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Conversion of a DWDM Signal to a Single Nyquist Channel based on a Complete Optical Fourier Transformation

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Abstract We propose a DWDM-to-Nyquist channel conversion scheme based on complete Optical Fourier Transformation and optical Nyquist filtering. We demonstrate conversion from 50-GHz-grid 16x10 Gbit/s DPSK DWDM to a 160-Gbit/s Nyquist channel (0.9 symbol/s/Hz spectral efficiency) with 1.4 dB power penalty.

Introduction

In the past decades, dense wavelength division multiplexing (DWDM) has enabled significant increases in capacity, but this is no longer sufficient. Due to the rapid increase in Internet traffic, it is soon expected to reach the capacity of the currently installed communication systems¹. Recently, a Nyquist pulse technique has been proposed, which allows the signal bandwidth to be narrowed without intersymbol interference (ISI), enabling terabit/s transmission with high spectral efficiency². Over the last ten years, the time-domain optical Fourier transformation (OFT) or *time lens* principle has been shown to be a very versatile tool for manipulating the shapes of optical signals in both the time- and frequency-domains. This has led to demonstrations of e.g. distortion-less transmission³, OTDM-to-WDM conversion⁴ and all-optical OFDM transmission systems⁵.

In this paper, we propose a DWDM to Nyquist channel conversion scheme based on complete OFT and narrow optical Nyquist filtering. Using this scheme, we convert 16 10-Gbit/s differential phase-shift keying (DPSK) channels placed on a 50-GHz DWDM grid to a 160-Gbit/s Nyquist channel with a total bandwidth of 178 GHz, thus greatly improving the spectral efficiency from 0.2 to 0.9 symbol/s/Hz. A full bit error rate (BER) characterization is performed, revealing a converted Nyquist channel with $BER < 10^{-9}$ and only 1.4 dB average power penalty compared to the DWDM system. This technique could provide a simple approach to enhance the spectral efficiency of existing commercial DWDM-based systems without large system upgrades, yielding larger total system capacity.

Principle

The complete OFT is based on two quadratic phase-modulation stages (*time lenses*) with chirp rate K , separated by a dispersion medium of $D = \beta_2 L$ (where β_2 is 2nd order dispersion and L is length), that satisfies $K = 1/D$ (a K - D - K

configuration). Unlike other partial OFT schemes^{3,4}, this configuration enables both time-to-frequency and frequency-to-time conversion at the same time, thus performing an exchange between the temporal and spectral envelopes of the input signal. The chirp rate K determines the scaling factor between the time and frequency domains according to $\Delta t = \Delta \omega K$.

The principle of the DWDM to Nyquist channel conversion scheme is shown in Fig. 1. The DWDM transmitter generates an N -channel DWDM signal with frequency spacing $\Delta \omega$ at symbol rate f_s (A). The DWDM channels with flat-top temporal waveforms are bit-wise synchronized. A complete OFT using a K - D - K configuration is then applied to exchange the temporal and spectral envelopes of the input DWDM signal. After the OFT, the N -channel DWDM signal (A) is thus converted to an OTDM signal with channel spacing $\Delta T = \Delta \omega K$ and overlapping flat-top channel spectra. (B). A rectangular optical bandpass filter with bandwidth $BW = 2\pi/\Delta T$ is then used to Nyquist filter the center of the overlapping spectra, resulting in sinc-shaped Nyquist pulses with a half zero-crossing pulse duration given by $2\pi/BW$, set equal to ΔT to achieve orthogonality in the time-domain (C). To achieve maximum spectral efficiency, the OTDM channel spacing ΔT is set equal to $1/(Nf_s)$. The Nyquist OTDM channel can be received in the time-domain

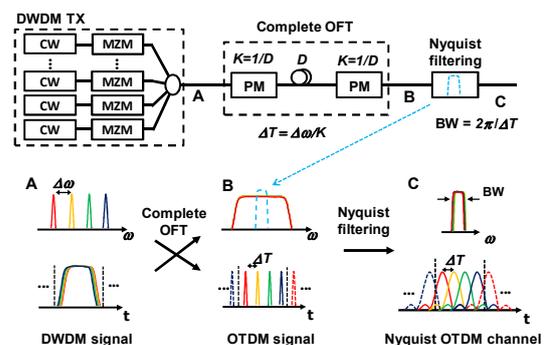


Fig. 1: Principle of DWDM signal to a single Nyquist channel conversion.

