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Efficient cascaded difference frequency conversion in periodically poled Ti:LiNbO$_3$ waveguides using pulsed and cw pumping

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ABSTRACT Using an FM-mode-locked Ti:Er:LiNbO$_3$ waveguide laser as the fundamental source, wavelength conversion by cascaded $\chi^{(2)}:\chi^{(2)}$-difference frequency generation with a conversion efficiency of up to +3 (−4.6) dB was demonstrated at a pulse repetition rate of about 2 (10) GHz. In addition, multichannel conversion was demonstrated with a fully packaged wavelength converter using a continuous fundamental source.

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1 Introduction

Wavelength conversion in wavelength-division-multiplexed (WDM) and time-division-multiplexed (TDM) optical networks is a key technology of future high bit-rate transport systems. Wavelength conversion offers a higher flexibility in traffic management and a dynamic reconfiguration of the optical network. In recent years, difference-frequency converters based on periodically poled LiNbO$_3$ (PPLN) waveguides have attracted considerable interest. They fulfill numerous requirements for ideal wavelength converters for telecommunications, such as strict transparency, independence of bit rate and data format, and low cross-talk. They offer a high conversion efficiency without attenuation of the signal, adding only negligible noise from spontaneous fluorescence. In addition, the wavelength conversion bandwidth is broad, and it is possible to cascade many converters. The simultaneous conversion of many wavelength channels, spectral inversion and parametric amplification are also attractive properties of difference-frequency converters. The demonstration of second-harmonic generation (SHG) of unprecedented efficiency in PPLN waveguides [1, 2] allowed the possibility of combining SHG and difference frequency generation (DFG) in a single device or even in the same waveguide or structure [3]. In such a cascaded-DFG (cDFG) device, a strong fundamental wave at λ_f is used to generate a pump wave at $\lambda_p = \lambda_f/2$ by frequency doubling. Simultaneously the pump wave interacts with a signal wave at λ_s to generate an idler wave at λ_i with $\lambda_i^{-1} = \lambda_p^{-1} - \lambda_s^{-1} = 2\lambda_f^{-1} - \lambda_s^{-1}$. In the following we report the first demonstration of cDFG with +3 (−4.6) dB conversion efficiency at a pulse repetition rate of ∼2 (∼10) GHz.

2 Fabrication and characterisation

Two different PPLN waveguides (samples Str332 and Pb133z) were fabricated by in-diffusion (7.5 h at 1060 °C) in an argon inert gas atmosphere and 1 h post-diffusion at the same temperature in oxygen to re-oxidize the material of 7-μm-wide and 98-nm-thick Ti-stripes into the $-Z$-face of a 0.5-mm-thick LiNbO$_3$ substrate (Fig. 1). We found that subsequent electric field poling was not possible due to a shallow domain-inverted layer on the $+Z$-face. Therefore, we had to remove that layer by careful grinding. As domain inversion always starts on the $+Z$-face [4], it is advantageous to have the waveguides on that face of the sample. Taking these considerations into account, we performed as the next fabrication step a homogeneous polarisation reversal of the whole sample. Thereafter, the microdomain structure with a $\Lambda = 17$ ($\Lambda = 16.6$) μm period was fabricated by using the electric field poling method with the structured photoresist on the $+Z$-side. The length of the PPLN waveguides was about 78 (86) mm. After polishing the waveguide end-faces, we characterized its properties by several means. To reveal the domain pattern quality, we selectively etched a part of the sample surface using concentrated HF:HNO$_3$ acid (see Fig. 2).

A near-infrared camera was used to confirm that the waveguide is single mode in the spectral region of interest (around $\lambda = 1.55$ μm). The waveguide loss was determined to be 0.15 (0.14) dB cm^{-1} at 1.523 μm wavelength. We assume that the loss at about 780 nm wavelength, i.e. at the pump wavelength for DFG, is about 0.3 dB cm^{-1}. To investigate the nonlinear performance of the waveguide we carried out single-pass SHG experiments using a wavelength-tunable external cavity laser (tuning range 1500–1580 nm). As a result, a normalized device efficiency of 570 (500) % W^{-1} was measured, corresponding to a length-normalized efficiency of 9.4 (6.8) % W^{-1} cm^{-2}.

