based on intradyne detection technique.

Fig. 3(a) is the measured modulation spectrum of the 160-Gb/s OTFDM-QPSK signal, which had a rectangular profile with 3-dB bandwidth of 80 GHz, half of the conventional QPSK signals (i.e., a spectral efficiency of 2 bit/s/Hz). Thanks to the rectangular spectral shaping, the OTFDM signal can be transmitted with such a minimum occupying bandwidth without losing orthogonality between the tributaries. This is because, through the coherent matched detection, the correlation function of a tributary of the OTFDM-QPSK signal with the local comb yields the Nyquist waveform with the null points placed at the sampling points of neighboring channels. Ideally, the demultiplexed signal will not experience any crosstalk and interference from neighboring channels. Fig. 3(b) shows a measured correlation function, which was taken scanning the delay between the signal and local comb. The suppression ratio at the null points, i.e. crosstalk from the neighboring channel, was kept more than 13 dB. For appropriately demultiplexing the OTFDM-QPSK signal, the delay was aligned at the center of the correlation function to overlap the local comb with one of the tributary channels; as a result, we observed clear QPSK constellations of the demultiplexed channel, as shown in Fig. 3(c). We also evaluated bit error rate characteristics of all demultiplexed channels. Receiver sensitivity at BER < 1e-3 was -24 dBm at the worst channel (Fig. 3(d)).

4. Conclusions

In this paper, optical time-frequency domain multiplexing (OTFDM) was proposed and demonstrated. We demonstrated 2-b/s/Hz, 160-Gb/s OTFDM-QPSK, which was optically modulated (multiplexed) and demodulated (demultiplexed) entirely in the time-domain without use of multiplexing filters or electrical FFTs. OTFDM is a solution for ultrafast transmission with great spectral efficiency.

References


Fig. 1. Principles of OTFDM: (a) transmitter based on multi-parallel modulator, (b) receiver based on coherent matched detection

OTFDM Transmitter
Multi-parallel modulator

OTFDM Receiver
Coherent matched detection

Rectangular comb generation

Fig. 2. Experimental setup (CH.2-CH.8 were generated with a delay-line based 1 × 8 OTDM multiplexer)

Fig. 3. (a) Optical spectrum of 160-Gb/s OTFDM-QPSK signal, (b) correlation function between a tributary and local comb (c) constellations of a coherent matched detected OTFDM-QPSK signal, (d) BER characteristics of demultiplexed channels