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Abstract *We propose a novel all-optical WDM regeneration scheme for DPSK signals based on optical Fourier transformation and phase sensitive amplification. Phase regeneration of a WDM signal consisting of 4x10-Gbit/s phase noise degraded DPSK channels is demonstrated for the first time.*

Introduction

All-optical regeneration of wavelength division multiplexed (WDM) signals could play an important role in future optical communication systems. Although various solutions have been demonstrated using self-phase modulation effects in highly nonlinear fibers, they are limited to amplitude modulated signals[1]. Modern communication systems use both amplitude and phase modulation to achieve higher spectral efficiencies and higher total capacities. Recently, phase sensitive amplifiers (PSAs) have emerged as a promising all-optical way to regenerate phase-encoded signals. However only single channel optical regeneration has been demonstrated for differential phase-shift keying (DPSK) and quadrature phase-shift keying (QPSK)[2]. It is important to extend PSA schemes to WDM regeneration. However, such WDM regeneration has not been demonstrated yet. The main challenge lies in keeping multiple pumps and the data signal carriers in-phase at the PSA input, which is not possible for WDM channels with random phase carriers.

In this paper, we propose a novel all-optical WDM regeneration scheme for DPSK signals based on optical Fourier transformation (OFT) and phase sensitive amplification. OFT, also known as the optical time lens principle has been shown to be a very powerful tool for manipulating the shape of optical signals in and between the time and frequency domains[3]. Here, OFT is used for converting the WDM signal to an optical time division multiplexed (OTDM) signal, where the individual channels are separated in time, not in wavelength, and hence easy to regenerate using a PSA. Using this scheme, we simultaneously regenerate four 10-Gbit/s phase noise degraded incoherent DPSK WDM channels. The power penalty is improved by 1.3 dB at BER=10^{-3}. Forward error correction (FEC) is employed, resulting in error-free performance for all regenerated WDM channels. To the best of our knowledge, this is the first demonstration of all-optical DPSK-WDM phase regeneration.

Principle

The main idea of the proposed scheme is to convert all DPSK WDM channels to a phase coherent OTDM (PC-OTDM)[4] signal intermediately using OFT and cross-phase modulation (XPM), then regenerate the PC-OTDM tributaries simultaneously in a single PSA, and finally convert it back to WDM channels. The principle of all-optical WDM regeneration of DPSK signals is shown in Fig. 1. A number of WDM DPSK channels (**A**) with channel spacing $\Delta\upsilon$ are passed through a 1 bit delay interferometer (DI) and converted to OOK signals (**B**). To achieve multi-channel conversion in the DI, $\Delta\upsilon$ is accurately set to an integer multiple of the symbol rate. An OFT composed of quadratic phase modulation with chirp rate *K* and a dispersion medium with dispersion D, is employed for WDM to OTDM conversion. After the OFT, the WDM signal is thus converted to an incoherent OTDM OOK signal with tributary spacing given by $\Delta t=2\pi\Delta\upsilon/K$ (**C**). XPM in a highly nonlinear fiber (HNLF) is employed to transfer the data modulation from the OOK signal to the phase of a continuous wave (CW) carrier (**D**), resulting in a PC-OTDM DPSK signal (**E**). After combination with two
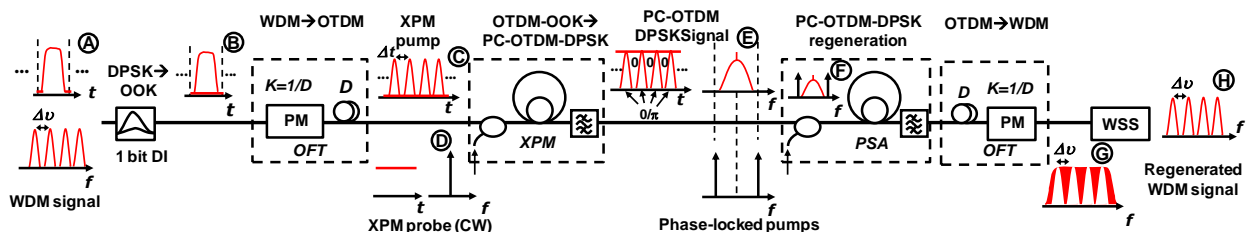