To achieve phase-matching for frequency doubling of the fundamental radiation at a wavelength of 1562 (1556) nm, we had to adjust the device temperature to 100 (188) °C. Figure 3 shows the SHG phase-match curve. From the full width at

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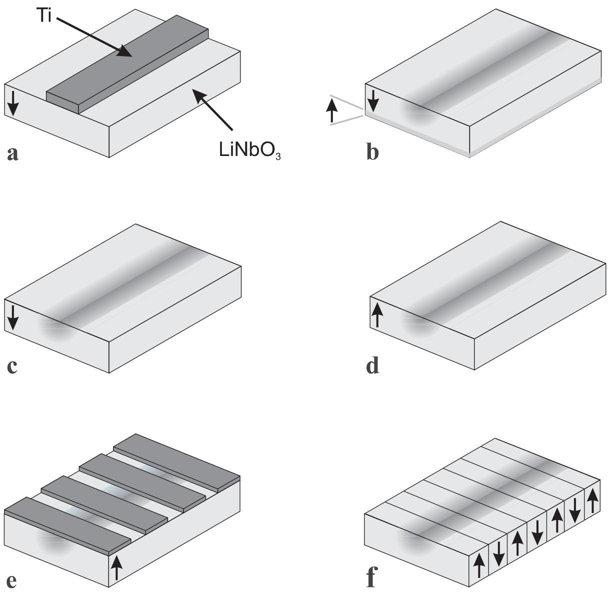

FIGURE 1 Fabrication steps to obtain periodically poled Ti:LiNbO$_3$ (PPLN) waveguides. **a** Definition of a titanium stripe on the $-Z$-face. **b** In-diffusion of titanium at high temperatures. During in-diffusion a domain-inverted layer merges with the $+Z$-face. **c** Removal of the domain-inverted layer by grinding. **d** Inversion of the spontaneous polarisation of the whole sample. **e** Photolithographical definition of a photoresist grating. **f** Periodic electric field poling with liquid electrodes

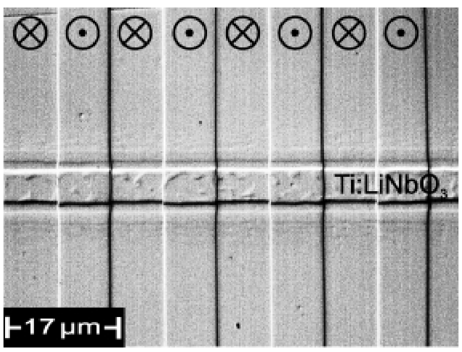

FIGURE 2 Photograph of a selectively etched PPLN sample with a titanium-in-diffused waveguide

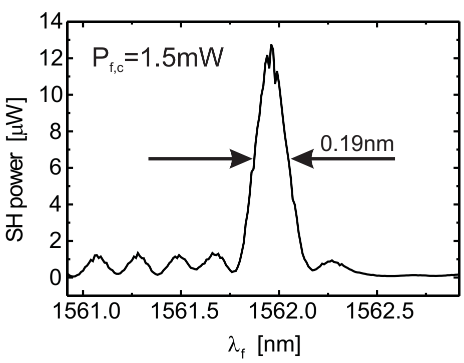

FIGURE 3 Measured second-harmonic generation (SHG) phase-match curve of the periodically poled waveguide

half maximum (Str332: $\Delta\lambda_{3\,\mathrm{dB}} = 0.19$ nm; Pb133z: $\Delta\lambda_{3\,\mathrm{dB}} = 0.2$ nm) an effective interaction length of 62 (59) mm was evaluated. From the device efficiency we conclude that the nonlinear waveguide attains 86 (82) % of the ideal effective nonlinearity ($d_{\mathrm{eff,ideal}} = 2/\pi \cdot d_{33} = 12.1\ \mathrm{pm\,V^{-1}}$) [5].

