Optical Parametric Amplification in Ti:PPLN Channel Waveguides

Rahman Nouroozi*, Hubertus Suche, Werner Grundkötter, Raimund Ricken, Viktor Quiring and Wolfgang Sohler
Angewandte Physik, Department Physik, Universität Paderborn,
D 33098 Paderborn, Germany
*Rahman.nouroozi@upb.de

Abstract—**Optical parametric amplification via cascaded SHG/DFG in Ti:PPLN channel waveguides has been investigated using a Q-switched DPSS-laser of low pulse duty cycle as fundamental source to avoid photorefraction. More than 26 dB of parametric gain was achieved in a 95 mm long waveguide with 15 W of fundamental peak power.**

Keywords- nonlinear optics; optical parametric amplifier; PPLN, waveguide

I. Introduction

Optical parametric amplification (OPA) is a very promising way to get large bandwidth, low (quantum-limited) noise, coherent and phase sensitive amplification. Therefore, corresponding devices are completely transparent, attractive in particular for telecom applications. Among the different OPA approaches [1,2], cascaded second harmonic generation and difference frequency generation with simultaneous signal amplification (cSHG/DFG(OPA)) in periodically poled $LiNbO_3$ (PPLN) waveguides [3] is of particular interest: (i) the largest nonlinear coefficient can be exploited enabling the development of integrated amplifiers much shorter than fiber-optical devices, (ii) stimulated Brillouin scattering (SBS), self- and cross phase modulation (SPM, XPM) do not deteriorate the OSNR and, therefore, need not to be overcome by sophisticated pump modulation schemes [2], (iii) the cascaded process allows using telecom devices for pumping, and (iv) the actual pump wave is generated internally by SHG.

Pulsed OPA in PPLN was first demonstrated in 1998 in the bulk [4] and later in proton-exchanged waveguides with two successive sections of different domain periodicities for SHG and OPA using a mode-locked Er-doped fiber laser as fundamental source [1].

In this contribution we report pulsed OPA by cSHG/DFG (OPA) in a low-loss Ti-indiffused PPLN waveguide of constant poling periodicity using a Q-switched diode pumped solid state (DPSS) laser fundamental source. A gain of up to 26 dB was demonstrated at 15 W fundamental peak power.

II. Principle of operation

In cSHG/DFG(OPA) the actual pump wave for the DFG/OPA process is generated internally by SHG of the fundamental wave. The signal is amplified and a wavelength converted (idler) wave is generated at the difference frequency $\omega_i = \omega_p - \omega_s$ (Fig. 1). Due to quasi phase-matched SHG a selective excitation of a single spatial pump mode is guaranteed.

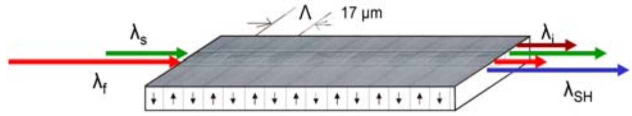

Fig.1: Scheme of OPA of a signal (λ_s) wave by cSHG/DFG(OPA) in a Ti:PPLN channel guide. The fundamental wave (λ_f) generates its second harmonic (λ_{SH}) as pump wave for the DFG/OPA-process. The idler (λ_i) is the wavelength-converted signal (λ_s) wave.

The evolution of fundamental-, SH-, signal- and idler power levels in the waveguide has been calculated for cw-operation. An effective interaction length of 45 mm, homogeneous quasi-phase matching, and ~3 W coupled fundamental power have been assumed for the example presented in Fig. 2. The fundamental wave is continuously depleted mainly due to SHG but also due to DFG and OPA (here ~ 16 dB).

