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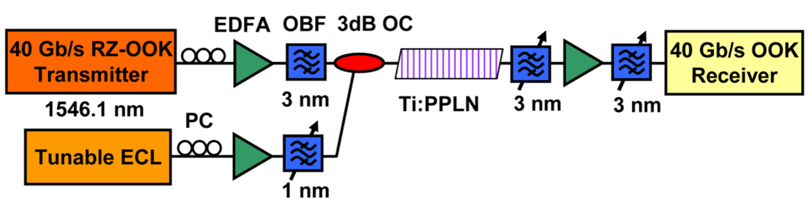


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# Tunable All-Optical Wavelength Conversion Based on Cascaded SHG/DFG in a Ti:PPLN Waveguide Using a Single CW Control Laser

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**Abstract:** Tunable all-optical wavelength conversion (AOWC) of a 40-Gb/s RZ-OOK data signal based on cascaded second-harmonic generation (SHG) and difference-frequency generation (DFG) in a Ti:PPLN waveguide is demonstrated. Error-free performances with negligible power penalty are achieved for the wavelength-converted signal at 1535, 1538, 1541, 1551, 1554, and 1557 nm, respectively.

**Index Terms:** All-optical wavelength conversion (AOWC), periodically poled lithium niobate (PPLN), second-harmonic generation (SHG), difference-frequency generation (DFG).

## 1. Introduction

Tunable all-optical wavelength conversion (AOWC) will be a key function in future wavelength-division multiplexing (WDM) networks, which can effectively utilize wavelength sources in photonic networks [1]. Various mechanisms have been used for AOWC such as four-wave mixing (FWM), cross-phase modulation (XPM), and second-order nonlinear interaction [2]–[12]. Periodically poled LiNbO3 (PPLN) waveguides efficiently exploit second-order nonlinear effects by quasi-phase matching (QPM) for wavelength conversion; they offer ultrafast response, negligible quantum-limited amplified spontaneous emission (ASE) noise, wide conversion range, and potential of high conversion efficiency [5]–[14]. Based on cascaded sum-frequency generation and difference-frequency generation (cSFG/DFG) in a PPLN waveguide, tunable AOWC using two continuous-wave (cw) pumps could be achieved by changing the wavelength of one of these lasers [5]–[7]. By conventional cascaded second-harmonic generation and difference-frequency generation (cSHG/DFG) with a strong cw pump, the wavelength of the converted signal cannot be flexibly tuned [8], [9].

In this paper, we experimentally demonstrate and numerically model tunable AOWC for a 40-Gb/s return-to-zero on–off keying (RZ-OOK) signal by cSHG/DFG in a Ti:PPLN waveguide using a *single* tunable cw control wave only. The RZ-OOK signal is set to the QPM wavelength for SHG and is sufficiently amplified to generate wavelength-converted data at half the original wavelength with high efficiency. Via DFG with the control wave, a wavelength-shifted signal (idler) in the C-band is simultaneously generated. The wavelength of the converted signal has been tuned from 1535 to

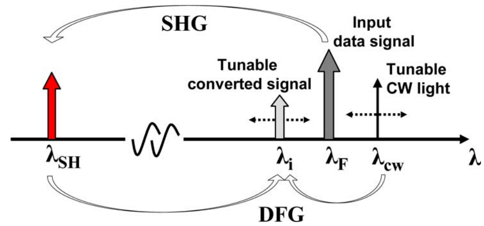


Fig. 1. Operation principle of the tunable AOWC based on cascaded SHG/DFG in a Ti:PPLN waveguide.

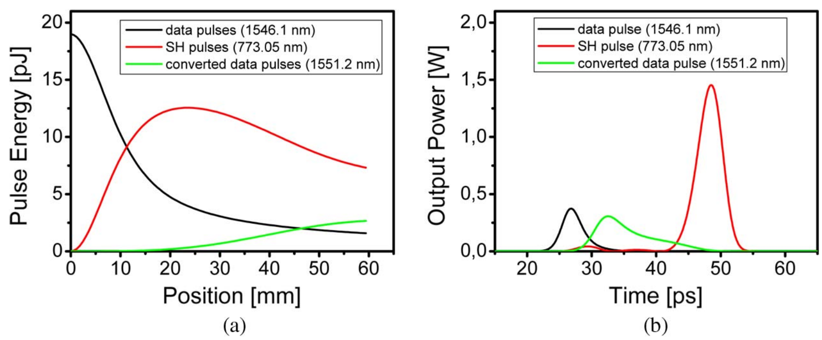


Fig. 2. (a) Evolution of data, SH, and converted data pulses versus position in the Ti:PPLN waveguide. (b) Simulated pulse shape of data, SH, and converted data pulses at the output of the integrated wavelength converter.

1557 nm with error-free performance. This principle of wavelength conversion has been proposed and theoretically analyzed in [10] and was experimentally demonstrated using a ring laser configuration to provide the tunable cw control wave in [11].