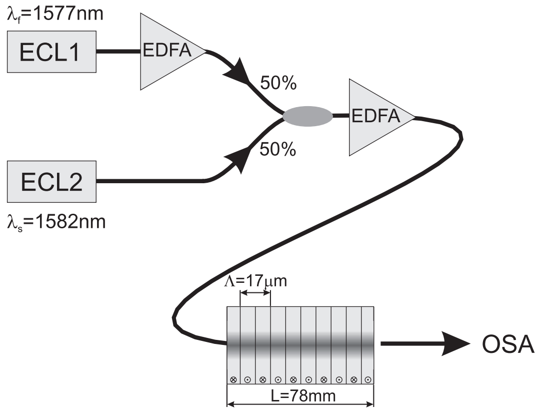

FIGURE 4 Experimental setup used to investigate cw cDFG

3 Experimental setups

3.1 *cDFG with a cw fundamental laser source*

Figure 4 shows the setup used to investigate cDFG. Sample Str332 was used as the nonlinear frequency converter. The fundamental laser source for the frequency-doubling process was a tunable semiconductor laser (external cavity laser: ECL1). We used a second external cavity laser (ECL2) for a signal laser. The pre-amplified fundamental and (unamplified) signal radiation were superimposed in a single fibre using a 50/50 fibre-optic coupler. By using a high-power, erbium-doped fibre amplifier (HP-EDFA) we boosted the total incident power to 320 mW with a fundamental-to-signal power ratio of 16 dB (fundamental power = 213.7 mW; signal power = 5.3 mW; amplified spontaneous emission [ASE] power = 101 mW). Despite the pre-amplification of the fundamental source, a significant amount of ASE was superimposed to the boosted fundamental and signal radiation. To avoid the photorefractive effect (optically induced changes in the index of refraction result in a reduction in the conversion efficiency of the device), we operated the frequency converter at temperatures much higher than 100 °C. The amplification bandwidth of the EDFA limited the maximum operation temperature to 200 °C as the resulting phase-matching wavelength for SHG shifted to 1577 nm.

3.2 *Multichannel conversion with a cw fundamental laser source*

Figure 5 shows the experimental setup used to investigate multichannel conversion in a cDFG scheme (sam-

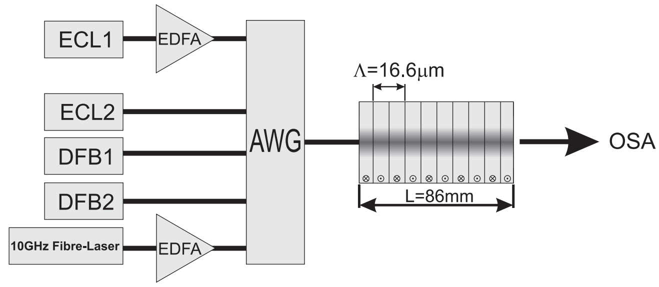

FIGURE 5 Experimental setup used to investigate multichannel conversion. ECL1 is used as the fundamental laser source. The other lasers are tuned to four different ITU wavelengths 200 GHz apart

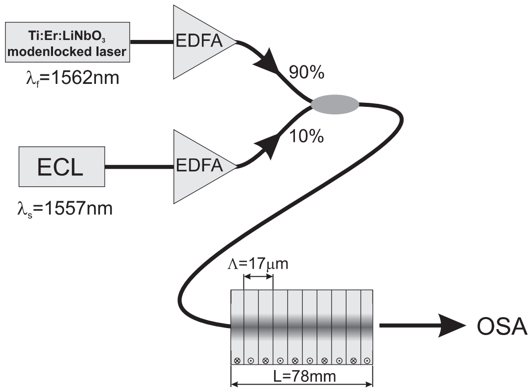

FIGURE 6 Schematic of the cDFG experiment with a pulsed fundamental wave and a cw signal

