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16 Channel WDM Regeneration in a Single Phase-Sensitive Amplifier through Optical Fourier Transformation

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Abstract We demonstrate simultaneous phase regeneration of 16-WDM DPSK channels using optical Fourier transformation and a single phase-sensitive amplifier. The BERs of 16-WDM×10-Gbit/s phase noise degraded DPSK signals are improved by 0.4-1.3 orders of magnitude.

Introduction

Optical signal processing (OSP) based on nonlinear optical phenomena may enable energy and cost reductions compared to electronic processing when many wavelength channels are processed simultaneously in a single device¹. All-optical regeneration is a key nonlinear OSP functionality, which reduces signal impairments without optical-electrical-optical conversion. Regeneration of coherent data formats using e.g. phase-sensitive amplifiers (PSAs) has been experimentally demonstrated for differential phase-shift keying (DPSK)², and even 8 QAM signals³. Most optical regeneration techniques only operate on a single or few channels level, but to offer energy-efficiency, they must be WDM compatible. Recent reports have shown optical amplitude regeneration of up to 12-channel WDM signals using a group-delay-managed nonlinear medium⁴, and up to 6-channel WDM phase regeneration was successfully demonstrated using multiple PSAs¹. However, both these WDM-regeneration proposals are challenging to scale to higher WDM channel counts.

In this paper, we demonstrate the highest reported number of regenerated WDM channels in a single regenerator. We employ a single phase-regenerator in a scheme, which is truly scalable in WDM channel numbers. We demonstrate for the first time regeneration of 16 WDM-channels 50-GHz spaced carrying 10 Gbit/s DPSK each. We extend our previous proposal⁵ relying on a single PSA in between a parallel-to-serial conversion of WDM channels and a serial-to-parallel conversion to WDM channels by using time lens based optical Fourier transformation (OFT)⁶. This approach enables scaling from 4x WDM⁵ to now 8x and 16x WDM regeneration. The BER performance is improved by 0.4-1.3 orders of magnitude for all regenerated WDM channels. To the best of our knowledge, we have simultaneously achieved records for the highest number and the narrowest spacing of the regenerated WDM channels.

Principle and Experimental Setup

The principle of WDM phase regeneration of DPSK signals is shown in Fig. 1. The main idea is to convert the WDM signals to a high-speed serial single wavelength channel, which is then straightforward to regenerate without mixing between many pumps and wavelength channels. After regeneration, the serial signal is simply converted back again to a WDM signal. The conversion between parallel and serial formats is based on OFT units composed of quadratic phase modulation with chirp rate K and a dispersive medium with dispersion D . In the current implementation, the phase information is first transferred to amplitude modulation through a delay-interferometer (DI). The regenerator then converts the serial signal to a phase coherent serial signal by cross-phase modulation (XPM), and then phase regenerates this signal in a single PSA. Finally, the regenerated serial signal is converted back to WDM in a second OFT stage.

The experimental setup is shown in Fig. 2. 16 continuous wave (CW) carriers centred from 1551.30 to 1557.34 nm with 50 GHz spacing are generated by a WDM signal source, where carriers 1-8 are directly generated from 8 CW lasers, and carriers 9-16 are generated from a CW laser and a Mach-Zehnder modulator (MZM) based comb generator. The obtained 16 CW carriers are DPSK modulated with a 10 Gbit/s $2^{31}-1$ PRBS in another MZM. The modulated 16-channel WDM signal is split into 4 paths with different path lengths connected to the four input ports of the wavelength selective switch (WSS1) for data decorrelation. Within the

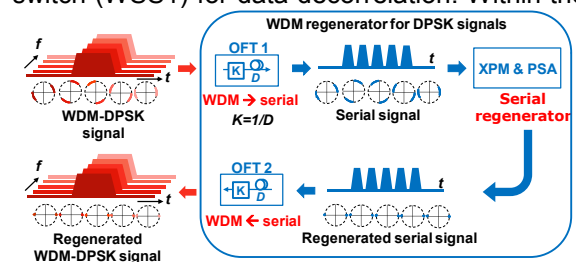


Fig. 1: Principle of WDM phase regeneration of DPSK signals.

