Simultaneous Polarization-Insensitive Wavelength Conversion of 80-Gb/s RZ-DQPSK Signal and 40-Gb/s RZ-OOK Signal in a Ti:PPLN Waveguide

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***Abstract*—Simultaneous all-optical wavelength conversion of an 80-Gb/s return-to-zero differential quadrature phase shift keying (RZ-DQPSK) data signal and a 40-Gb/s return-to-zero ON--OFF keying (RZ-OOK) data signal using a Ti:PPLN waveguide in a polarization-diversity loop configuration are demonstrated. The wavelength conversion is fully transparent to polarization, data rate, modulation format, and modulation level. The conversion efficiency for the signals was -21 dB, which includes 9.2-dB passive losses in the whole Ti:PPLN subsystem. Error-free performance for both wavelength-converted signals was achieved for polarization-scrambled input data signals without additional penalty caused by the polarization scrambling.**

***Index Terms*—All-optical wavelength conversion (AOWC), periodically poled lithium niobate (PPLN), polarization insensitive, second-harmonic generation (SHG).**

I. Introduction

WAVELENGTH conversion 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 [1]. Moreover, wavelength converters 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] .

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Because of these considerations, it is straightforward that a desirable wavelength converter should be transparent to polarization, data rate, pulsewidth, modulation format, and modulation level. In addition, an ideal wavelength converter should be able to generate a converted signal without optical SNR (OSNR) degradation or other signal distortions. Moreover, to be useful in WDM networks, the wavelength converter should allow for the simultaneous conversion of multiple wavelengths.

In this context, all-optical wavelength conversion (AOWC) offer advantages over optical--electrical--optical (O/E/O) schemes, such as simultaneous conversion of several WDM channels, as well as transparency to data rate and modulation format. Various techniques for AOWC have been proposed using highly nonlinear fibers (HNLFs) [3]–[5], semiconductor optical amplifiers (SOAs) [6]–[8], or periodically poled lithium niobate (PPLN) waveguides [9]–[15]. They were mainly based on third-order nonlinear $(\chi^{(3)})$ effects or cascaded $\chi^{(2)}$ processes, such as XPM, four-wave mixing (FWM), or cascaded second-harmonic and difference-frequency generations (cSHG/DFG). The FWM and cascaded $\chi^{(2)}$ processes have advantages over XPM in terms of transparency to the modulation format.

AOWC based on FWM in a HNLF can offer large conversion bandwidth and high conversion efficiency [3], [17]. However, it suffers from signal distortions due to unwanted $\chi^{(3)}$ effects, such as XPM, self-phase modulation (SPM), and especially stimulated Brillouin scattering (SBS), which are difficult to avoid. AOWC based on FWM in SOAs has a reduced impact from SBS, and the SOA can amplify signals during the conversion process [7] leading to a high overall conversion efficiency. However, the technique suffers from patterning effects, a poor conversion bandwidth, and OSNR degradation due to amplified spontaneous emission (ASE) noise generated by the SOA.

AOWC based on the cascaded $\chi^{(2)}$ processes in PPLN is attractive, since its characteristic is close to an ideal AOWC. Only negligible quantum-limited ASE noise and almost no signal distortions are introduced into the converted signal. The cascaded $\chi^{(2)}$ processes act like a FWM process, but free of other undesired $\chi^{(3)}$ effects. The technique is transparent to pulsewidth and modulation format. The conversion efficiency is in general lower compared to HNLFs, but has the potential to be further increased, as described in [10] and [15]. Moreover, the broad conversion bandwidth allows for simultaneous conversion of several WDM channels without interchannel crosstalk [16]. Despite these advantages, PPLN suffers from the photorefractive

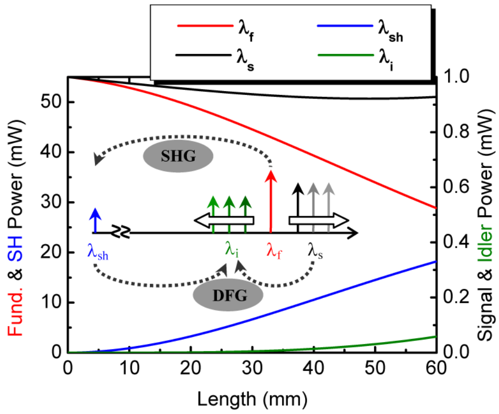


Fig. 1. Calculated evolution of fundamental ($\lambda_f = 1546$ nm), second-harmonic ($\lambda_{\rm sh} = 773$ nm), signal ($\lambda_s = 1551$ nm), and idler ($\lambda_i = 1541$ nm) power levels along the waveguide for 55 mW of coupled fundamental power and 1 mW of coupled signal power. Inset: Schematic diagram of the cSHG-/DFG-based wavelength conversion in a Ti:PPLN waveguide.

