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# Wavelength Conversion of a 40-Gb/s RZ-DPSK Signal Using Four-Wave Mixing in a Dispersion-Flattened Highly Nonlinear Photonic Crystal Fiber

Peter A. Andersen, Torger Tokle, Yan Geng, Christophe Peucheret, and Palle Jeppesen

**Abstract**—Wavelength conversion of a 40-Gb/s return-to-zero differential phase-shift keying signal is demonstrated in a highly nonlinear photonic crystal fiber (HNL-PCF) for the first time. A conversion efficiency of  $-20$  dB for a pump power of 23 dBm and a conversion bandwidth of 31 nm, essentially limited by the gain bandwidth of erbium-doped fiber amplifiers, are obtained in only 50-m dispersion-flattened HNL-PCF with nonlinear coefficient equal to  $11 \text{ W}^{-1} \cdot \text{km}^{-1}$ . This experiment demonstrates the potential of four-wave mixing in HNL-PCF as a modulation format and bit rate transparent wavelength conversion mechanism in future high-speed systems.

**Index Terms**—Differential phase-shift keying (DPSK), four-wave mixing (FWM), highly nonlinear (HNL) fiber, photonic crystal fiber (PCF), wavelength conversion.

## I. INTRODUCTION

A HIGH-SPEED wavelength converter is an essential part within a high-capacity all-optical wavelength-division-multiplexing system and, thus, considerable interest in the development of a practical wavelength converter exists [1]. Modern high-speed optical systems are likely to use advanced modulation formats such as differential phase-shift keying (DPSK) and return-to-zero DPSK (RZ-DPSK) due to their various advantages compared with conventional on-off keying, for example better receiver sensitivity associated with balanced detection, larger dispersion tolerance, and better resilience to fiber nonlinear effects [2]. With the recent interest in phase-modulated signals for optical communication systems, suitable wavelength conversion techniques need to be found. Conventional methods such as those relying on cross-gain modulation in a semiconductor optical amplifier (SOA) or cross-phase modulation (XPM) in a nonlinear optical loop mirror [3] or in an interferometric SOA wavelength converter [1] disregard the phase information as they depend on the power of the signals. Four-wave mixing (FWM) in a fiber is a phase and intensity modulation preserving process that is furthermore independent of the bit rate owing to the virtually instantaneous response of the Kerr nonlinearity of fused silica, therefore satisfying the major requirements for transparent wavelength conversion in all-optical systems [4], [5]. So far, wavelength conversion of phase-modulated signals has been demonstrated using FWM in a nonlinear fiber for simultaneous amplitude

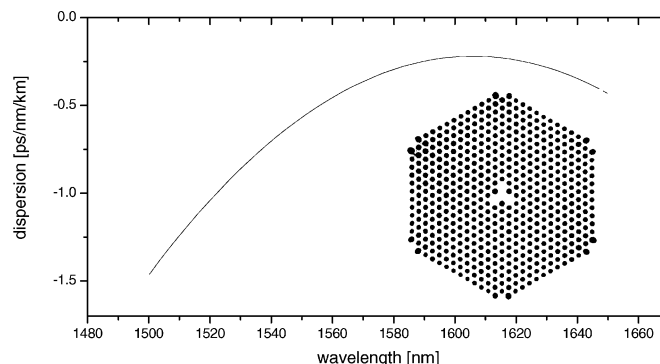


Fig. 1. Measured dispersion curve of the 50-m HNL-PCF. The inset shows the microstructured region of the HNL-PCF where the three-fold symmetry is obtained from three missing holes.

shift keying/DPSK modulation [6], or in an SOA for RZ-DPSK signals [7], at 2.5 and 10 Gb/s, respectively.

The design freedom offered by the crystal fiber technology makes highly nonlinear photonic crystal fibers (HNL-PCFs) very suitable for special applications where the fiber parameters should be tailored to satisfy specific demands, namely a flat dispersion profile, a high nonlinearity coefficient, and low loss. The dispersion of HNL-PCFs can be tailored to satisfy the phase-matching requirements for FWM. FWM wavelength conversion in an HNL-PCF has been reported for nonreturn-to-zero intensity modulated signals at 10 Gb/s [8], [9], as well as for phase conjugation at 40 Gb/s [10].