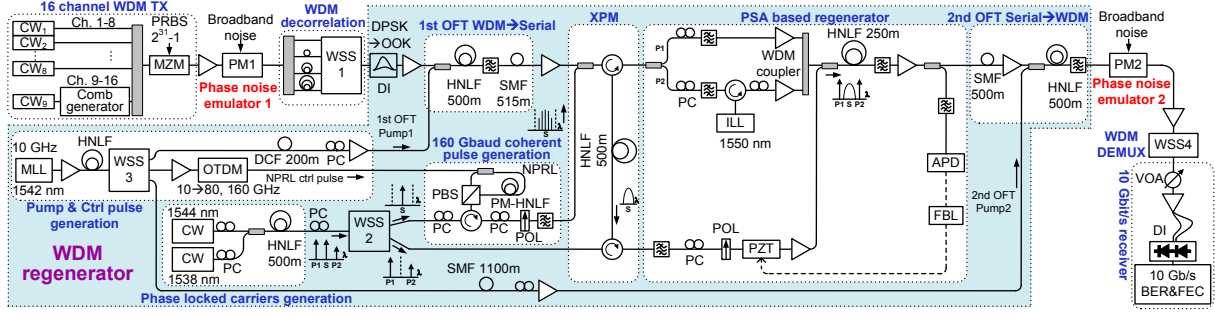


Fig. 2: Experimental setup of 16 x 10 Gbit/s DPSK WDM regeneration

regenerator, a 1-bit (100 ps) DI is used to simultaneously convert all DPSK WDM channels to OOK signals. The obtained OOK WDM signal is converted to a 160 Gbaud serial signal by the first OFT. Note that the WDM channels are aligned in time at the first OFT, which may be assured using time lens synchronisation⁷. The quadratic phase modulation is implemented by a four-wave mixing (FWM) process in a highly nonlinear fibre (HNLf) using linearly chirped rectangular pump pulses. The pump pulse source consists of a mode-locked laser (MLL) at 1542 nm spectrally broadened in a 400 m HNLf. Pump1 is obtained by filtering in WSS3 and propagation in 200 m dispersion compensating fibre (DCF). The chirp rate $K = 0.078 \text{ ps}^{-2}$ is set for conversion of 50 GHz frequency grid to 4 ps temporal spacing. Pump2 is dispersed in 1100 m SMF for serial to WDM conversion at the inverse second OFT.

For the PSA stage, three CW phase-locked carriers are generated by single-pump FWM in a 500 m HNLf; P1 (1538 nm), S (1544 nm) and

P2 (1550 nm). The signal carrier S is then separated from the pump (P1) and idler (P2) by WSS2, and optically carved into a 1.2 ps 160 Gbaud coherent pulse train in a fibre-based nonlinear polarization-rotating loop (NPRL)⁸. The pulse train S and the PSA pumps are sent into a 500-m HNLf in counter-propagating directions using optical circulators. The obtained 160 Gbaud OOK signal is coupled into the HNLf to act as an XPM pump co-propagating with the coherent pulse train. By carefully adjusting the pump power and time delay, the 160 Gbaud pulse train S is DPSK modulated optically, generating a phase-coherent DPSK signal. Before the PSA, the pumps P1 and P2 are further split for independent amplification and an injection locked laser (ILL) is used to increase the power, and thus the OSNR of carrier P2. The signal and pumps are then launched into the PSA consisting of a 250 m HNLf with stable phase-matching for improved nonlinear efficiency (HNLf-SPINE). The input power for S is 3.5 dBm and 22 dBm for P1 and P2. For active phase locking, 10% of the signal power is detected by a slow speed avalanche photodiode (APD) after a narrow optical filter for a feedback loop (FBL) based on a piezoelectric actuator (PZT)². After the PSA, the regenerated 80- or 160-Gbaud serial signals are converted back to WDM signals by the second OFT. Finally, after WDM demultiplexing, the BER of each channel is measured in a 10-Gbit/s DPSK receiver including a DI and balanced photo-detection. The same scheme is used for 8-channels regeneration with $K=0.039 \text{ ps}^{-2}$.

To emulate the positioning of the regenerator within a transmission link, two broadband phase noise emulators, consisting of a phase modulator (PM) driven by broadband phase noise with approximately Gaussian distribution obtained by detecting the amplified spontaneous emission noise of an EDFA, are inserted before and after the regenerator. The phase noise is quantified by the variance of optical phase, estimated by $D_i = (\pi \cdot \sigma_e^i \cdot N_\pi^i)^2$, with σ_e^i being the standard deviation of the electrical driving voltage for PM_i and N_π^i being the half-wave

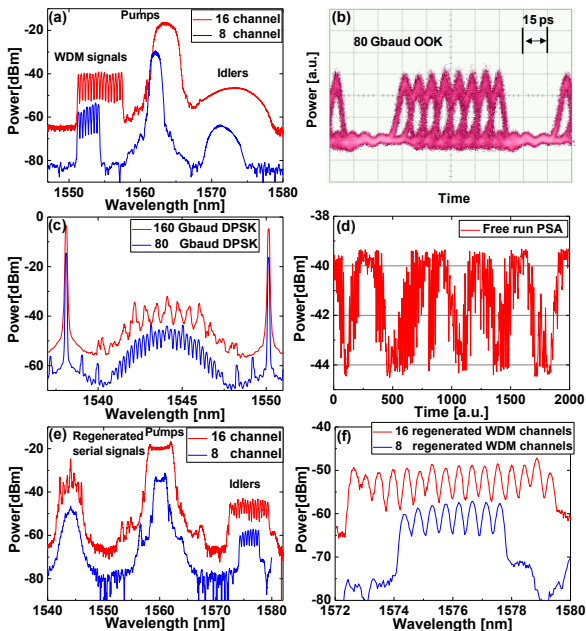


Fig. 3: (a) spectra of first OFT output, (b) waveform of the converted 80 Gbaud OOK signal, (c) spectra at the PSA output, (d) output power variation at 1544.75 nm for PSA with 160 Gbaud signal, (e) second OFT output, (f) a zoom-in on the idler.

