Polarization-Insensitive 320-Gb/s In-Line All-Optical Wavelength Conversion in a 320-km Transmission Span

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***Abstract*—Polarization-insensitive in-line all-optical wavelength conversion (AOWC) of a single-channel 320-Gb/s RZ-DQPSK data signal in the middle of a 320-km transmission span is reported. The technique is based on a Ti:PPLN waveguide in a polarization diversity scheme. The conversion efficiency of the signal was −21 dB, which includes 9.2 dB of passive losses in the whole Ti:PPLN subsystem. Error-free performance for the in-line wavelength converted signal after 320-km transmission was successfully achieved.**

***Index Terms*—In-line all optical wavelength conversion, optical time-division multiplexing (OTDM), periodically poled lithium niobate (PPLN), polarization insensitive.**

I. Introduction

ALL optical wavelength conversion (AOWC) will be a key function in future wavelength division multiplexing (WDM) networks, which can effectively resolve packet contention without requiring additional path or packet buffering and can be transparent to data rate and modulation format [1]. Moreover, AOWC can also enable interconnection between independently managed WDM networks by means of optical cross-connect nodes, capable of extraction and reallocation of different wavelength channels [2].

In this context, in-line wavelength conversion is desirable since it enables to receive input signals from one remote node and retransmit the wavelength converted signals to another remote node [3] and [4]. Up to now, a limited number of in-line wavelength converters at high bit rates (160 Gb/s and above) have been demonstrated using either highly nonlinear fiber (HNLF) or semiconductor optical amplifier (SOA) [5] and [6].

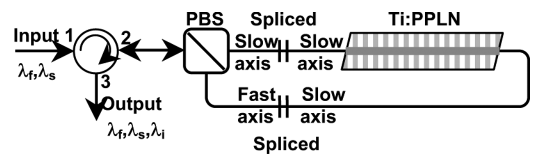

Fig. 1. Polarization-insensitive PPLN subsystem. The slow axis of the PMF is oriented perpendicular to the waveguide surface.

We have recently reported polarization insensitive wavelength conversion of a 320 Gb/s return-to-zero differential-quaternary-phase-shift-keying (RZ-DQPSK) signal using a Ti:PPLN waveguide [7]. The AOWC exploiting cascaded second harmonic and difference frequency generation (cSHG/DFG) in a periodically poled Lithium Niobate (PPLN) waveguide has promising features for fully transparent and cascadable wavelength conversion, such as independence of encoding format, ultrafast response, negligible spontaneous emission noise, wide conversion bandwidth, large dynamic range and the potential of high conversion efficiency [7]–[11]. In this letter, we demonstrate polarization insensitive in-line all-optical wavelength conversion for a 320 Gb/s RZ-DQPSK signal in the middle of a 320-km transmission span. The 320 Gb/s RZ-DQPSK signal is first transmitted over 160-km dispersion managed fiber (DMF), then converted to a new wavelength, and finally transmitted over another 160-km DMF. To the best of our knowledge this is the highest operation speed of an in-line wavelength converter reported to date.

II. Operation Principle

As shown in Fig. 1, the key device of the in-line wavelength converter is the polarization insensitive PPLN subsystem, which is a polarization maintaining loop configuration enabling bidirectional nonlinear wavelength conversion in a low-loss ($\sim$ 0.1 dB/cm) 80 mm long Ti:PPLN-waveguide operated at $\sim 180°$C. This loop represents a polarization diversity scheme with an intrinsic equalization of the differential group delay [4], [7]–[9]. The two polarization components of the signal wave λ_s are routed by the PBS and PM-fibers contra-directionally as TM-modes through the PPLN-waveguide and the corresponding components of the converted signal (idler) wave λ_i are recombined in the PBS and routed to port 3 of the circulator. Polarization insensitive operation is optimized by adjusting the polarization of the fundamental wave λ_f at port 1 to get an equal power splitting at the PBS outputs. The passive loss of the polarization insensitive PPLN subsystem is about 9 dB.