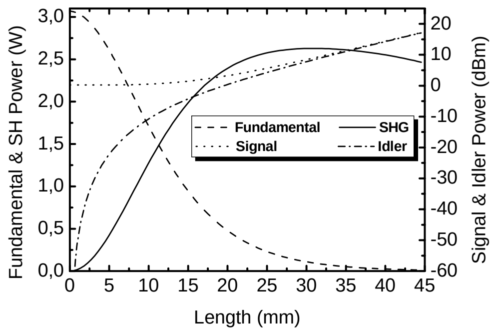

Fig. 2: Calculated evolution of cw-fundamental-, SH-, signal-, and idler power levels along the waveguide for 3 W of coupled fundamental power.

III. Fabrication and experimental setup

7 µm wide strip waveguides of low propagation losses (< 0.1 dB/cm @ 1550 nm) were fabricated by indiffusion (9h/1060°C) of photolithographically delineated 100 nm thick Ti-stripes into Z-cut $LiNbO_3$. Afterwards, the waveguides were periodically poled with a period Λ=16.3 µm using the field assisted poling method [5]. To avoid Fabry-Perot cavity effects, which might lead to the onset of parametric oscillation, the waveguide end-faces were angle-polished and AR-coated.

This work was funded by the Deutsche Forschungs-gemeinschaft (DFG) within the framework of the project "Contention Resolution in Optical Burst Switching (OBS) using Wavelength Conversion".

To avoid photo-refraction at high power operation, 2.5 ns long pulses of a low duty cycle (8.2×10^{-6}) passively Q-switched laser at 1535 nm wavelength were used as the fundamental radiation. The cw signal was combined with the pulsed fundamental wave using a dichroic mirror and launched together into the temperature stabilized waveguide. To achieve quasi-phase-matching the waveguide was heated to 165°C. At the output a tunable bandpass filter selected the signal. It was monitored by an InGaAs-PIN-photodiode of 15 GHz bandwidth and a digital oscilloscope of 1.5 GHz bandwidth.

IV. RESULTS AND DISCUSSION

In Fig. 3, transmitted fundamental-, generated SH- and amplified signal are displayed for low (0.8 W, left) and high (6 W, right) of coupled fundamental peak power as example.

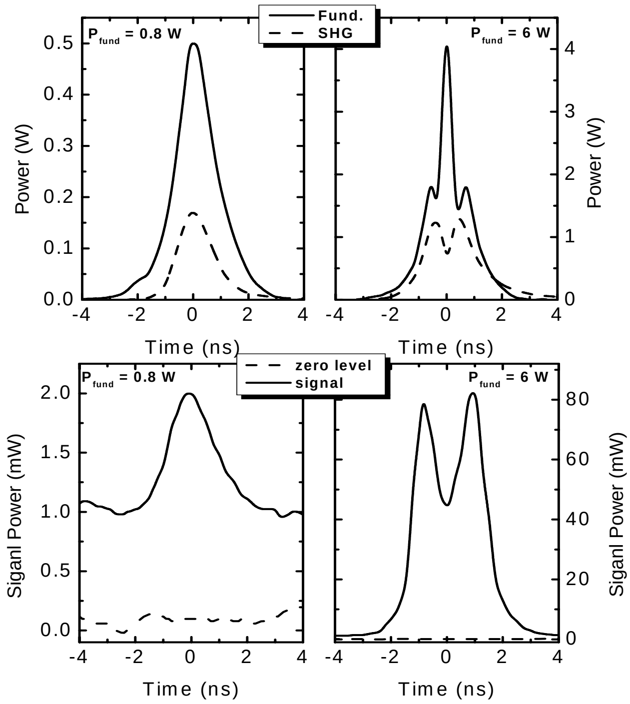

Fig. 3: Upper diagrams: measured output fundamental (solid), SHG (dashed) pulses; lower diagrams: measured output signal pulses without (dashed) and with (solid) parametric gain; coupled fundamental power levels: 0.8 W (left) and 6 W (right).

At low fundamental power the fundamental pulse is continuously depleted leading to an single peaked SH pulse (left). At high fundamental power the depletion of the fundamental pulse becomes nonmonotonic resulting in a distorted double peaked SH-pulse (right). We attribute this effect to the shrinking of the quasi-phase matching (QPM) acceptance bandwidth [6]. Even small deviations from exact QPM (e.g due to temperature fluctuations and/or waveguide inhomogeneities) lead to a power level dependent non-monotonic evolution of the fundamental wave along the guide. As a consequence the shape of the SH-pulse can significantly deviate from the square of the pulse shape of the input fundamental wave.

