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Simultaneous Regeneration of Two 160 Gbit/s WDM Channels in a Single Highly Nonlinear Fiber

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Abstract *We experimentally demonstrate simultaneous all-optical regeneration of two 160 Gbit/s WDM channels in a single HNLF using fiber optical parametric amplification. Receiver sensitivities at a BER of 10^{-9} are improved by about 2.1 dB and 4.9 dB for the two channels, respectively. The BER is not degraded by the presence of a second channel.*

Introduction

All-optical regeneration is a highly desirable functionality for high bit rate transmission based on either advanced multilevel modulation formats or high symbol rates, where the OSNR requirements become very strict[1]. As most transmission today is based on WDM systems, it would be highly desirable to be able to regenerate WDM signals, but this has so far proved very difficult. On the other hand, optical regeneration of ultra-high bit rate single channel may be achievable with a low energy consumption. All-optical regeneration of a 640 Gbit/s channel has been demonstrated using a periodically poled lithium niobate (PPLN) device[2]. It would be very beneficial if such a high speed optical regenerator could deal with multichannel signals.

In this paper, we demonstrate simultaneous all-optical regeneration of two 160 Gbit/s WDM signals by fiber optical parametric amplification (FOPA) in a single HNLF. The regeneration performance is confirmed by bit-error rate (BER) test, and the performance is not degraded by the presence of a second channel. The set-up could be scaled to four WDM channels with polarization multiplexing.

Principle

Semiconductor devices[3], nonlinear waveguides[4],

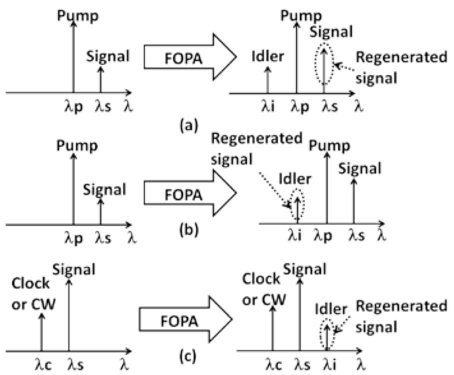

Fig.1: Principles of regeneration using FOPA. The principle used in this paper is (c).

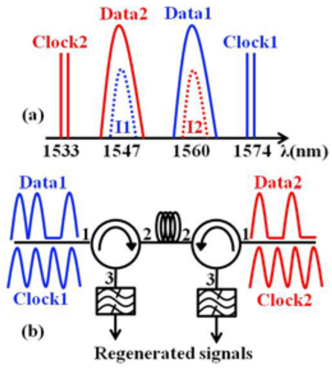

Fig. 2: (a) Wavelength position of the signals and clocks. (b) Scheme of the regenerator.

and highly nonlinear fibers (HNLF)[5] have all been demonstrated for regeneration. Previously, FOPAs were often used for regeneration in the two schemes shown in Fig.1 (a) - (b). In both cases, the amplitude noise on '1' levels can be suppressed due to the gain saturation of the signal or idler. However, the noise on the '0' levels will be amplified. If the degraded data signal is applied as the pump as in Fig.1(c), the obtained mixing product will exhibit significantly enhanced extinction ratio and noise suppression on both '0' and '1' levels[6], due to the quadratic dependence of data power at low power ('0' levels) and the deteriorated phase match caused by a nonlinear phase shift at high power ('1' levels)[7].

Fig.2 (a) shows the wavelength allocation for the regenerator setup. Two counter-propagating data signals act as pumps on two clock signals, thus generating amplitude regenerated and retimed data replicas on the idler wavelengths. The wavelengths of data1 and data2 are 1560 nm and 1547 nm, and that of clock1 and clock2 are 1574 nm and 1533 nm, respectively.

Fig.2 (b) shows a schematic of the regenerator. A bidirectional scheme is adopted. Data1 and clock1 are fed into the HNLF in the forward direction and data2 and clock2 in

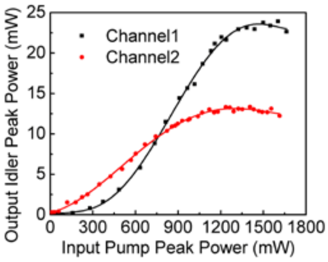

Fig. 3: FOPA transfer curves for the two channels.

reverse direction. Circulators placed on both sides of the 200 m HNLF1 (zero-dispersion wavelength at 1553.3 nm, dispersion slope S=0.017 ps nm^{-2} km^{-1} and non-linear coefficient γ = 10.5 $W^{-1}km^{-1}$) are used to separate the counter-propagating signals in the fiber. It should be noted that data1 exchanges wavelength with data2 in this scheme.

