ICTON '06, Nottingham, June 2006

All-Optical Wavelength Conversion, Parametric Amplification, Multiplexing, and Switching in Integrated PPLN-Devices

W. Sohler [1], W. Grundkötter [1], H. Herrmann [1], J. H. Lee [1], Y. H. Min [1], V. Quiring [1], H. Suche [1], R. Schiek [2], T. Pertsch [3], F. Lederer [3], R. Iwanow [4], G. I. Stegeman [4], S. L. Jansen [5]

1: University of Paderborn, D-33095 Paderborn, Germany; 2: University of Applied Sciences Regensburg, D-93049 Regensburg, Germany; 3: Friedrich-Schiller-Universität Jena, D-07743 Jena, Germany; 4: CREOL / School of Optics, University of Central Florida, Orlando FL, USA 5: University of Technology, Eindhoven, The Netherlands and Siemens AG, D-81730 München, Germany;
e-mail: sohler@physik.upb.de; FON: +49 5251 605885

ABSTRACT:

Recent progress achieved with integrated optical devices exploiting quasi-phasematched second order nonlinear interactions in periodically poled Ti:LiNbO$_3$ waveguide structures is reported. Wavelength conversion, parametric amplification, multiplexing, and switching are demonstrated as examples of ultra-fast all-optical signal processing in the 1.5-µm wavelength range for transparent optical networks.

Keywords:

1. INTRODUCTION

During the last years optical channel guides of excellent quality have been developed in Periodically Poled Lithium Niobate (PPLN), using either (annealed) proton exchange (APE) or Ti-indiffusion for fabrication. APE:PPLN guides usually have a somewhat smaller cross-section, yielding a higher (normalized) efficiency of nonlinear optical interactions [1]. On the other hand, Ti:PPLN channels have very low losses down to 0.03 dB/cm. Their excellent homogeneity over a length of up to 90 mm enabled the development of very efficient quasi-phasematched quadratic nonlinear integrated optical devices for ultra-fast all-optical signal processing. (Simultaneous multi-) wavelength conversion, dispersion compensation, parametric amplification, λ-selective time division (de-) multiplexing, phase- and polarization-switching as well as spatial switching have been demonstrated [2].

Moreover, homogeneous nonlinear directional couplers and waveguide arrays with up to 100 coupled channels have been developed to demonstrate new all-optical switching concepts.

It is the aim of this contribution to review all-optical signal processing mainly in Ti:PPLN waveguide structures. Applications in the field of optical communications are emphasized.

2. WAVELENGTH CONVERSION

All-optical wavelength conversion based on quasi-phasematched quadratic nonlinear interactions in Ti:PPLN channel waveguides offers a large bandwidth or tuning range, respectively, quantum-limited noise, and ultra-fast response and operation speed. Second Harmonic Generation (SHG), Difference Frequency Generation (DFG), cascaded SHG and DFG (cSHG/DFG), Sum Frequency Generation (SFG), and cascaded SFG and DFG (cSFG/DFG) have been exploited for efficient λ-conversion.

In **cSHG/DFG** a strong fundamental wave at λ_f is used to generate via SHG a pump wave at $\lambda_p = \lambda_f /2$ to allow simultaneous DFG with a signal at λ_s (see Fig. 1).

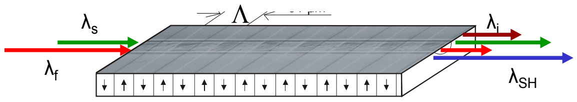

Figure 1: Scheme of cSHG/DFG in a Ti:PPLN waveguide; a periodicity Λ of about 17 µm is used for quasi-phase matched nonlinear interactions in the near infrared around 1550 nm wavelength.

By the second process a λ-converted signal - the idler wave - is generated at λ_i with $\lambda_i^{-1} = 2\lambda_f^{-1} - \lambda_s^{-1}$. As this process is accompanied by spectral inversion of the signal, it can also be used for mid-span dispersion compensation in fiber optical communication links. Moreover, simultaneous multi-wavelength conversion is possible. As an example, Fig. 2 presents on the left the simultaneous λ-conversion of the emission of two DFB lasers, of an extended cavity semiconductor laser (ECL) and of an actively mode-locked fiber laser (5 ps; 10 GHz) at ITU-wavelengths of 200 GHz channel spacing. 175 mW of fundamental power was fed to the input pigtail of the

Ti:PPLN wavelength converter of 16.6 µm domain periodicity operated at 188.5 °C. A conversion efficiency of –10dB was achieved in a spectral range of about 55 nm (FWHM) width [3].

