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Time Lens based Optical Fourier Transformation for Advanced Processing of Spectrally-efficient OFDM and N-WDM Signals

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Abstract: We review recent progress in the use of time lens based optical Fourier transformation for advanced optical signal processing, with focus on all-optical generation, detection and format conversion of spectrally-efficient OFDM and N-WDM signals.

OCIS codes: (060.4080) Modulation; (060.4230) multiplexing; (070.7145) ultrafast processing.

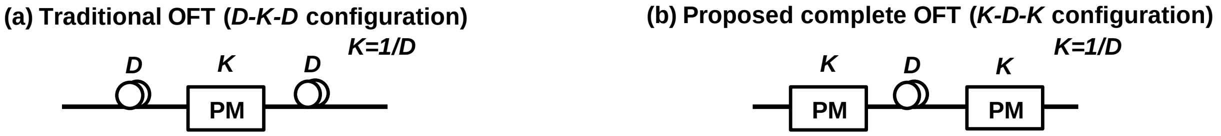
1. Introduction

To cope with the rapid traffic growth in optical communication networks, it has become increasingly important to develop novel signal processing technologies for more energy- and spectrally-efficient communication systems [1]. Recent studies have focused on orthogonal frequency division multiplexing (OFDM) [2] and Nyquist wavelength division multiplexing (N-WDM) [3], which both take advantage of the orthogonality to enable channel spacing close or equal to the symbol rate, thus resulting in a high spectral efficiency (SE). With the help of advanced coherent detection and electronic digital signal processing (DSP) technologies, OFDM and N-WDM have been used to demonstrate high SE super-channels with more than 1 Tbit/s capacity [4]. However, due to the bandwidth limitation of electronics, scaling the bandwidth of the DSP based system will also scale the number of components and their combined power consumption. On the other hand, optical signal processing (OSP) can explore nonlinear optical phenomena which have a response time on the order of femtoseconds, thus allowing for processing bandwidth beyond one THz. In general, OSP may be considered suitable only for relatively simple functionalities, and complex digital logic for spectrally-efficient signals may turn out to be challenging to implement optically.

In this paper, we introduce a novel time lens based complete optical Fourier transformation (OFT) technique for advanced optical signal processing of OFDM and N-WDM signals. A number of recent demonstrations of complex high-speed optical signal processing using complete OFT will also be reviewed, including generation, detection and format conversion of OFDM and N-WDM signals. These demonstrations show that simple OFT implementations can be used to achieve relatively complex signal processing operations on OFDM and N-WDM signals.

2. Time lens based complete OFT

Time lenses are based on the space-time duality of light, which states that a quadratic phase modulation of a temporal waveform is analogous to the action of a thin lens on a spatial beam, hence the expression “time lens” [5]. By combining a time lens with suitable dispersion both before and after the lens, an OFT can be realized as shown in Fig. 1(a) [6]. Recently, the time lens based OFT has been shown to be a very versatile and powerful tool for ultrafast signal processing. It can transfer the temporal profile of an optical signal into the frequency domain and vice-versa. This has led to demonstrations of e.g. distortion-less transmission [7] ultrafast optical oscilloscope [8] and Optical time-division multiplexing (OTDM) to WDM conversion [9]. These demonstrations are realized by a “partial” OFT, where only one-way conversion can be achieved, either from the time- to the frequency-domain, or from the frequency- to the time-domain. A partial OFT scheme is not sufficient for processing of OFDM and N-WDM signals, since it introduces a residual chirp or dispersion which will impact the orthogonality of OFDM and N-WDM signals. To overcome this challenge, we proposed a new time lens based complete OFT, cf. Fig. 1(b) [10]. The proposed OFT is based on two quadratic phase-modulation stages ($\delta\phi = Kt^2/2$) with chirp rate K, separated by a dispersive medium with $D = \beta_2 L$ (where β_2 is the 2nd order dispersion and L is the length), which satisfies the condition $K=1/D$ (a *K-D-K* configuration). Unlike the partial OFT schemes, this configuration enables complete time-to-frequency and frequency-to-time conversions simultaneously, thus performing an exchange between the


(a) Traditional OFT (*D-K-D* configuration)

(b) Proposed complete OFT (*K-D-K* configuration)

Fig. 1. Schematic diagrams of a time lens based OFT, (a) traditional D-K-D configuration, (b) proposed K-D-K configuration for signal processing of spectrally-efficient signals.