effect [18], which limits the applicable pump power, and thus limits the conversion efficiency. One solution to avoid photorefractive damage at high pump powers is to operate the PPLN at a high temperature, where charges are easily removed from trap levels in the LN crystal [9]. Another possibility is doping the LN crystal with Mg or Zn to increase the photoconductivity and to decrease in this way photorefractive effects enabling device operation at room temperature, even with high input power, as recently shown experimentally [14], [15].

In this paper, we report the simultaneous AOWC of an 80-Gb/s return-to-zero differential quadrature phase shift keying (RZ-DQPSK) data signal and a 40-Gb/s return-to-zero ON--OFF keying (RZ-OOK) data signal using a Ti:PPLN waveguide in a polarization-diversity loop configuration. The wavelength conversion is fully transparent to polarization, data rate, modulation format, and modulation level. Polarization-insensitive operation with error-free performance is achieved for both converted data signals.

II. Operation Principle

The wavelength conversion scheme is based on cSHG/DFG in a Ti:PPLN waveguide. In order to obtain a converted signal in the telecommunication C-band by DFG, the pump wavelength has to be $\sim$0.78 μm. By using SHG in the same waveguide, the $\sim$0.78-μm pump can be generated inside the device from a C-band fundamental wave (λ_f). As illustrated in the inset of Fig. 1, the continuous wave (CW) pump $(\lambda_{\rm sh})$ is generated by quasi-phase matched SHG. Simultaneously with this process, a wavelength-shifted idler (λ_i) is generated by quasi-phase-matched DFG of second-harmonic $(\lambda_{\rm sh})$ and signal waves (λ_s).

Moreover, the calculated evolution of fundamental, SH, signal, and idler power levels in a Ti:PPLN waveguide is shown in Fig. 1 for CW operation. To allow a qualitative comparison with the experimental results (see Section IV), an effective interaction length of 60 mm, homogeneous quasi-phase matching, 55 mW of coupled fundamental power, and 1 mW of coupled signal power have been assumed. The fundamental wave is continuously depleted due to SHG. Simultaneously, the growth of the idler wave together with the onset of optical parametric amplification due to DFG can be observed.

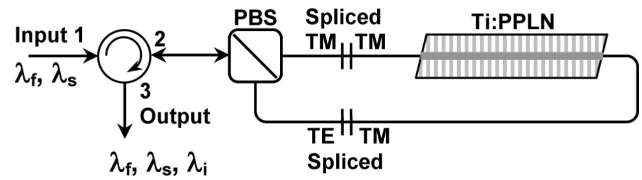


Fig. 2. Polarization-insensitive PPLN subsystem.

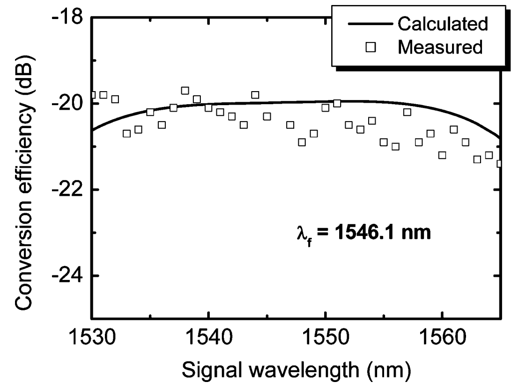


Fig. 3. Calculated and measured conversion efficiency versus signal wavelength for the fundamental wavelength at 1546.1 nm.

Wavelength conversion based on cSHG/DFG can be fully transparent to data rate, modulation format, and modulation level [19]. However, as $\chi^{(2)}$-based nonlinear optical wavelength conversion in PPLN is inherently polarization dependent, a polarization-diversity scheme, processing both polarization components independently, is needed to get polarization-transparent wavelength conversion as well.