## 2. Operation Principle and Modeling Results

Fig. 1 illustrates the concept of the tunable AOWC based on cSHG/DFG. The input data signal is set within the QPM wavelength range; it acts as fundamental wave $(\lambda_F)$ and generates via quasi-phase-matched SHG a converted data signal at $\sim 0.77~\mu$m $(\lambda_{SH})$. This process is numerically modeled using a versatile computer code described in [15]; all parameters are taken from the experiment (see below) despite the waveguide length. An effective (interaction) length of 60 mm is chosen instead of the actual sample length. In this way, the nonlinear interactions are simulated well, but the GVD-induced effects are underestimated. The evolution of both, data (fundamental) and SH pulses, can be observed as calculated pulse energy versus position in a waveguide of 60-mm effective interaction length in Fig. 2(a). Gaussian input pulses of 5-ps full-width at half-maximum (FWHM) have been assumed. Simultaneously with the SHG process, a wavelength-shifted idler ($\lambda_i$; converted data pulses) in the C-band is generated by DFG between the SH wave $(\lambda_{SH})$ and a tunable cw control wave $(\lambda_{CW})$ and amplified by optical parametric amplification (OPA) within the PPLN waveguide. The growth of the energy of the converted data pulses is shown in Fig. 2(a), which is calculated by integrating pulse power as a function of time [15]. Fig. 2(a) shows that an input pulse energy of 19 pJ in combination with the cw control wave of 0.5 pJ within a bit period, as used in the experiments, is sufficient to get a wavelength-converted data pulse of 2.5 pJ, which is enough to achieve error-free performance for the converted signal.

The efficiency of the processes exploited and the influence of group velocity dispersion (GVD) can be observed in Fig. 2(b), showing calculated data, frequency-doubled and wavelength-converted pulses at the output of the waveguide. GVD results in different arrival times leading to

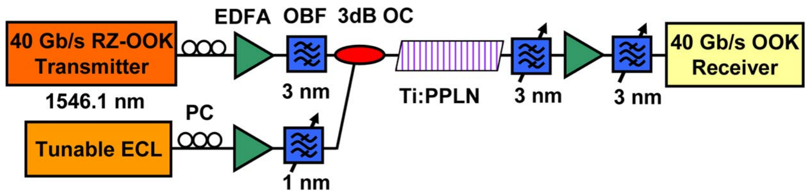


Fig. 3. Experimental setup for tunable AOWC of a 40-Gb/s RZ-OOK signal.

distortion and broadening of the converted data pulses in particular. The broadened (1/e) width of $\sim$10 ps will limit the operation speed to $\sim$50 Gb/s. By changing the wavelength of the control wave, the idler wavelength (converted data) can be easily adjusted within a broad range of the C-band as demonstrated experimentally by tuning from 1535 to 1557 nm. Note that the phase of the data signal is doubled during the SHG process; therefore, this AOWC scheme is not transparent to the phase of the data signal.

## 3. Experimental Setup

Fig. 3 shows the experimental setup of the tunable AOWC for a 40-Gb/s RZ-OOK signal. The 40-Gb/s RZ-OOK transmitter consists of an external-cavity laser (ECL), an electroabsorption modulator (EAM)-based pulse carver, and a Mach–Zehnder modulator (MZM). The ECL emits a cw at 1546.1 nm, which is carved into pulses in the EAM with a repetition rate of 40 GHz and an FWHM of 5 ps. This pulse train is on–off keying (OOK) modulated to a 40-Gb/s RZ-OOK signal by the MZM driven by a 40-Gb/s PRBS signal from a bit pattern generator (BPG). The 40-Gb/s RZ-OOK signal is amplified by an EDFA, filtered by a 3-nm optical bandpass filter (OBF), passes a 3-dB fiber optical coupler (OC), and is finally launched into the Ti:PPLN waveguide by fiber butt coupling. The cw control wave, generated by a tunable ECL, is amplified, filtered, and launched into the waveguide through the second port of the 3-dB OC. The launched (average) power of the data signal and the cw control wave is 25.8 and 13.2 dBm, respectively. The polarizations of both, data signal and control wave, are aligned to TM mode and parallel to the optical c-axis of the Ti:PPLN waveguide by polarization controllers (PCs). The 80-mm-long Ti-diffused PPLN waveguide of 16.3-$\mu$m periodicity has a width of 7 $\mu$m; it is operated at a temperature of 179.3 °C to avoid photorefractive effects as far as possible. The waveguide propagation losses (for TM-polarization) at the wavelength of 1550 nm are about 0.1 dB/cm. The total fiber-to-fiber loss is about 6.5 dB including $\sim$1-dB propagation loss and $\sim$5.5-dB coupling loss. At the output of the PPLN waveguide, two tunable 3-nm filters and an EDFA in between are used to filter out the converted 40-Gb/s RZ-OOK signal. The converted signal (idler) is detected by a 40-Gb/s OOK receiver, which consists of an optical preamplifier, a photodetector (PD), and an error analyzer. Alternatively, the full output spectrum can be measured by an optical spectrum analyzer (OSA).