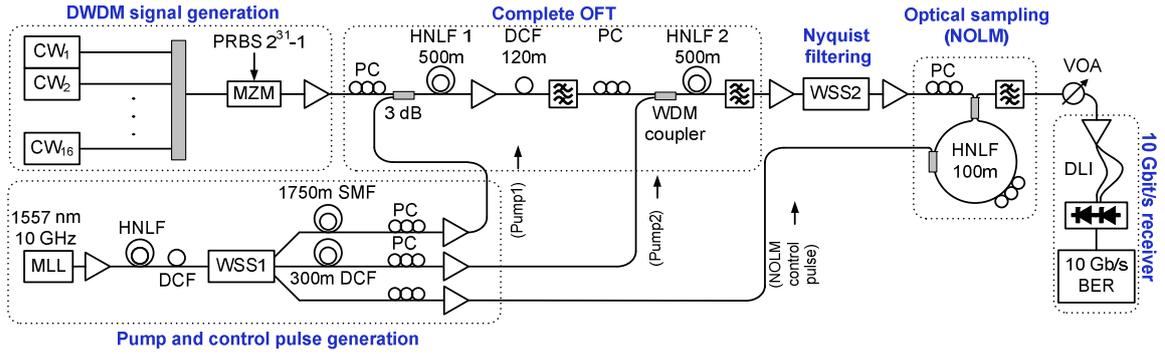


Fig. 2: Experimental setup of 16 x 10 Gbit/s DPSK DWDM to a single Nyquist channel conversion

using optical sampling² or in the frequency-domain using OFT-based time-to-frequency conversion⁶.

Experimental setup and results

The experimental setup is shown in Fig. 1. The DWDM signal source consists of 16 distributed feedback laser diodes (DFB-LDs), centered from 1547.40 to 1553.32 nm with a 50 GHz (0.4 nm) spacing. The outputs of the CW lasers are then DPSK modulated with a 10 Gbit/s $2^{31}-1$ PRBS in a Mach-Zehnder modulator, resulting in a 16x10 Gbit/s DPSK DWDM signal placed on a 50 GHz grid as shown in Fig.3 (a). Then, a complete OFT is used for the DWDM to Nyquist channel conversion. The quadratic phase modulation is implemented based on a four wave mixing (FWM) process in a highly nonlinear fiber (HNLF) using linearly chirped rectangular pump pulses. As a FWM pump pulse source, we use a mode-locked laser at 1557 nm, and its spectrum is broadened via self-phase modulation in a 400-m dispersion-flattened HNLF (DF-HNLF) with normal dispersion. To obtain linearly chirped pumps, the output spectrum of the DF-HNLF is filtered using a wavelength selective switch (WSS₁), and each pump is subsequently propagated through an appropriate length of dispersion medium. The first pump is dispersed in a 1750 m SMF in order to convert a 50 GHz frequency grid to 6 ps temporal spacing (scaling factor $\Delta t/\Delta\omega=19.1 \text{ ps}^2$), resulting in a 55 ps chirped rectangular pump pulse. As the data signal is phase-conjugated after the first FWM process, the second pump is dispersed in a 300 m dispersion compensating fiber (DCF) having the opposite dispersion value of the 1750 m SMF, in order to achieve the same chirp rate K. The central wavelengths of the pumps are set at 1563 nm.

The first FWM output is shown in Fig. 3 (a). After extraction, the idler is dispersed in 120 m DCF, then combined with pump₂ and coupled into HNLF₂ for the second FWM process. The resulting spectrum is shown in Fig. 3(b). The generated idler is the 160 Gbit/s OTDM signal

converted from the 16-channel DWDM signal. Note that the 55-ps rectangular RZ waveform obtained after the first OFT is converted to a 3.7 nm rectangular spectrum according to the scaling factor of the complete OFT. Fig. 3(c) shows the resulting OTDM waveform with 6 ps spacing, and a short guard interval between every 16 tributaries. A 166 GHz rectangular Nyquist filter implemented by WSS₂ is then used to filter the central part of the OTDM spectrum into a Nyquist OTDM channel as shown in Fig. 3(b). The resulting Nyquist OTDM spectrum is shown in Fig. 4(a). A 167 GHz rectangular spectrum is achieved (measured at the 6 dB level). However, due to the limited frequency resolution of the WSS, the width measured at

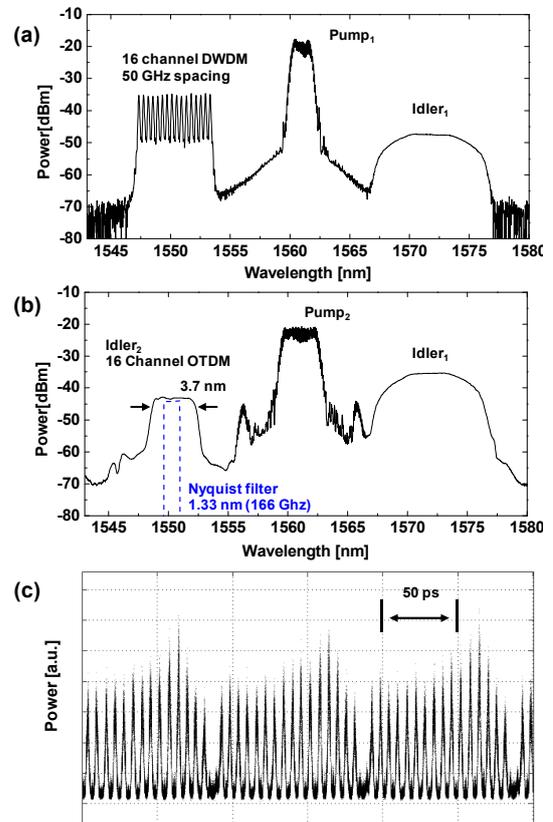


Fig. 3: Optical spectra after the first (a), second (b) FWM process in the HNLF and (c) waveform of the second idler