In this letter, we report on wavelength conversion of a 40-Gb/s RZ-DPSK signal using FWM in a dispersion-flattened HNL-PCF. We show a conversion efficiency of  $-20$  dB for an average pump power of 23 dBm and a conversion bandwidth of 31 nm, only limited by the bandwidths of erbium-doped fiber amplifiers (EDFAs) and tunability of optical bandpass filters (OBPFs). The quality of the converted signal is maintained over the entire conversion bandwidth with a power penalty of less than 2.5 dB. The HNL-PCF used is spliced to standard fiber, making it a possible candidate for a practical implementation of an all-optical transparent wavelength converter in future optical systems.

## II. FIBER PROPERTIES

The fiber used in this experiment is a 50-m-long HNL-PCF whose cross section is represented as an inset in Fig. 1. Its nonlinear coefficient is equal to  $11 \text{ W}^{-1} \cdot \text{km}^{-1}$  [11] and its dispersion, also shown in Fig. 1, is negative with a variation smaller than 1.5 ps/nm/km between 1500 and 1650 nm. Such a fiber

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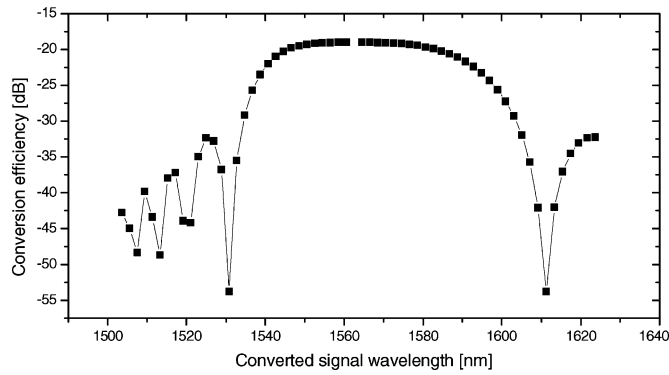


Fig. 2. Simulated conversion efficiency as a function of converted signal wavelength when the signal is fixed at 1562.5 nm and the pump power is 23 dBm.

structure has been reported earlier to provide one of the lowest values of dispersion slope (less than  $10^{-3}$  ps/nm<sup>2</sup>/km) for an HNL fiber [12], as well as remarkable flexibility in terms of dispersion control [11]. For the specific sample used in the experiment, the dispersion slope is equal to 0.01 ps/nm<sup>2</sup>/km at the signal wavelength of 1562.5 nm. The microstructured fiber is spliced to standard-single mode fiber pigtailed, leading to a total loss of 3 dB at 1550 nm.

Fig. 2 shows split-step simulation results for the continuous-wave (CW) FWM conversion efficiency when the signal is fixed at 1562.5 nm and the pump is swept over  $\pm 30$  nm from the signal. The conversion efficiency is defined here as the ratio between the power of the converted signal and the original signal at the output of the HNL-PCF. The simulation is based on the dispersion curve shown in Fig. 1. A maximum conversion efficiency of  $-19$  dB for a pump power of 23 dBm, as well as a full-width half-maximum conversion bandwidth of 50 nm are predicted for this 50-m-long fiber piece, assuming the states of polarization of the pump and signal remain perfectly aligned over propagation.