## 4. Experimental Results

The optical spectra at the output of the PPLN waveguide with converted wavelengths of 1535 and 1557 nm are shown in Fig. 4(a) and (b). By changing the wavelength of the cw control wave, the converted wavelength has been tuned to 1535, 1538, 1541, 1551, 1554, and 1557 nm, respectively, keeping the wavelength of the input data constant. For an effective nonlinear interaction length of 60 mm in the 80-mm-long Ti:PPLN waveguide used, the SHG acceptance bandwidth is 0.17 nm assuming a cw input signal. It is therefore smaller than the bandwidth of the input (data) pulses, and a certain filtering will be the result, which can also be seen in Fig. 4. The influence of an acceptance bandwidth smaller than the bandwidth of the input data pulses is analyzed with more details in [14]. Our numerical results [see Fig. 2(a) and (b)] also include these distorting effects, which are more prominent for the converted data pulses. The conversion efficiency defined by the pulse energy of the converted data at the waveguide output with respect to the pulse energy of

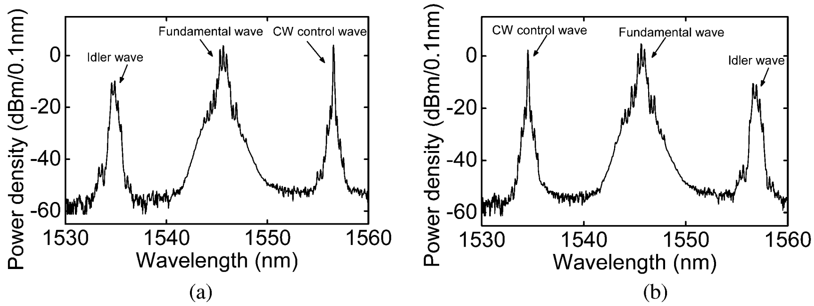


Fig. 4. Optical spectra at the output of the Ti:PPLN waveguide with different converted wavelengths. (a) 1535 nm; (b) 1557 nm.

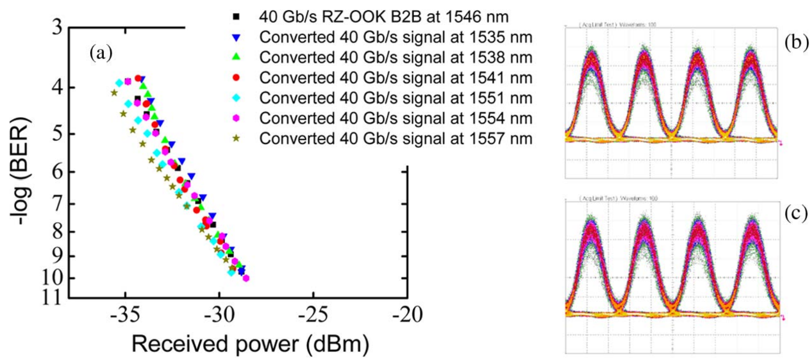


Fig. 5. (a) Results of BER measurements for the back-to-back 40-Gb/s RZ-OOK signal at 1546 nm and the converted 40-Gb/s RZ-OOK signal at 1535, 1538, 1541, 1551, 1554, and 1557 nm, respectively. Eye diagrams of the converted signals at 1535 nm (b) and 1557 nm (c).

the input data is approximately $-9$ dB [see Fig. 2(a)], which can also be estimated as ratio of the integrated powers of converted to fundamental waves as shown in the spectra (see Fig. 4).

With subsequent filtering, bit error rates (BERs) of the converted signals have been measured as a function of the received power in the 40-Gb/s OOK receiver, as shown in Fig. 5(a). BER curves are plotted for the 40-Gb/s RZ-OOK back-to-back (B2B) and for the converted 40-Gb/s RZ-OOK signals at 1535, 1538, 1541, 1551, 1554, and 1557 nm, respectively. All the converted signals show error-free performances $(\text{BER} = 10^{-9})$ and cause negligible power penalty compared with the back-to-back case. The slightly different slopes of the BER curves are due to the different sensitivities of the receiver at different wavelengths. The 40-Gb/s eye diagrams of the converted signals at 1535 and 1557 nm are shown in Fig. 5(b) and (c), respectively. The clear eye opening also indicates a good performance of the tunable AOWC despite the pulse distortions observed by numerical modeling.

## 5. Conclusion

We have demonstrated tunable AOWC for a 40-Gb/s RZ-OOK signal based on cascaded SHG/DFG in a Ti:PPLN waveguide using a single cw control laser. Error-free operation with negligible power penalty has been achieved for the converted signal at 1535, 1538, 1541, 1551, 1554, and 1557 nm wavelength, respectively.

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