As shown in Fig. 2, the key device of the transparent wavelength converter is the polarization-insensitive PPLN subsystem consisting of a Ti:PPLN channel guide operated in a polarization-maintaining fiber loop [20]. In this way, bidirectional nonlinear wavelength conversion of both polarization components of the signal is achieved. Moreover, this polarization-diversity scheme automatically provides an intrinsic equalization of the differential group delay [9], [10]. The two polarization components of the signal wave $\lambda_{\rm sig}$ 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 total loss of the polarization-insensitive PPLN subsystem, including coupling loss, circulator, and PBS, is 9.2 dB.

The heart of the PPLN subsystem is a Ti-diffused (1060 °C, 8.5 h) PPLN waveguide of 7 μm width and 80 mm length. Standard electric field poling with a microdomain periodicity of 16.4 μ m was applied to achieve quasi-phase matching in the C-band at elevated temperatures. High-temperature operation ($\sim$180 °C) was necessary to avoid optically induced changes of

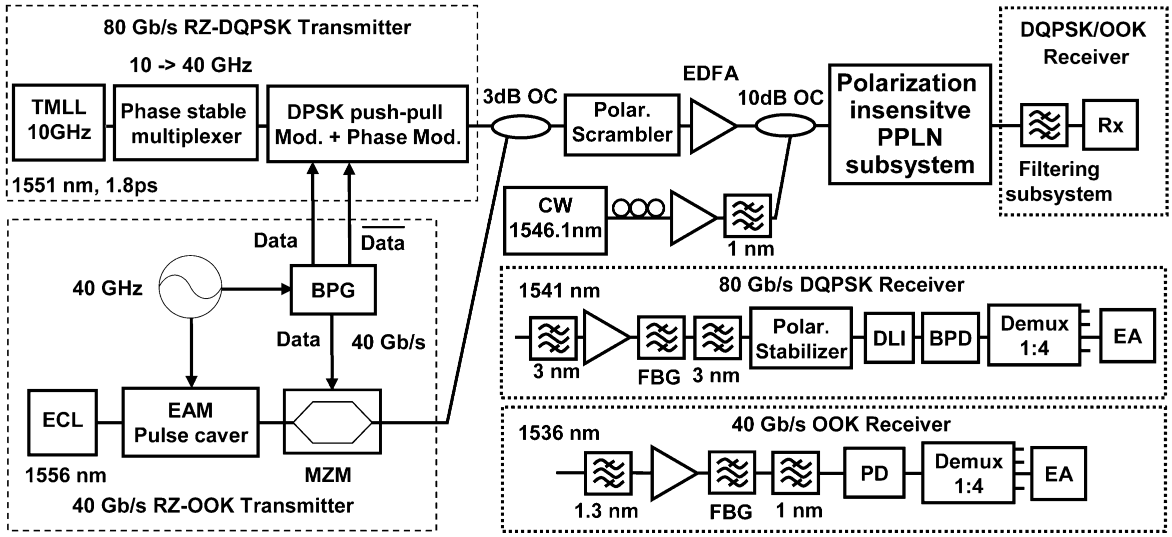


Fig. 4. Experimental setup for the polarization-insensitive simultaneous AOWC of an 80-Gb/s RZ-DQPSK signal and a 40 Gb/s RZ-OOK signal.

the index of refraction ("optical damage"). The waveguide propagation losses at 1550-nm wavelength are ~0.1 dB/cm (for TM polarization). The end facets of the waveguide are angle polished under 5.8° and AR coated to avoid Fabry--Perot effects. The sample is mounted on a copper base plate to enable homogeneous heating and a precise temperature control.

The essential parameter of a wavelength converter is the conversion bandwidth, i.e., conversion efficiency versus signal wavelength. The conversion efficiency, which is defined as the ratio of the output power of the converted signal at port 3 and the input power of the data signal at port 1, is about -21 dB and flat over the complete C-band, as shown in Fig. 3. The conversion efficiency includes the passive loss of the PPLN subsystem. The intrinsic conversion efficiency of the PPLN waveguide can be obtained by subtracting the passive losses of 9.2 dB. The broad conversion bandwidth (>40 nm) allows wavelength conversion of a high-speed (large-bandwidth) signal or of multiple low-speed (small-bandwidth) WDM channels simultaneously.