### III. EXPERIMENTAL SETUP

A schematic of the setup used in this experiment is shown in Fig. 3. Light from a CW laser was modulated using a Mach-Zehnder (MZ) modulator biased at a peak in its transfer function, driven with a 20-GHz clock signal to generate a 40-GHz pulse train with a pulsedwidth of 33% of the time slot, or 8.3 ps. A second MZ modulator biased at null point and driven with a 40-Gb/s  $2^{31} - 1$  pseudorandom bit sequence added phase modulation resulting in a 40-Gb/s RZ-DPSK signal. The signal was combined with a pump from a CW laser before amplification up to a total average power of 25 dBm. The pump power at the HNL-PCF input was 23 dBm. The stimulated Brillouin scattering threshold of the HNL-PCF was measured to be  $\sim 21$  dBm when the same pump laser was used, therefore limiting the conversion efficiency of the fiber. The states of polarization of both the signal and the pump were optimized in order to ensure the highest conversion efficiency. A polarization insensitive scheme could also be implemented as in [9]. Furthermore, the PCF has been shown earlier to exhibit small birefringence values of the order of  $10^{-5}$  to  $10^{-4}$  [11]. At the fiber output, the converted signal

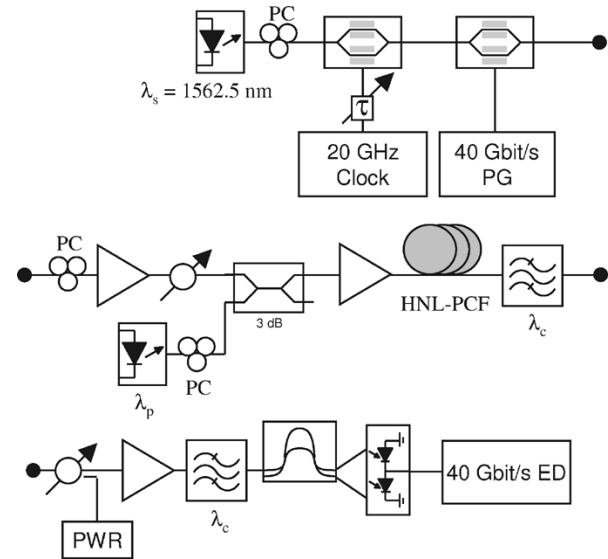


Fig. 3. Schematic of the experimental setup.  $\lambda_s$ : Signal wavelength.  $\lambda_p$ : Pump wavelength.  $\lambda_c$ : Converted signal wavelength. PC: Polarization controller. PWR: Optical power meter. PG: Pattern generator. ED: Error detector.

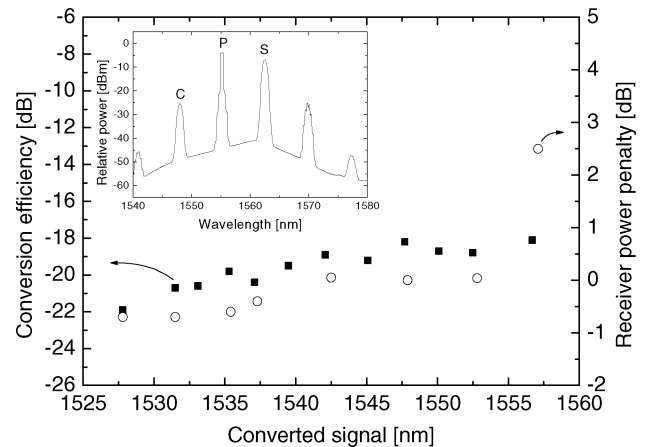


Fig. 4. Conversion efficiency and conversion power penalty versus wavelength. The signal is fixed at 1562.5 nm and the pump wavelength is swept from 1559.8 to 1545.2 nm. The inset shows the output spectrum from the HNL-PCF, with the pump at 1555.2 nm (P), and the signal at 1562.5 nm (S). (C) denotes the converted signal at 1548.0 nm (Resolution bandwidth: 1 nm).

was filtered out using a tunable OBPB with a 3-dB bandwidth of 0.9 nm. After filtering, the converted signal was detected in a preamplified receiver consisting of an EDFA preamplifier, a 0.9-nm OBPB, a 1-bit delay interferometer, and two 45-GHz photodiodes in a balanced configuration. The signal quality was quantified by measuring the bit-error rate (BER) using a 40-Gb/s error detector. The signal wavelength was fixed at 1562.5 nm while the pump wavelength was swept from 1559.8 to 1545.2 nm, allowing wavelength conversion of the signal to shorter wavelengths.