Manuscript received June 23, 2010; revised January 04, 2011; accepted February 19, 2011. Date of publication February 24, 2011; date of current version April 27, 2011.

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Digital Object Identifier 10.1109/LPT.2011.2119473

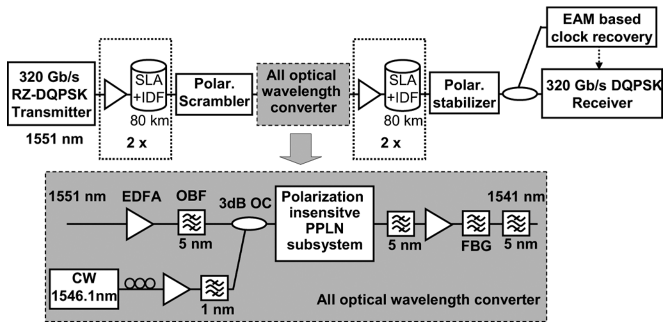

Fig. 2. Experimental setup for the polarization-insensitive in-line AOWC.

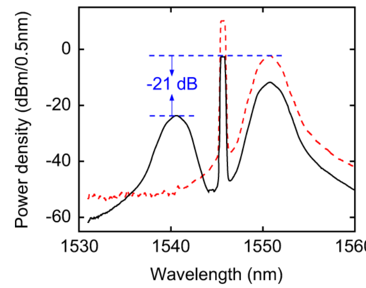

Fig. 3. Spectrum at the input (dashed red line) and the output (black line) of the polarization-insensitive PPLN subsystem.

III. Experimental Setup

The experimental setup for the polarization insensitive in-line all-optical wavelength conversion is shown in Fig. 2. It included a 320 Gb/s RZ-DQPSK transmitter, two 160-km transmission spans, the in-line AOWC and a 320 Gb/s DQPSK receiver. The RZ-DQPSK transmitter consisted of a pulse source, a 10 GHz-to-40 GHz phase stable pulse multiplier, a DQPSK modulator and a 40 Gbaud to 160 Gbaud optical time division multiplexer. The pulse source was a tunable semiconductor mode locked laser (TMLL), which produced a 1.4 ps, 10 GHz (STM-64) optical pulse train at 1551 nm, multiplied to 40 GHz with a passive phase stable multiplexer. A two stage modulator was used to encode the DQPSK signal. The first stage was a Mach–Zehnder $LiNbO_3$ device driven in push-pull mode by a 40 Gb/s PRBS signal $(2^7 - 1)$ from a pattern generator to encode the π phase shift. The second stage was a $LiNbO_3$ phase modulator to encode the additional $\pi/2$ phase shift, driven by the same electrical signal with a sufficient delay for decorrelation. The modulated 40 Gbaud (80 Gb/s) RZ-DQPSK signal was then multiplexed in time by a passive fiber-delay multiplexer (MUX x4) to generate a 160 Gbaud (320 Gb/s) RZ-DQPSK signal.

The 320 Gb/s RZ-DQPSK signal at 1551 nm was first transmitted over a 100% dispersion and dispersion-slope compensated 160-km transmission span, consisting of two 80-km DMF spans (53 km Super Large Area fiber (SLA) with D = 20 ps/nm/km and 27 km Inverse Dispersion Fiber (IDF) with $D = -40$ ps/nm/km, provided by OFS Denmark). Then, the data signal was wavelength converted to 1541 nm and retransmitted over another 100% dispersion and dispersion-slope compensated 160-km transmission span. The launch power into each 80-km span was 10 dBm and the polarization into the transmission span was chosen arbitrarily.