Firstly, we test the power transfer functions of the FOPA. The measurements are done with the peak power of clock1 and clock2 fixed to 17.2 dBm and 21.2 dBm, which are optimized for the saturation of the FOPA with different pump wavelength. As shown in Fig. 3, the quadratic idler response of the FOPA at lower pump level allows for reducing 0- level noise. For higher pump (input data) power, the idler power saturates because of the nonlinear phase mismatch[7]. Thus, the noise on '0' and '1' levels can be suppressed simultaneously as explained above.

Experimental setup and results

The experimental setup for 3R regeneration of the two 160 Gbit/s WDM channels is shown in Fig.4 (a). It includes the generation of the two data channels, two clock signals, a regenerator, a non-linear optical loop mirror (NOLM) OTDM demultiplexer and a BER test.

10 GHz short pulses (pulse width: 1.5 ps) generated from a mode-locked laser (MLL) at λ_c=1542 nm are split into three parts. One part is used as the control pulses for the NOLM. The other two are used to generate the two OTDM data signals and the two clocks. In the two-channel signal generation unit, the 10 GHz pulse train is modulated with a pseudorandom bit sequence (2^{31}-1 of PRBS). A 10-to-160 Gbit/s optical fiber-based multiplexer produces the 160 Gbit/s OTDM signal. The 160 Gbit/s OTDM signal is amplified by an Erbium-doped fiber amplifier (EDFA2), and then injected into a 400 m dispersion-flattened HNLF (DF-HNLF) (dispersion D=-0.45 ps/nm/km and slope S=0.006 ps/nm^2 km at 1550 nm, and γ =10.5$W^{-1}km^{-1}$) to generate a supercontinuum. The supercontinuum is launched into a degradation subunit. Here, the supercontinuum is phase modulated with an asynchronous 2.5 Gbit/s PRBS (2^7-1) signal. A 14 m DCF transforms the asynchronous phase modulation into random timing jitter. Amplitude noise is introduced by adding broadband amplified spontaneous emission (ASE) noise. The bias voltage of the data modulator is also adjusted to degrade the input data. After filtering in a wavelength selective switch (WSS), two degraded OTDM signals at λ_{s1}=1560 nm, λ_{s2}=1547 nm are obtained. Note that only in-band ASE noise is maintained after the WSS.

The two-clock generation is based on cross-

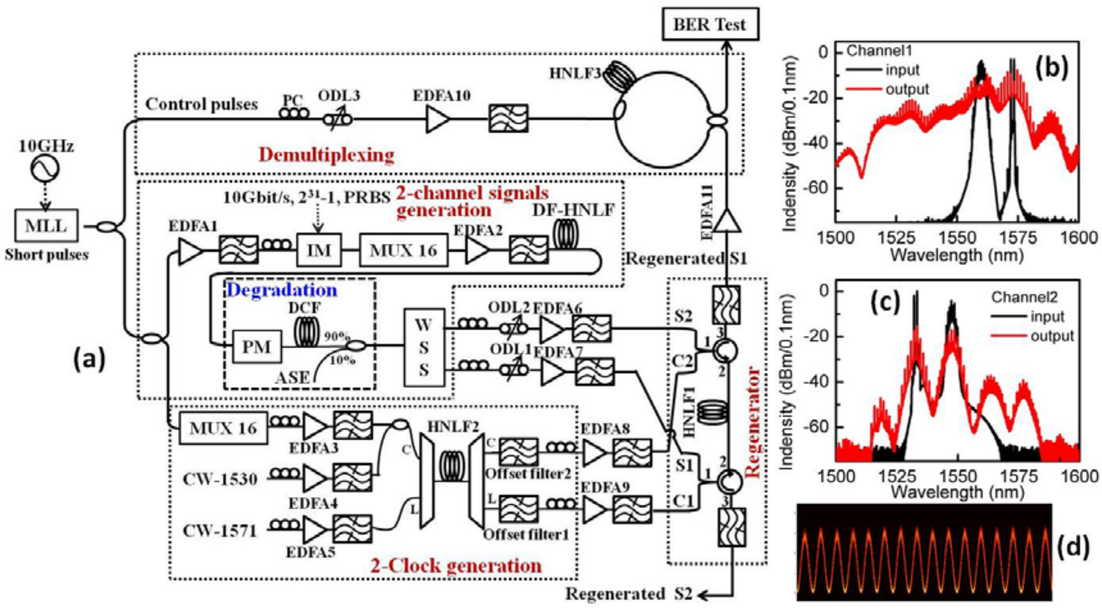

Fig.4: (a) Experiment setup of the regeneration for two 160 Gbit/s OTDM signals. (b) Spectra at input and output of HNLF for Ch1. (c) Spectra at input and output of HNLF for Ch2. (d) Waveform of clock2.