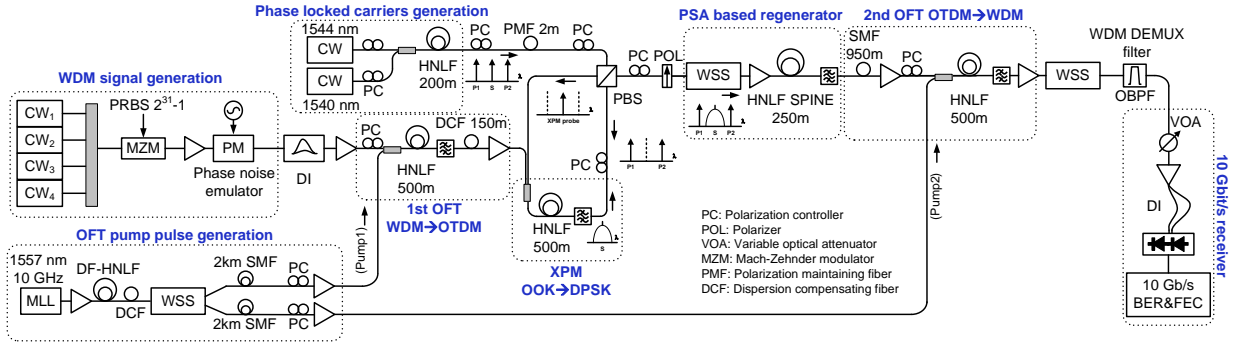**Fig. 1:** Principle of all-optical WDM regeneration of DPSK signals

Fig. 2: Experimental setup of 4 x 10 Gbit/s DPSK WDM regeneration

phase-locked pumps, the obtained PC-OTDM DPSK signal (**F**) is sent to a HNLF to achieve phase sensitive amplification for phase regeneration. The second OFT is then used to convert the regenerated PC-OTDM channel back to WDM channels (**G**). Note that after the OFT, the unmodulated CW parts are finally removed by a wavelength selective switch (WSS) (**H**). This scheme allows numerous WDM channels to be regenerated in a single PSA without detrimental interchannel cross-talk, since there are no channels overlapping in time.

Experimental setup and results

The experimental setup is shown in Fig. 2. The WDM signal source consists of 4 distributed feedback laser diodes (DFB-LDs), centered from 1548.8 to 1551.2 nm with a 100 GHz (0.8 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. Phase noise is emulated on all DPSK WDM channels using a phase modulator driven by a 4.7 GHz unsynchronized sinusoidal RF signal. The modulation index is 0.59. A 1 bit (100 ps) DI is used to simultaneously convert all DPSK WDM channels to OOK channels. The obtained OOK WDM signal is sent to the first OFT for WDM to OTDM conversion. The quadratic phase modulation is implemented based on a four-wave mixing (FWM) process in a HNLF using linearly chirped rectangular pump pulses. As a source for the OFT pump pulses, we use a mode-locked laser at 1557 nm followed by

spectral broadening in DF-HNLF. Both pumps (1st and 2nd OFT) are obtained through filtering in a WSS followed by 2 km SSMF propagation, yielding a chirp rate K = 0.048 ps^{-2} suitable for conversion between a 13 ps temporal spacing and a 100 GHz frequency grid. The output of the first OFT is shown in Fig. 3a. The generated idler is the obtained OTDM-OOK signal.

To achieve a suitable set of phase-locked pumps with the signal carrier for PSA, we use a phase-locking-free scheme based on an XPM loop[5]. Three phase-locked carriers P1 (1540 nm), S (1544 nm) and P2 (1548 nm) are generated based on FWM in a 200 m HNLF. The polarization of carrier S is rotated 90° by aligning the input polarization at 45° with respect to the primary polarization axis of a 2 m polarization maintaining fiber (PMF), where the PMF birefringence was matched to the spacing of the three carriers. After a polarizing beam splitter (PBS), the carrier S and P1, P2 are sent in opposite directions inside an optical loop containing 500 m of HNLF. The obtained OTDM-OOK signal is coupled into the loop as XPM pump in the same direction with S, and by carefully adjusting the pump power, the carrier S is DPSK modulated optically (Fig. 3b). The counter propagating pumps experience only a constant phase offset. After XPM, the two pumps P1, P2 and the DPSK signal S are aligned to exit the loop using a polarization controller (PC). Here, S is still orthogonally polarized to P1 and P2, and a polarizer is used to project them onto the same plane of polarization. A WSS is used to equalize the pumps, remove out of band noise and adjust the power and phase of S relative to the pumps P1 and P2, in order to optimize the PSA performance. The signal S and pumps P1, P2 are amplified to 23.5 dBm, and launched into a 250 m HNLF to achieve phase sensitive amplification with stable phase-matching for improved nonlinear efficiency (HNLF-SPINE)[5].