In the in-line AOWC, the signal was amplified by an EDFA, then filtered by a 5 nm optical bandpass filter (OBF) and finally launched into the polarization insensitive PPLN subsystem through a 3 dB coupler (OC). The signal power was 19.5 dBm at the input of the polarization insensitive PPLN subsystem. The CW pump light at 1546.1 nm, acting as a fundamental wave to be frequency doubled in the PPLN waveguide, was amplified by a high-power EDFA, filtered and launched into the polarization insensitive PPLN subsystem through the second input of the 3 dB coupler. The fundamental power was 24.5 dBm at the input of the polarization insensitive PPLN subsystem. The polarization controller for the fundamental wave in front of the EDFA was adjusted for optimum polarization insensitive operation. At the output of the polarization insensitive PPLN subsystem the signal was launched into a filtering subsystem, which consisted of two 5 nm OBFs, an EDFA in between and a tunable fiber Bragg grating (FBG). The FBG was used to block the fundamental wave, and the OBFs separated the wavelength converted signal at 1541 nm from the fundamental and the original signal waves. The polarization state of the data signal could be rapidly changed using a polarization scrambler in front of the AOWC, to test the polarization insensitivity of the in-line AOWC setup. In the DQPSK receiver a polarization stabilizer was used to descramble the converted data signal in order to mitigate the polarization sensitivity of the receiver.

The 320 Gb/s RZ-DQPSK receiver consisted of an electroabsorption modulator (EAM) based clock recovery, an optical preamplification stage, an EAM demultiplexer, a delay line interferometer (DLI), a balanced photo-detector, an electrical 1:4 demultiplexer and an error analyzer. The EAM demultiplexer was synchronized to the recovered clock and used to select individual channels out of the four 80 Gb/s (40 Gbaud) OTDM tributaries for BER measurements. The DLI had a free spectral range of 40 GHz and was used to demodulate the I or Q channel from the demultiplexed 80 Gb/s DQPSK signal. Since no DQPSK precoder was used in the transmitter, the error analyzer (EA) was programmed to the expected bit pattern, which limited the word length in our experiments to $2^7 - 1$. We used a variable optical attenuator (VOA) at the receiver input to vary the received power.

IV. Experimental Results

The spectrum at the input and the output of the polarization insensitive PPLN subsystem is shown in Fig. 3. The conversion efficiency for the 320 Gb/s RZ-DQPSK signal with polarization scrambling is -21 dB (defined as the ratio of the output power of the wavelength converted signal to the input power of the data signal), which includes the 9 dB passive losses of the PPLN subsystem. About 6 dB of the passive losses are due to waveguide coupling ($\sim$ 5 dB) and transmission ($\sim$ 1 dB); the rest is due to the fiber-optic PBS and the circulator. A further improvement of the coupling efficiency seems to be feasible.

We also investigated the pulse broadening after the in-line AOWC. The back-to-back pulsewidth was 1.48 ps measured by autocorrelation, as shown in Fig. 4. The pulsewidth was slightly broadened to 1.65 ps after 320-km transmission without AOWC (Fig. 4) mainly due to the small amount of polarization mode dispersion (PMD) of the fiber. The mean differential group delay (DGD) of the fiber link was 0.7 ps. In this experiment, the AOWC-unit (marked with grey in Fig. 2) was removed from the transmission link. The pulsewidth after 320-km transmission with in-line AOWC was 1.76 ps (Fig. 4). The additional slight pulse broadening caused by the AOWC is mainly

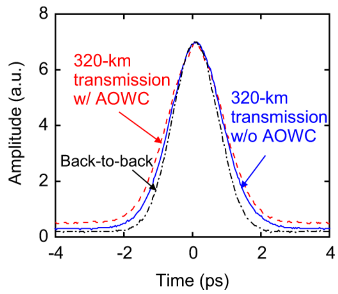

Fig. 4. Autocorrelation trace of the data pulse back-to-back (black dashed–dotted line) and after 320-km transmission without in-line AOWC (blue solid) and with in-line AOWC (red dashed).