III. Experimental Setup

The experimental setup for the polarization-insensitive simultaneous AOWC of an 80-Gb/s RZ-DQPSK signal and a 40-Gb/s RZ-OOK signal is shown in Fig. 4. It included an 80-Gb/s RZ-DQPSK transmitter, a 40-Gb/s RZ-OOK transmitter, the transparent all-optical wavelength converter, a 40-Gb/s OOK receiver, and an 80-Gb/s DQPSK receiver. The RZ-DQPSK transmitter consisted of a pulse source, a 10--40-GHz phase-stable pulse multiplier, and a DQPSK modulator. The pulse source was a tunable semiconductor mode-locked laser, which produced a 1.8-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 80-Gb/s DQPSK signal. The first stage was a Mach--Zehnder $LiNbO_3$ device driven in push--pull mode by a 40-Gb/s pseudorandom binary sequence (PRBS) signal (2^7-1) from a bit pattern generator (BPG) 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 de-correlation. The RZ-OOK transmitter consisted of an external cavity laser (ECL), an electroabsorption modulator (EAM) based pulse carver, and a Mach--Zehnder modulator (MZM). The ECL emits CW light at 1556 nm, carved into pulses by the EAM with a repetition rate of 40 GHz. This pulse train is OOK modulated with a Mach--Zehnder modulator driven by a 40-Gb/s PRBS signal (2^7-1) from the same BPG. The generated 40-Gb/s RZ-OOK signal has a duty cycle of 30%.

The generated 80-Gb/s RZ-DQPSK signal and 40-Gb/s RZ-OOK signal were coupled together through a 3-dB optical coupler (OC), then amplified by a high-power erbium-doped fiber amplifier (EDFA) and finally launched into the polarization-insensitive PPLN subsystem through the weak arm of a 10-dB OC. At the output of the 3-dB coupler, the average power of the DQPSK and OOK signal was 5.6 and 1.6 dB·m, respectively. The polarization of both data signals was scrambled in front of the high-power EDFA to test the polarization insensitivity of the AOWC. After amplification in the EDFA, the total signal power was 11.8 dB ·m at the input of the polarization-insensitive PPLN subsystem. The CW pump light at 1546.1 nm acting as fundamental wave was amplified by a second high-power EDFA, filtered and launched into the polarization-insensitive PPLN subsystem through the strong arm of the 10-dB coupler. The fundamental power was 24.8 dB·m at the input of the polarization-insensitive PPLN subsystem. The polarization controller in front of the EDFA was adjusted for polarization-insensitive conversion efficiency. At the output of the polarization-insensitive PPLN subsystem, the signals were launched into the DQPSK/OOK receivers, each comprising a filtering subsystem.

To detect the wavelength-converted DQPSK signal, the signal was launched into the 80-Gb/s DQPSK receiver. The filtering subsystem for this receiver consisted of two 3-nm optical bandpass filters (OBFs) centered at 1541 nm, an EDFA in between, and a fiber Bragg grating (FBG). The FBG notch filter was used to block the fundamental wave, and the OBFs separated the converted 80-Gb/s RZ-DQPSK signal at 1541 nm from the other signal waves. A polarization stabilizer was used to descramble the converted data signal in order to mitigate the polarization sensitivity of the receiver. The 80-Gb/s DQPSK receiver further includes a delay line interferometer (DLI), a balanced photodetector, directly attached to an electrical demultiplexer (1:4), and an error analyzer (EA). The DLI had a free spectral range of 40 GHz and was used to demodulate the I or Q channel from the 80-Gb/s DQPSK signal. Since no DQPSK precoder was used in the transmitter, the EA was programmed to the expected bit pattern, which limited the word length in our experiments to 2^7-1.

To detect the wavelength-converted OOK signal, it was launched into the 40-Gb/s OOK receiver. In this case, the filtering subsystem consisted of a 1.3-nm and a 1-nm OBF centered at 1536 nm, an EDFA in between, and an FBG. The FBG notch filter was also used to block the fundamental wave, and the OBFs separated the converted 40-Gb/s RZ-OOK signal at 1536 nm from the other signal waves. The 40-Gb/s OOK receiver consisted of a PD, an electrical demultiplexer (1:4), and an EA. Due to the low polarization dependence of the OOK receiver, a polarization stabilizer was not required.