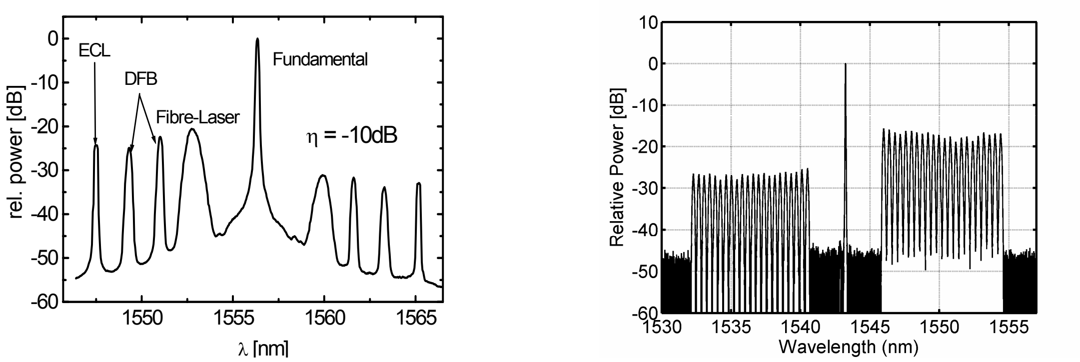

Figure 2: Output spectra of Ti:PPLN wavelength converters for multi-channel operation by cSHG/DFG (for details see text).

Polarization-independent operation was achieved by using polarization diversity in the same waveguide with the TM-(rotated TE-)component of the signal propagating to the right (left) together with counter-propagating pump waves in TM-polarization. Such a device was a key component in a field trial of the European IST-project ATLAS [4] and more recently in a 21.4 Gb/s (per channel) differential quadrature phase-shift keying (DQPSK) transmission experiments with 22 WDM channels over more than 10000 km [5]. In the latter experiment the polarization independent Ti:PPLN wavelength converter/phase conjugator was used in the middle of the span for compensation of chromatic dispersion and nonlinear impairments. Figure 2 shows on the right the output spectrum of the converter.

Even optically tunable λ-conversion could be demonstrated by exploiting **cSFG/DFG** [6]. Transform limited Gaussian signal pulses (λ_s) of 5 ps width are superimposed with two cw pump waves (λ_{p1}, λ_{p2}) and launched together into a 29 mm long channel guide of 16.6 µm micro-domain periodicity by fiber butt-coupling. The pulsed signal and the pump 1 (λ_{p1}) generate sum frequency pulses (λ_{sf}) perfectly phase matched. At the same time, the second pump 2 (λ_{p2}) interacts with the sum frequency wave (λ_{sf}) to generate λ-converted idler pulses (λ_i) by DFG. This process is slightly phase mismatched, but the conversion efficiency is hardly reduced in comparison to a phase matched interaction. The idler wavelength can be tuned by the wavelength of pump 2.

Fig. 3 shows as an example the optical spectra for two different wavelengths of pump 2, measured with 0.1 nm resolution after attenuation by about 7 dB. The power levels of both pump waves were controlled to be equal (~275 mW) resulting in a conversion efficiency from the (transmitted) signal to the generated idler of –4.7 dB. When the wavelength of pump 2 (λ_{p2}) was varied from 1533 nm to 1568 nm, the idler wavelength was tuned from 1559 nm to 1524 nm almost linearly. In this wavelength range, no significant change of the conversion efficiency was found. The theoretical calculation predicts a tuning range of more than 80 nm. There was a broadening of the idler pulses due to group velocity mismatch (3 ps/cm) of about 28 %.