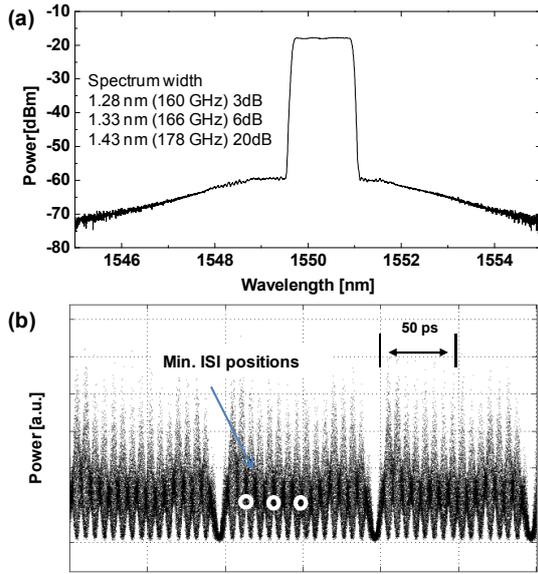


Fig. 4: Obtained Nyquist channel (a) optical spectrum, (b) temporal waveform

lower levels increases slightly (e.g. 178 GHz at the 20 dB level). Fig. 4(b) shows the Nyquist OTDM waveform, where the minimum-ISI positions are clearly observed with 6 ps spacing. These minimum-ISI positions correspond to the nulls of the sinc-shaped waveforms. The minimum-ISI position obtained in each tributary time-slot is then sampled in the NOLM, using a 1.1 ps wide control pulse for gating. Finally, the BER of each tributary is measured in a 10-Gbit/s pre-amplified DPSK receiver including a delay line interferometer (DLI) and balanced photo-detection.

Fig. 5 shows the BER measurements for all 16 demultiplexed Nyquist OTDM tributaries, where error-free operation ($BER < 10^{-9}$) is achieved for all tributaries with an average receiver sensitivity

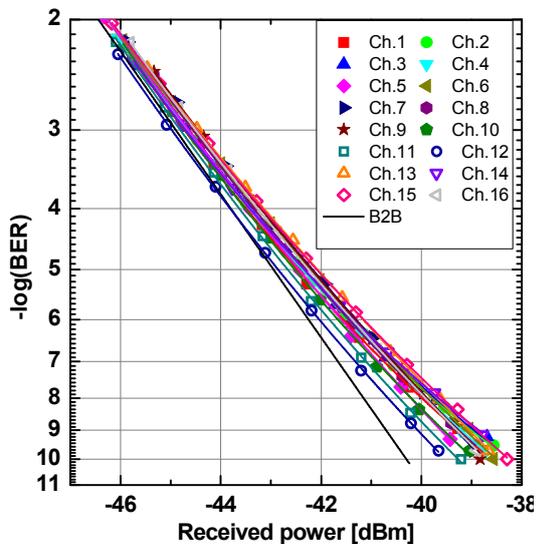


Fig. 5: BER performance of the 16 converted 10 Gbit/s DPSK Nyquist OTDM tributaries

of -39.3 dBm at $BER = 10^{-9}$. For reference, the BER performance of the original DWDM channels demultiplexed with an optical tunable filter (B2B) is also plotted in Fig. 5 (only a single channel is plotted since all DWDM channels have nearly identical BER performance). The average power penalty for all 16 tributaries at 10^{-9} is only 1.4 dB for the full system. Compared to the original signal, the converted signal bandwidth is compressed from 800 GHz to 178 GHz (20 dB level), resulting in a large spectral efficiency improvement from 0.2 to 0.9 symbol/s/Hz. Note that the optical sampling in the receiver could be replaced with a time-to-frequency converter (based on time-domain OFT) followed by optical bandpass filtering as in a standard DWDM receiver. Hence, our technique can potentially be made fully compatible with existing DWDM systems⁶.

Conclusions

We have proposed a DWDM to Nyquist channel conversion scheme based on complete OFT and optical Nyquist filtering. A 16x10 Gbit/s DPSK, 50-GHz spacing DWDM signal was successfully converted to a 160 Gbit/s Nyquist channel with 178 GHz total bandwidth, thus increasing the spectral efficiency from 0.2 to 0.9 symbol/s/Hz (theoretical limit 1 symbol/s/Hz). 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.

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