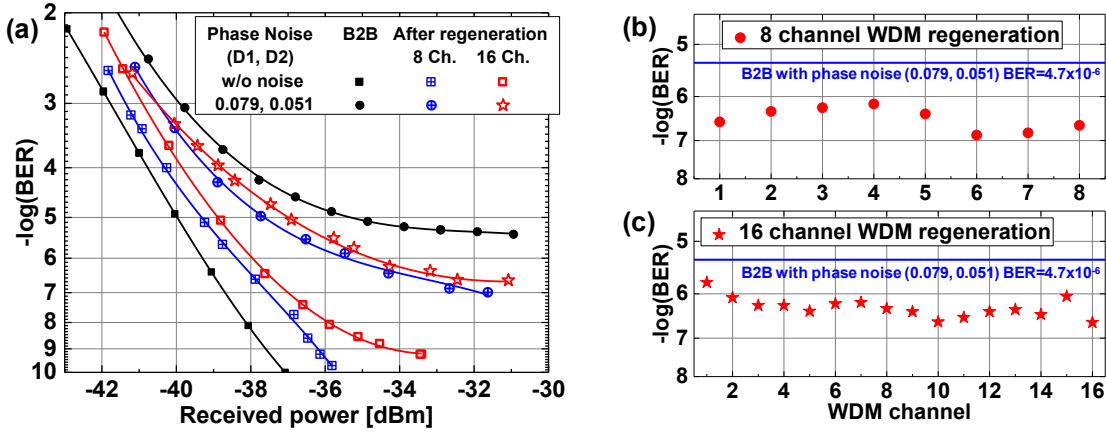


Fig. 4: Experimental results, (a) BER performance of 8- and 16-channel regeneration with dual noise emulators (D_1 , D_2), all channel regeneration performance at a received power of -32 dBm with noise (0.079, 0.051) for (b) 8-channel and (c) 16-channel WDM regeneration.

voltage of PM_i .

Experimental Results

The output spectra of the first OFT for both 8- and 16-channel regeneration are shown in Fig. 3(a). The generated idlers are obtained for 80- and 160-Gbaud OOK signals, and the waveform of the 80 Gbaud OOK signal is shown in Fig. 3b (160 Gbaud waveform is not available due to the resolution limitations). A 36 ps guard interval is inserted in every 100 ps time slot to allow for the second OFT to process all channels without overlap. The PSA output spectra for 80 and 160 Gbaud DPSK regeneration are reported in Fig. 3(c). The PSA output power variation at 1544.75 nm without active phase locking is shown in Fig. 3(d), showing a dynamic phase sensitive extinction ratio of 5 dB. The output spectra of the second OFT are shown in Fig. 3(e) with a zoom-in on the idlers in Fig. 3(f), where the obtained 8- or 16-channel WDM signals are observed with ~ 50 GHz spacing.

Experimental Data Results

The WDM regeneration is successfully achieved for both the 8- and the 16-channels cases, as confirmed by BER measurements (Fig. 4(a)). Starting from 8-channel WDM regeneration, the BER vs. received power of one regenerated 10-Gbit/s channel (Ch. 6) is measured. The regenerator is benchmarked against the back-to-back (B2B) BER curves with and without phase noise. The regenerator power penalty without noise is 1.2 dB at $\text{BER} = 10^{-7}$. For the B2B signal, when the phase noise is added by the two emulators with combination (D_1 , D_2) = (0.079, 0.051), it not only increases the power penalty, but also introduces error floors due to the statistical properties of the Gaussian noise. With regeneration in between the two noise emulators, significant BER improvement is achieved. In particular, without regeneration there is an error floor at $\text{BER} = 10^{-6}$. With

regeneration, the BER curve is improved by 1.5 orders of magnitude. The 16-channel WDM regeneration performance (Ch. 10) is also measured with the same phase noise combination. All WDM channels have nearly identical B2B performance regardless of the number of channels. Almost the same BER improvement is achieved for the 16-channel regeneration. The regenerator power penalty without noise is 0.5 dB worse than the 8-channel case at $\text{BER} = 10^{-7}$. We measured the regenerated channel performance of all channels for both 8-channel (Fig. 4(b)) and 16-channel WDM regeneration (Fig. 4(c)) at a fixed received power of -32 dBm. The BER is improved by 0.8-1.5 orders of magnitude for 8-channel WDM regeneration, and 0.4-1.3 orders of magnitude for 16-channel WDM regeneration.

Conclusion

We have demonstrated simultaneous WDM phase regeneration of 8- and 16-WDM DPSK channels using optical Fourier transformation and a single phase-sensitive amplifier. We achieved the record for the highest number of regenerated WDM channels with the narrowest spacing, showing a great potential for scalability.

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