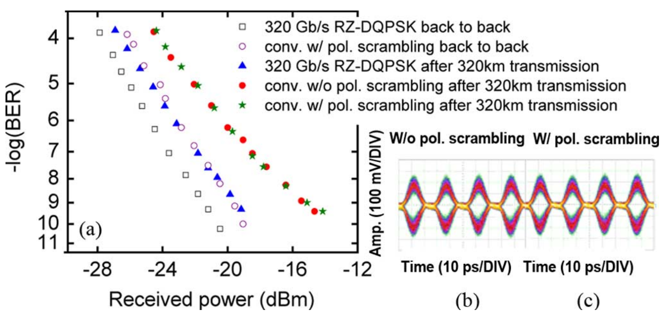

Fig. 5. (a) BER measurements for the unconverted 320-Gb/s RZ-DQPSK signal back-to-back, the converted 320-Gb/s RZ-DQPSK signal back-to-back, the unconverted 320-Gb/s RZ-DQPSK signal after 320-km transmission, and the in-line converted 320-Gb/s RZ-DQPSK signal after 320-km transmission with and without polarization scrambling (b) and (c) 40-Gb/s eye-diagrams of the transmitted, in-line wavelength converted, demultiplexed, and demodulated signal in the DQPSK receiver without and with polarization scrambling.

due to the three filters in the AOWC; our calculations and experiments show that the broadening of the wavelength converted signal pulses in the Ti:PPLN waveguide is negligible [7].

The results of the bit-error ratio (BER) measurements are shown in Fig. 5 as a function of the received power at the 320 Gb/s DQPSK receiver. BER curves are plotted for the unconverted 320 Gb/s RZ-DQPSK signal back-to-back (1551 nm), the converted 320 Gb/s RZ-DQPSK signal back to back with polarization scrambling (1541 nm), the unconverted 320 Gb/s RZ-DQPSK signal after 320-km transmission (1551 nm), and the in-line converted 320 Gb/s RZ-DQPSK signal after 320-km transmission (1541 nm) with and without polarization scrambling. Polarization insensitive in-line AOWC for the 320 Gb/s RZ-DQPSK signal after 320-km transmission span was successfully achieved with an error-free performance ($\mathrm{BER} < 10^{-9}$). Compared to the original signal (1551 nm), the converted signal back to back (1541 nm) causes 2 dB power penalty due to different sensitivities of the receiver at different wavelengths and the residual reflections in the imperfect loop configuration. For the in-line wavelength converted signal the power penalty after transmission is further increased by 4.5 dB, which is due to the transmission losses and the OSNR degradation. The transmission of the unconverted signal (1551 nm) causes 2 dB power penalty. The upcoming error-floor is due to the OSNR limitation by the finite conversion efficiency of the AOWC and the losses in the transmission span.

However, the results indicate that the additional penalty caused by the polarization scrambling is almost negligible, which demonstrate the polarization insensitivity of the in-line AOWC. The measurements shown in Fig. 5 are made for one I/Q component of one TDM tributary. I and Q components for all tributary channels were measured and the variation of the received power at $\mathrm{BER} = 10^{-9}$ was found to be less than 1 dB. The 40 Gb/s eye-diagrams (at $\mathrm{BER} = 10^{-9}$) for one I/Q component of the transmitted, in-line wavelength converted, demultiplexed and demodulated signal without and with polarization scrambling are shown in Figs. 5(b) and 5(c), respectively. The eye-diagrams show identical performance, thus also indicating the polarization insensitivity of the AOWC.

V. Conclusion

We have demonstrated polarization insensitive in-line AOWC for a 320 Gb/s RZ-DQPSK signal in the middle of a 320-km transmission span using a Ti:PPLN waveguide in a polarization diversity scheme. Error-free performance for the in-line converted signal after 320-km transmission was achieved with a polarization scrambler at the input of the AOWC. The BER measurements and eye-diagrams show identical performance with and without polarization scrambling, demonstrating the polarization insensitivity of the in-line AOWC.

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