After the PSA, the regenerated OTDM signal is sent to the second OFT for OTDM to WDM conversion. The output of the second OFT is
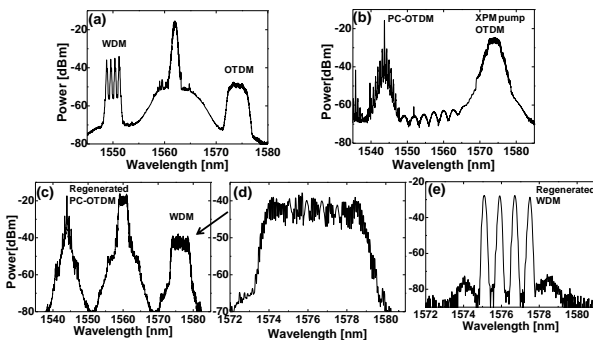

Fig. 3: Optical spectra of first OFT output(a), XPM output(b), second OFT output(c), a zoom-in on the idler(d) and the final regenerated WDM signal after WSS (e).
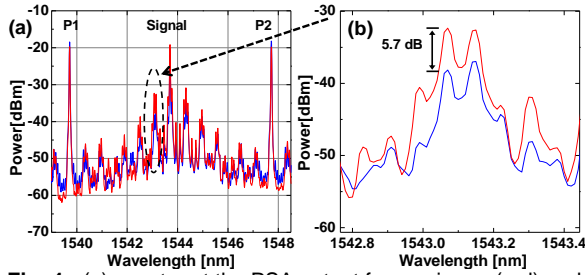
Fig. 4: (a) spectra at the PSA output for maximum (red) and minimum (blue) output signal power, (b) a zoom-in on the signal.

shown in Fig. 3c. A zoom-in on the idler is also shown in Fig.3d, where 4 obtained WDM channels are observed with some unwanted frequency components converted from the unmodulated CW carrier. The unwanted frequency components are removed by a WSS, resulting in 4 regenerated WDM channels (Fig. 3e). Finally, after WDM demultiplexing, the BER of each channel is measured in a 10-Gbit/s pre-amplified DPSK receiver including a DI and balanced photo-detection.

The PSA output spectrum for maximum and minimum output signal power is shown in Fig. 4a, by sweeping the relative phase between the pumps and signal. To avoid the influence from the unmodulated CW component, the phase sensitive extinction ratio 5.7 dB is measured at the side lobe as shown in Fig. 4(b). As all WDM channels are modulated by the same PRBS pattern, strong side lobes can be observed on the signal spectrum. Fig. 5a shows the BER performance of 4 regenerated phase noise degraded DPSK WDM channels. For reference, the back to back BER curves of the WDM
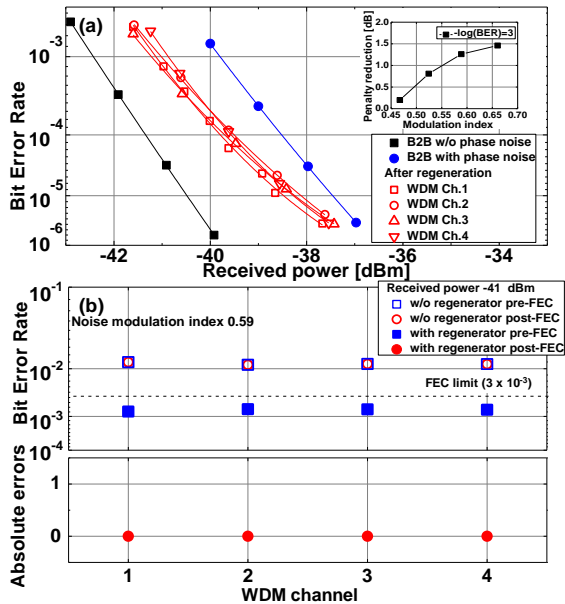
channels with and without phase noise are also plotted in Fig. 5a (only a single channel is plotted for both cases since all WDM channels have nearly identical BER performance). The power penalty is 2.6 dB at BER=10^{-3}, when phase noise is added. After WDM regeneration, the power penalty is reduced by 1.3 dB for all WDM channels. The inset of Fig. 5a shows the power penalty reduction versus different modulation index of the phase noise at BER=10^{-3}, which indicates a better regeneration performance for higher phase noise. We also measured the absolute pre-FEC and post-FEC errors for all WDM channels using a FEC module at a low received power level -41 dBm (Fig. 5b). Without the regenerator, the BERs of all 4 WDM channels were around 10^{-2} due to the added phase noise, making it impossible to recover the data by FEC. With the regenerator, the BER was improved to below the FEC limit 3×10^{-3} for all regenerated channels. The FEC module then properly recovers the data making us unable to measure any errors after FEC for all 4 regenerated WDM channels.

Conclusion

We have proposed a novel all-optical WDM regeneration scheme for DPSK signals based on optical Fourier transformation and phase sensitive amplification. Four 10-Gbit/s phase noise degraded DPSK WDM channels were regenerated simultaneously for the first time, achieving 1.3 dB power penalty improvement and error free performance with FEC for all channels. In principle, the system complexity of the proposed scheme does not scale with the number of WDM channels, making the scheme attractive for scaling to large number of WDM channels.

References

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Fig. 5: Experimental results, (a) BER performance of the regenerated WDM channels, inset: penalty reduction VS. different modulation index of the phase noise. (b) pre-FEC and post-FEC BER performance for all 4 regenerated WDM channels at a received power of −41 dBm.