IV. Experimental Results

The spectrum at the input and the output of the polarization-insensitive PPLN subsystem is shown in Fig. 5(a). The conversion efficiency for the 80-Gb/s RZ-DQPSK signal and the 40-Gb/s RZ-OOK signal with polarization scrambling (w/) is about -21 dB for both, which includes the 9.2-dB passive loss of the polarization-insensitive PPLN subsystem. The spectrum of the wavelength-converted 80-Gb/s RZ-DQPSK signal at 1541 nm after filtering is shown in Fig. 5(b), which is narrowed by the two 3-nm filters after the AOWC. The AOWC does not affect the spectral width, i.e., it is transparent to pulsewidth [10]. The fundamental light is well suppressed by the FBG notch filter. The power of the residual fundamental and the other signals are 33 dB lower compared to the wavelength-converted 80-Gb/s RZ-DQPSK signal. The spectrum of the wavelength-converted 40-Gb/s RZ-OOK signal at 1536 nm after filtering is shown in Fig. 5(c). The fundamental and the other signals are almost completely suppressed by the filters.

The results of the bit error ratio (BER) measurements for the wavelength-converted 40-Gb/s RZ-OOK signal are shown in Fig. 6(a) as a function of the OSNR at the 40-Gb/s OOK receiver. BER curves are plotted for the 40-Gb/s RZ-OOK signal back-to-back (B2B) before conversion (wavelength 1556 nm), and for the converted 40-Gb/s RZ-OOK signal with (w/) and without (w/o) polarization scrambling (wavelength 1536 nm). Polarization-insensitive operation is successfully achieved with an error-free performance $(\mathrm{BER} = 10^{-9})$. The wavelength conversion causes negligible OSNR penalty (less than 0.5 dB) at the BER of 10^{-9} compared with the B2B case (unconverted signal), independent of the polarization scrambler. The eye diagrams of the wavelength-converted 40-Gb/s RZ-OOK signal at $\mathrm{BER} = 10^{-9}$ without and with polarization scrambling are shown in Fig. 6(b) and (c), respectively. The eye diagrams also indicate that the wavelength-converted signals with and without polarization scrambling have almost identical performance.

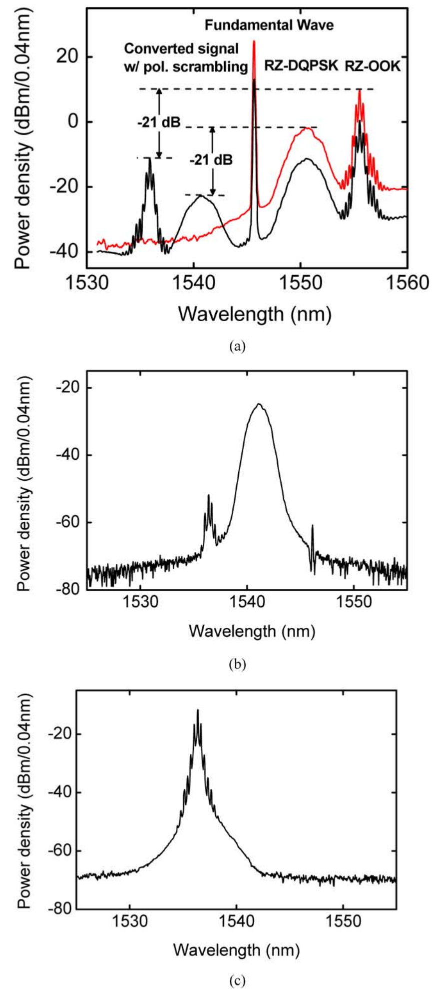
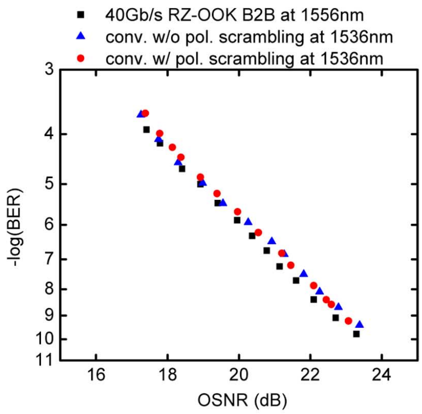
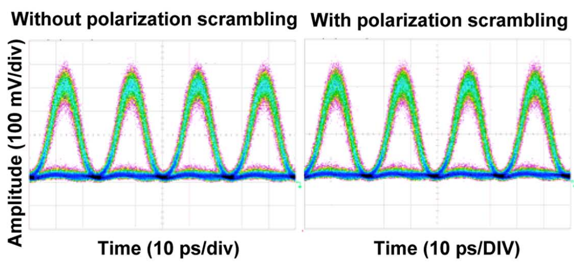


Fig. 5. (a) Spectrum at the input (black) and the output (red) of the polarization-insensitive PPLN subsystem. (b) Output spectrum of the wavelength-converted 80-Gb/s RZ-DQPSK signal after filtering. (c) Output spectrum of the wavelength-converted 40-Gb/s RZ-OOK signal after filtering.