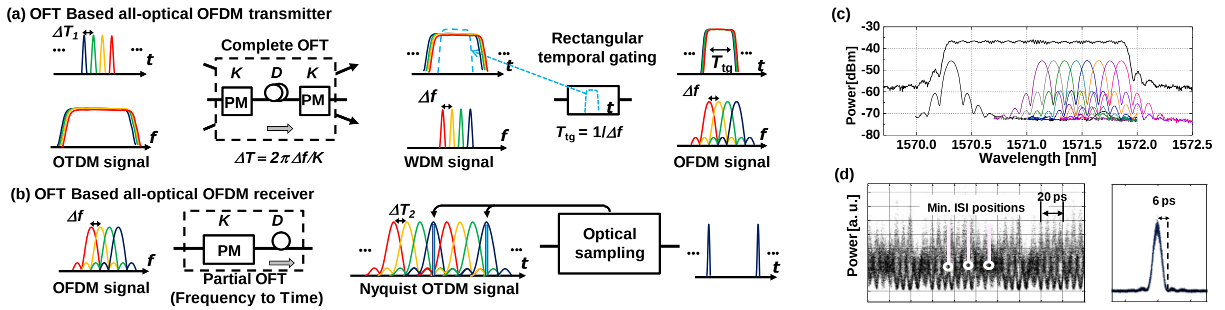


Fig. 2. (a) The principle of the OFT based all-optical OFDM transmitter and (b) receiver. (c) Experimental results, obtained OFDM signal and sinc-shaped subcarriers, (d) obtained Nyquist-OTDM signal and single Nyquist tributary waveform in the receiver.

temporal and spectral profiles of the input signal (a "complete" OFT) without any residual chirp or dispersion impacting the output signal. Note that the traditional OFT system with a *D-K-D* configuration in Fig. 1(a) can also realize simultaneous frequency-to-time and time-to-frequency conversion. However, it is not suitable for processing signals with high SE, since the dispersive elements involved before the phase modulation stage will generally broaden the waveform beyond the temporal aperture of the time lens (which cannot exceed the bit slot). In contrast, the proposed OFT with a K-D-K configuration can keep the waveform within the time-lens apertures, making this configuration more versatile for signal processing of spectrally-efficient signals.

3. All-optical OFDM transmission system utilizing time-lens based complete OFT

All-optical OFDM performs subcarrier multiplexing and demultiplexing in the optical domain, thereby circumventing speed limitations of electronics. An all-optical OFDM system can be implemented by optical discrete Fourier transformation (ODFT) based on cascaded delay interferometers [11], arrayed waveguide grating routers [12], or wavelength selective switches (WSS) [13]. However, the complexity of these ODFT schemes generally increases with the number of independent data-subcarriers. As an alternative, we have proposed a novel all-optical OFDM transmission system utilizing time lens based OFT as shown in Figs. 2(a) and (b) [14]. In the transmitter, all the OFDM subcarriers are simultaneously generated in real-time from an OTDM signal by a complete OFT in combination with rectangular temporal gating. In the receiver, a partial OFT is used to frequency-to-time convert the OFDM spectrum into a Nyquist OTDM signal. The Nyquist OTDM signal is subsequently time-demultiplexed by sampling each subcarrier at the inter-symbol-interference (ISI)-free point using a narrow optical sampling gate [15]. Finally, the demultiplexed signal is detected by a base rate receiver. In the experimental demonstration, a 160 Gbit/s OFDM signal with 16 subcarriers was generated as shown in Fig. 2(c). To achieve the sufficient *K* and the temporal aperture for OFT, the quadratic phase modulations were implemented based on four-wave mixing (FWM) process [8]. After 100 km transmission, the OFDM signal was converted into Nyquist OTDM signal by partial OFT. The obtained Nyquist-OTDM signal is shown in Fig. 2(d) with the waveform of a single Nyquist OTDM-tributary. The Nyquist-OTDM signal was subsequently received by optical sampling at the ISI free position using a nonlinear optical loop mirror. A BER<10^{-9} was obtained for all 16 subcarriers. Spectral efficiency of 0.8 symbol/s/Hz was thus achieved, which is close to the signal channel theoretical limit of 1 symbol/s/Hz. In comparison with ODFT based processing of OFDM signals, the proposed time lens based OFT scheme is essentially simple, and the implementation complexity does not increase with the number of subcarriers. In addition, another all-optical OFDM demultiplexing using time lens based spectral magnification has been demonstrated [16], which allows direct detection of all subcarriers without using sampling gates, further reduces the complexity of the system.

4. Conversion from DWDM to Nyquist OTDM

Nyquist OTDM signal take advantage of the orthogonality in time domain, also enabling high spectral efficiency [15]. Recently, we proposed conversion from DWDM to spectrally-efficient Nyquist OTDM based on complete OFT and optical Nyquist filtering [10]. The principle is shown in Fig. 3(a). The DWDM transmitter generates an N-

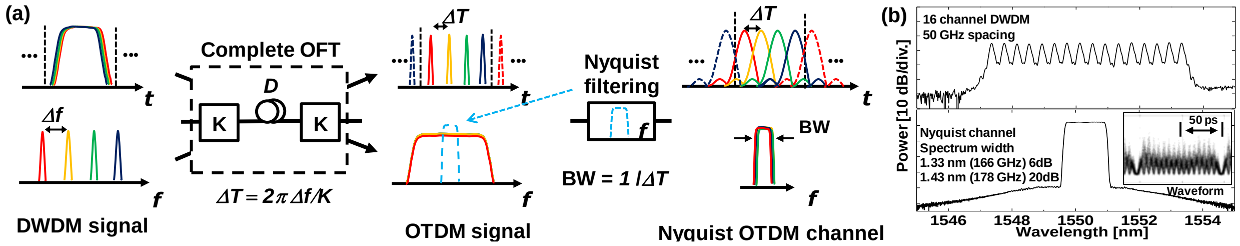


Fig. 3. (a) Principle of DWDM signal to a single Nyquist channel conversion, (b) conversion from a 16x10 Gbit/s DPSK, 50-GHz spacing DWDM signal to a 160 Gbit/s Nyquist channel with 178 GHz total bandwidth, inset is the temporal waveform.