### IV. RESULTS

The inset in Fig. 4 shows the spectrum at the output of the HNL-PCF with the signal located at 1562.5 nm, the pump at 1555.2 nm, and the converted signal at 1548.0 nm. The first and second sidebands of the FWM process are clearly seen. The optical signal-to-noise ratio of the converted signal is found to be

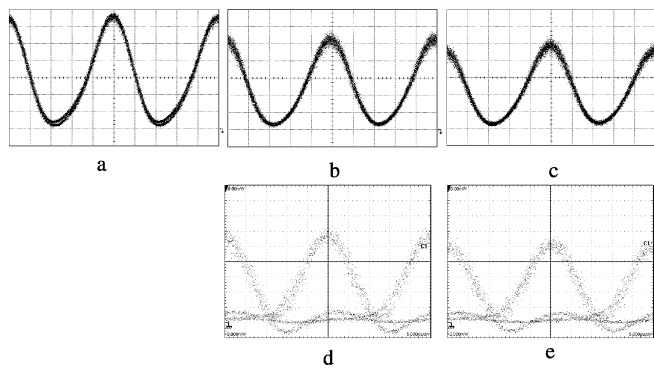


Fig. 5. (a) Waveforms for the transmitted signal at 1562.5 nm and (b) for the converted signal at 1537.4 nm and (c) 1531.5 nm. (Horizontal scale is 5 ps per division.) Single-ended detection eye diagrams of the converted signal measured at (d) 1537.4 nm and (e) 1531.5 nm are also represented.

better than 25 dB in a 1-nm resolution bandwidth. Fig. 4 shows the conversion efficiency (same definition as above) versus converted signal wavelength when the signal is fixed at 1562.5 nm. These results demonstrate a 3-dB bandwidth of the conversion efficiency as broad as 31 nm, limited by the gain bandwidth of the EDFA preamplifier and the tuning range of the OBPFs.

The receiver power penalty, defined as the increase in receiver average input power required to reach a BER of  $10^{-9}$ , is also shown as a function of wavelength in Fig. 4. The high penalty value obtained for small detuning of the pump is believed to be due to the overlap between the converted signal and the pump wavelength that has been broadened by XPM. Away from the pump, the penalty is seen to vary over a maximum of 1-dB excursion within the investigated wavelength region. Those small variations are within the uncertainty of the sensitivity measurement that is partly attributed to reproducibility in the tuning of the OBPFs and delay interferometer at the different converted signal wavelengths. The wavelength dependence of the receiver performance is taken into account in the calculation of the penalty by comparing the sensitivity of the converted signal to the sensitivity of the original DPSK signal at the same wavelength.

Fig. 5 shows the waveforms of the transmitted signal at 1562.5 nm and the converted signal at 1537.4 and 1531.5 nm. The demodulated eye diagrams of the two converted signals (after single-ended detection) are also shown in Fig. 5. It can be seen that the signal waveform is very well preserved after wavelength conversion and the demodulated eye diagrams show very little deterioration. The conversion efficiency and the wide conversion band make the 50-m-long HNL-PCF a very suitable candidate for broad-band wavelength conversion of phase-modulated signals, even at high bit rates using RZ pulse shape (40-Gb/s RZ-DPSK signals).

## V. CONCLUSION

Wavelength conversion of a 40-Gb/s RZ-DPSK signal has been successfully demonstrated using a 50-m-long HNL-PCF in a simple FWM scheme. A conversion efficiency of  $-20$  dB for an average pump power of 23 dBm at the HNL-PCF input, and a 3-dB conversion bandwidth of 31 nm were obtained. A low wavelength conversion power penalty was demonstrated over a wide wavelength range, only limited by the EDFA bandwidth and the tunability of the OBPFs. The HNL-PCF has, therefore, been shown to be a very good candidate for wavelength conversion of 40-Gb/s RZ-DPSK signals using FWM across the entire *C*-band.

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