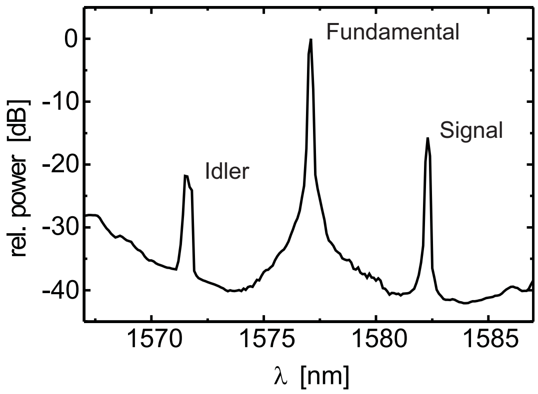

FIGURE 7 Measured optical spectrum in cw operation of the fundamental and signal waves

ple Pb133z). One fundamental source (external cavity laser: ECL1) and four signal laser sources at International Telecommunication Union (ITU) wavelengths were used to perform the experiment. One of the signal lasers was a fibre-amplifier-boosted, mode-locked fibre laser with a 10 GHz repetition rate. A 16-channel arrayed waveguide grating (AWG; channel spacing = 200 GHz) was used to multiplex the different channels. The insertion loss of the AWG is about 3 dB. The single-ended output of the multiplexer was connected to the fibre pigtailed and packaged frequency converter, which was operated at about 190 °C to avoid photorefractive damage. Most of the ASE of the EDFA was blocked by the multiplexer due to its narrow-band spectral transmission characteristic of about 0.7 nm (FWHM) and low cross-talk (< -28 dB).

3.3 *cDFG with a pulsed fundamental laser source*

Figure 6 shows the setup for cDFG in a pulsed mode. We again used the nonlinear waveguide of sample Str332 operated at a sample temperature of 100 °C. The fundamental source was a mode-locked integrated optical Ti:Er:$LiNbO_3$ laser (1562 nm center wavelength) [6] with a repetition rate of 1.8973 GHz (second-harmonic mode-locking) and 9.93 GHz (tenth-harmonic mode-locking). Using an optical autocorrelator, a pulse width of 12.4 (6) ps was measured, leading to a pulse duty cycle of ∼16 (∼12.3) dB. With an optical spectrum analyzer of 0.1 nm resolution, a spectral width (FWHM) of 0.35 (0.65) nm was determined. This leads to a time-bandwidth product of 0.52 (0.48), slightly exceeding the transform limit for Gaussian pulses. The mode-locked fundamental source was boosted to an average incident power of 88 mW using a 2 W HP-EDFA. Phase-matching was achieved at a temperature of 100 °C. The SHG pulses are about a factor of $\sqrt{2}$ shorter, thus leading to a duty cycle of −17.5 (−13.8) dB for the 12.4 (6)-ps-long fundamental pulses. An external cavity laser operated at 1557 nm was used as the signal source. Fundamental and signal radiation were combined with a 90/10 fibre-optic coupler.

4 Experimental results

4.1 *cDFG with a cw fundamental laser source*

In cw operation of the all-optical wavelength converter, we measured a ratio of − 6.1 dB for the output levels of signal and idler power (Fig. 7); this agrees well with a calculated efficiency of − 6.2 dB, if we assume a 80% coupling efficiency for the sample. Due to operation at 200 °C the signal and idler output power was very stable as a function of time, without any fluctuations induced by photorefractive effects. Due to the fairly long fundamental wavelength necessary to obtain phase-matching at 200 °C, it was not possible to completely saturate the HP-EDFA, leading to an increased amount of ASE especially towards shorter wavelengths.

4.2 *Multichannel conversion with a cw fundamental laser source*

The result for simultaneous conversion of four different ITU wavelengths is shown in Fig. 8. The incident fundamental power was boosted to 175 mW. A very stable conversion efficiency of −10 dB for each channel was observed for at least 2 h. Instabilities on a longer timescale were mainly due to a slow change in the polarisation state at the output of our EDFA (no polarization-maintaining amplifier). The measured optical signal-to-noise ratio (OSNR) of the converted signal (idler) ranged between 17 and 21 dB for a 0.5 nm resolution bandwidth of the optical spectrum analyzer, depending on the distance of the converted channel from the fundamental line. A further improvement is possible by increasing the signal input power. An increase in the input power of one channel from 0 up to +10 dBm did not cause any measurable degra-