The pulse shape of the amplified signal follows the SH-pulse envelope (Fig. 3, lower diagrams). By comparing the peak power level during amplification with the cw-signal power level without amplification a parametric gain of about 3 dB for 0.8 W and 20 dB for 6W coupled fundamental power has been achieved.

In Fig. 5 the measured and calculated (for cw and 45 mm effective interaction length) parametric gain is plotted versus the coupled fundamental power. With about 15 W more than 26 dB of parametric gain has been achieved. In the range of undistorted SHG (up to about 4 W of coupled fundamental power) a good agreement between measured and calculated parametric gain has been achived.

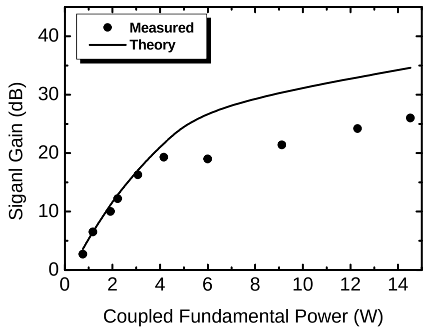

Fig. 5: Measured and calculated signal gain versus coupled fundamental peak power in a Ti:PPLN channel waveguide of 45 mm long effective interaction length and 16.3 µm micro-domain period, operated at 165°C.

V. CONCLUSIONS

Pulsed optical parametric amplification by cSHG/DFG (OPA) in a 95 mm long (45 mm long effective interaction length) Ti:PPLN channel waveguide is reported. To avoid photorefraction in high power operation a Q-switched DPSS-laser emitting short pulses of low duty cycle has been used. With 15 W of fundamental peak power ~ 26 dB of signal gain has been measured. This result is in reasonably good agreement with numerical simulations.

REFERENCES

[1] A. Galvanauskas, K. K. Wong, K. El Hadi, M. Hofer, M. E. Fermann, D. Harter, M. H. Chou, M. M. Fejer, "Amplification in 1.2-1.7 µm communication window using OPA in PPLN waveguides", Elec. Lett. 35, p. 731-733 (Apri1 1999).

[2] Thomas Torounidis, Peter A. Andrekson, and Bengt-Erik Olsson, "Fiber-Optical Parametric Amplifier With 70-dB Gain", IEEE Photonics Technology Letters, Vol. 18, No. 10, May 15, 2006.

[3] W. Sohler, W. Grundkötter, J.H. Lee, Y.L. Lee, Y.H. Min, V. Quiring, H. Suche, R. Schiek, T. Pertsch, F. Lederer, R. Iwanow, G.I. Stegeman: "All-optical signal processing in periodically poled LiNbO3 waveguide structures", Proc. ECOC2004, Vol. 2, paper Tu3.4.1 (invited) pp 192-195, Stockholm, September.

[4] A. Galvanauskas, A. Hariharan, and D. Harter, "High-Energy Femtosecond Pulse Amplifi-cation in a Quasi-Phase-Matched Parametric Amplifier", Opt. Lett. 23, p. 210-212 (February 1998).

[5] G. Schreiber, H. Suche, Y.L. Lee, W. Grundkötter, V. Quiring, R. Ricken, and W. Sohler:"Efficient cascaded difference frequency conversion in periodically poled Ti:LiNbO3 waveguides using pulsed and cw pumping", Applied Physics B, Special Issue on Integrated Optics, vol. 73, 501-504 (2001).

[6] K. R. Parameswaran, J. R. Kurz, R. V. Roussev, M. M. Fejer, "Observation of 99% pump depletion in single-pass second-harmonic generation in a periodically poled lithium niobate waveguide", Optics Letters, 27, p. 43-45 (January 2002).