The results of the BER measurements for the wavelength-converted 80-Gb/s RZ-DQPSK signal are shown in Fig. 7(a) as a function of the OSNR at the 80-Gb/s DQPSK receiver. BER curves are plotted for the 80-Gb/s DQPSK signal B2B before conversion (wavelength 1551 nm), and for the converted 80-Gb/s DQPSK signal with and without polarization scrambling (wavelength 1541 nm). Polarization-insensitive 80-Gb/s RZ-DQPSK wavelength conversion is successfully achieved with an error-free performance $(\mathrm{BER} = 10^{-9})$. The wavelength conversion causes 2-dB OSNR penalty at the BER of 10^{-9} compared with the B2B case (unconverted signal) due to residual reflections in the imperfect loop configuration, and the 2-dB OSNR penalty was also observed in the wavelength conversion of a single-channel DQPSK signal [10]. However, the additional penalty caused by the polarization scrambling is negligible. The results shown in Fig. 7(a) are obtained for the I channel. The Q channel was also measured and the variation of the OSNR required for $\mathrm{BER} = 10^{-9}$ was found to be less than 1 dB. The 40-Gb/s eye diagrams of the wavelength-converted and demodulated signal $(\mathrm{BER} = 10^{-9})$ without and with polarization scrambling are shown in Fig. 7(b)

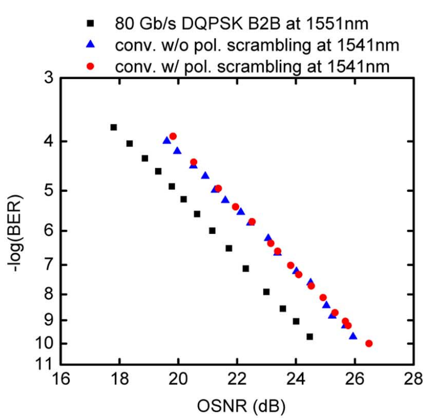


(a)

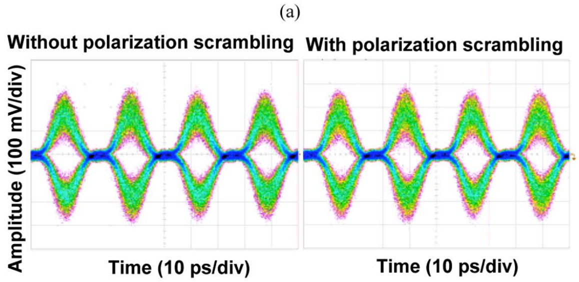


(b) (c)

Fig. 6. (a) Results of BER measurements for the 40-Gb/s RZ-OOK signal B2B, and for the converted 40-Gb/s RZ-OOK signal with and without polarization scrambling. (b) and (c) Eye-diagram of 40 Gb/s of the wavelength-converted signal in the OOK receiver without and with polarization scrambling.



(a)



(b) (c)

Fig. 7. (a) Results of BER measurements for the 80-Gb/s DQPSK signal B2B, and for the converted 80-Gb/s DQPSK signal with and without polarization scrambling. (b) and (c) Eye-diagram of 40 Gb/s of the wavelength-converted and demodulated signal in the DQPSK receiver without and with polarization scrambling for one DQPSK channel.

and (c), respectively. The eye diagrams indicate again that the wavelength-converted signals with and without polarization scrambling have almost identical performance.

V. Conclusion

We have demonstrated wavelength conversion transparent to polarization, data rate, modulation format, and modulation level. A 40-Gb/s binary-amplitude-modulated signal and an 80-Gb/s quaternary-phase-modulated signal were simultaneously converted from the red subband of the C-band to the blue subband using polarization scrambling for both data signals. The wavelength conversion was based on cascaded SHG/DFG in a Ti:PPLN waveguide, incorporated in a polarization-diversity scheme. Error-free performance for both converted signals was achieved with polarization-scrambled input data signals. The conversion efficiency for both signals was -21 dB, which includes the 9.2-dB passive losses of the PPLN subsystem. The BER measurements and eye diagrams with and without polarization scrambling show identical performance, which demonstrates the good polarization insensitivity of the Ti:PPLN AOWC.

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Hubertus Suche, photograph and biography not available at the time of publication.

Wolfgang Sohler, photograph and biography not available at the time of publication.

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