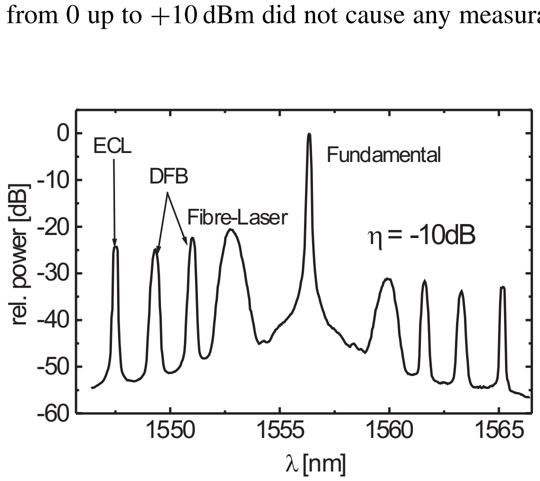

FIGURE 8 Experimental result for multichannel cDFG

dation of the conversion efficiency for all four channels. The observed improvement of the OSNR was also 10 dB. Some residual noise in the spectrum was due to the unblocked ASE from the fibre amplifiers.

4.3 *cDFG with a mode-locked fundamental laser source at a repetition rate of* ∼ 2 GHz

Figure 9 shows the measured spectral and power characteristics of our frequency converter; for pulsed pumping an average converted idler power 14.5 dB below the transmitted signal power was measured. Considering the idler pulse duty cycle of − 17.5 dB, this leads to a peak conversion efficiency of +3 dB. The estimated peak power of the converted pulses is 1.9 mW. It should be mentioned that the conversion efficiency of +3 dB simultaneously means an optical parametric amplification of the signal of +3 dB.

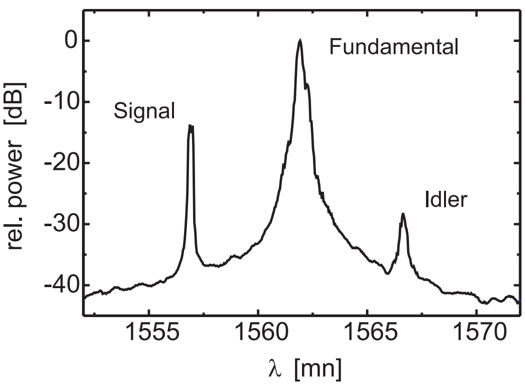

FIGURE 9 Optical spectrum of the pulsed fundamental and idler wave at a repetition rate of 2 GHz and with a cw signal wave

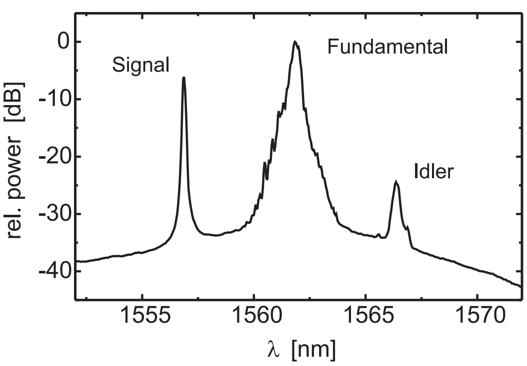

FIGURE 10 Result with a pulsed fundamental laser source at a repetition rate of 10 GHz

4.4 *cDFG with a mode-locked fundamental laser source at a repetition rate of* 10 GHz

Due to the broader fundamental spectrum of about 0.65 nm and some photorefractive damage due to the larger pump duty cycle (− 13.8 dB), it was not possible to achieve a conversion efficiency > 0 dB (Fig. 10). On the other hand, the measured efficiency of > − 4.6 dB is to our knowledge the best result reported to date at such a high repetition frequency.

5 Summary and conclusions

We demonstrated for the first time nonlinear optical wavelength conversion with an efficiency of +3 (−4.6) dB at a repetition rate of 2 (10) GHz using cascaded difference frequency generation in a periodically poled Ti:$LiNbO_3$ waveguide. We also demonstrated multi-channel wavelength conversion without any reduction of the conversion efficiency by the other wavelength channels. In the future the performance of our frequency converters will be improved. A device with 935 % W^{-1} second-harmonic conversion efficiency has been reported [7, 8] and waveguides of significantly reduced photorefractive sensitivity, such as stoichiometric Mg:$LiNbO_3$ [9] and 5 mol % MgO:$LiNbO_3$, are being investigated. On the modelling side, numerical simulations that take the group velocity dispersion between pump, signal, and idler pulses into account are underway.

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