phase modulation (XPM) and two rectangular offset filters. A 10-to-160 GHz optical fiber-based multiplexer is used to produce a 160 GHz pulse train. The 160 GHz short pulses are amplified by EDFA3, and then launched into the HNLF2 (zero-dispersion wavelength at 1551.6 nm and slope S=0.017 ps/nm^2 km at 1550 nm, non-linear coefficient γ =10.5 W^{-1}km^{-1}) together with two continuous wave (CW) laser beams at 1571 nm and 1530 nm, respectively. At the output of HNLF2, two rectangular filters at an offset of ~3 nm are used to select two tones of the spectrum to generate two 160 GHz clocks.

For the regenerator, S1 is amplified by the high-power EDFA7. Optical delay line1 (ODL1) is used to align data1 to clock1 when they are launched into the HNLF1. The same goes for data2 and clock2. Two circulators are used to separate the counter-propagating signals in the fiber. The idlers of the FOPA are filtered and the regenerated signals are obtained.

The following NOLM is used to demultiplex the 160 Gbit/s regenerated signals down to a 10 Gbit/s signal. The NOLM operation is based on XPM in a 15 m HNLF3 (zero-dispersion wavelength at 1545 nm, S=0.015 ps/nm^2 km at 1550 nm, and γ =10.5 W^{-1}km^{-1}). Finally, the demultiplexed 10 Gbit/s regenerated signal is detected by a 10 Gbit/s pre-amplified receiver and tested for BER.

The output power of EDFA7, EDFA9, EDFA6 and EDFA8 are 26.4 dBm, 22.3 dBm, 26.7 dBm and 26.6 dBm, respectively. Spectra at input and output of HNLF1 for Ch1 and Ch2 are shown in Fig.4 (b) and (c) respectively. The conversion efficiency of the FOPA at the two wavelengths is different due to dispersion[7]. Only the waveform of clock2 is shown in Fig.4 (d) due

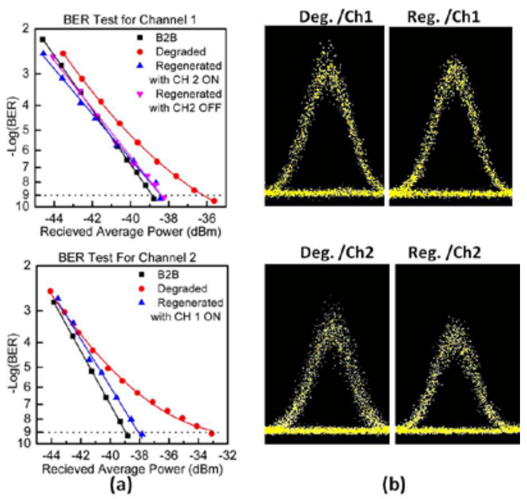

Fig.5: (a) 10 Gbit/s BER performance after demultiplexing 10Gbit/s for Ch1 and Ch2.
(b) 160Gbit/s eye diagrams of degraded and regenerated signal for Ch1 and Ch2.

to the wavelength limitation of the optical sampling oscilloscope (OSO). The use of a sine-waveform clock allows for the re-timing capability of the regenerator [4]. The root-mean-square (RMS) timing jitter is improved from 240 fs to 170 fs (measured by OSO) after regeneration of Ch1. BER measurements on the two channels are finally shown in Fig.5 with the degraded and regenerated eye diagrams. There is a clear reduction of noise due to regeneration for both channels. The BER performance of the regenerated Ch1 with Ch2 ON is quite similar to that with Ch2 OFF, indicating there is almost no cross-talk between the two channels in the HNLF.

The degradation of the signals causes an obvious error floor in the BER performance. Compared with the back-to-back case, the degraded Ch1 and Ch2 have a 2.7 dB and 5.9 dB receiver power penalty at a BER of 10^{-9}, respectively. After regeneration the error floor is notably suppressed and the receiver powers at 10^{-9} BER are improved by 2.1 dB and 4.9 dB (for Ch1 and Ch2) respectively, which are very close to those of the original B2B signals.

Conclusions

We have experimentally demonstrated simultaneous all-optical regeneration of two 160 Gbit/s WDM signals using FOPA in a single HNLF with data signals as pumps enabling simultaneous 0- and 1-level noise suppression. The sensitivities at 10^{-9} are improved by 2.1 dB and 4.9 dB for Ch1 and Ch2. The BER performance shows no degradation of the two channel regeneration case compared to the single channel case.

Acknowledgements

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