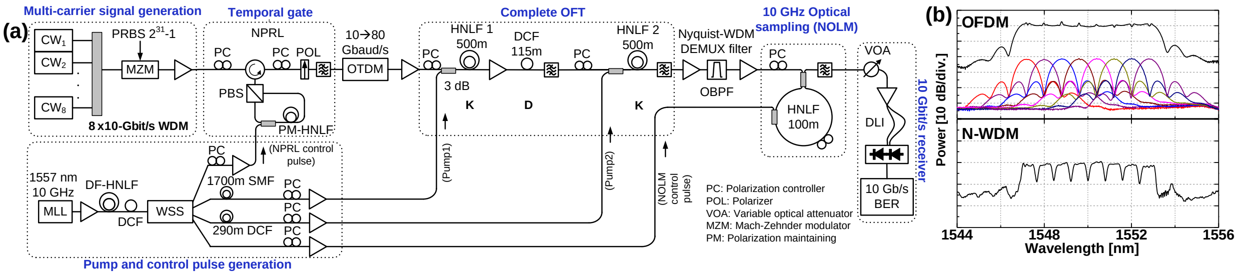


Fig. 4. (a) Experimental setup for conversion of an 8-subcarrier 640 Gbit/s OFDM super-channel to an 8×80-Gbit/s N-WDM super-channel, (b) optical spectra of the original OFDM signal and individual subcarriers (top) and of the output N-WDM signal (bottom).

channel DWDM signal with frequency spacing of Δf, where all DWDM channels are temporally synchronized. A complete OFT with a *K-D-K* configuration is then applied to convert the DWDM signal to an OTDM signal with tributary spacing of $\Delta T=2\pi\Delta f/K$. A rectangular optical bandpass filter (Nyquist filtering) with bandwidth of BW=1/ΔT is then used to filter the center of the overlapping spectra, resulting in a Nyquist OTDM signal with sinc-shaped tributaries. The half zero-crossing width is set equal to ΔT, achieving orthogonality in the time-domain. In the experimental demonstration, a 16x10 Gbit/s DPSK, 50-GHz spacing DWDM signal was successfully converted to a 160 Gbit/s Nyquist OTDM signal with 178 GHz total bandwidth as shown in Fig. 3 (b), thus increasing the spectral efficiency from 0.2 to 0.9 symbol/s/Hz. The Nyquist-OTDM signal is subsequently received by optical sampling using a narrow time-gate. The average power penalty was only 1.4 dB for the full system. This technique may provide a simple and economical solution to upgrade commercial DWDM systems.

5. Conversion from OFDM to N-WDM

Presently, both the OFDM and N-WDM multiplexing technologies are being investigated for commercial communication systems. If employed side by side, it may be very important to have an efficient tool for converting signals between these two types of systems. However, such functionality is currently not possible unless complex optical/electrical/optical conversion and DSP are used. To cope with this challenge, we have proposed a novel all-optical ultra-high-speed OFDM to N-WDM conversion scheme based on complete OFT [17]. The complete OFT can realize such conversion by exchanging the temporal and spectral profiles of the input OFDM signal. The experimental setup is shown in Fig. 4 (a). An 8-subcarrier 640 Gbit/s differential phase-shift keying (DPSK) OFDM super-channel is generated based on rectangular temporal gating and OTDM technique. A complete OFT is used for the OFDM to N-WDM conversion. In the receiver, the converted eight 80-Gbit/s N-WDM channels are received by WDM demultiplexing using a rectangular filter, followed by optical sampling using a narrow time-gate. In this demonstration, a 640 Gbit/s OFDM signal was successfully converted to eight N-WDM channels as shown in Fig.4 (b), achieving BER<10^{-9} performance for all channels. The SE remains unchanged at 0.8 symbol/s/Hz after conversion. To the best of our knowledge, this is the first demonstration of OFDM to N-WDM conversion. In principle, this OFT-based technique can also be employed for N-WDM to OFDM conversion. It could therefore provide a simple and energy-efficient link between spectrally-efficient OFDM and N-WDM systems if synchronization between OFT and input signals can be handled properly.

6. Conclusion

In this paper, a novel time lens based complete OFT technique for advanced optical signal processing of OFDM and N-WDM signals has been introduced, and various demonstrations have been reviewed. Time-lens based OFT has the benefits of allowing for ultra-fast complex OSP, and may become a very important enabling technology for the future energy- and spectrally-efficient optical communication systems.

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