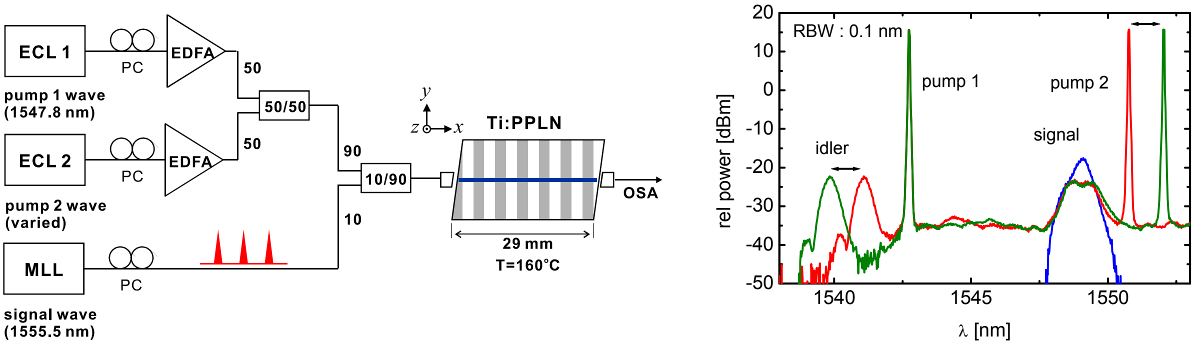

Figure 3: Output spectra showing all-optical tuning of the idler by the wavelength of pump 2 exploiting cSFG/DFG.

3. OPTICAL PARAMETRIC AMPLIFICATION

Cascaded difference frequency generation (cSHG/DFG) is always accompanied by optical parametric amplification (OPA) of the signal. Theory predicts that in PPLN waveguides a small signal gain larger than 30 dB can be achieved, high quality waveguides of sufficient length, negligible photorefractive effects and sufficient pump power assumed. Such parametric amplifiers would be attractive devices of quantum limited noise figures for future all-optical transparent communication networks. It is remarkable that the center wavelength of their gain characteristics with a spectral width of 50-70 nm can be adjusted by the period of the microdomain structure alone. As an example Fig. 4 presents on the left the calculated small signal gain in 80 mm and 160 mm long Ti:PPLN channel guides as function of the wavelength.

Experimentally, a cw-gain of up to 4 dB was observed in a 8.3 cm long structure with 765 mW coupled pump power (λ = 1558 nm). In a pulsed mode of operation (100 ns; 1 MHz) a gain of 12 dB was achieved with 1.3 W peak power (see Fig. 4 on the right). The measured gain is still considerably smaller than the predicted one.

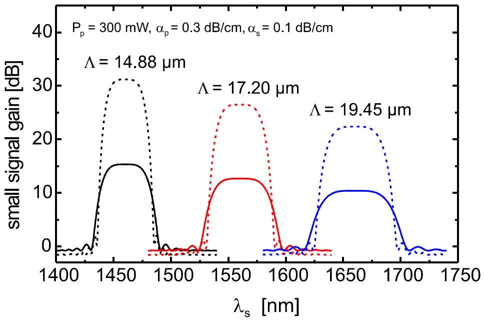

Figure 4: Calculated small signal gain as function of the wavelength for three different periodicities of the microdomain structure of Ti:PPLN channel guides of 80 mm (solid line) and 160 mm (dashed line) length.

4. WAVELENGTH-SELECTIVE TIME DIVISION DEMULTIPLEXING

The potential of ultrafast nonlinear optical interactions in Ti:PPLN waveguides can be fully exploited in a pulsed mode of operation. For example, demultiplexing of 10 Gbit/s OTDM-channels from a 4*10 Gbit/s data stream with simultaneous λ-conversion was demonstrated with 5 ps/40 GHz signal and 5 ps/10 GHz pump pulses based on cSHG/DFG [7]. It is remarkable, that two Ti:PPLN λ-converters have been used in the experiment (Fig. 5, left). The first one generated the λ-shifted pump pulses (5 ps/10 GHz; λ = 1554 nm) for the second, which is operated as difference frequency generator via cSHG/DFG. By an appropriate adjustment of the relative delay of signal and pump pulses a specific OTDM-channel can be demultiplexed (Fig. 5, right).

As another example selective OTDM-channel dropping was demonstrated exploiting SFG [8].

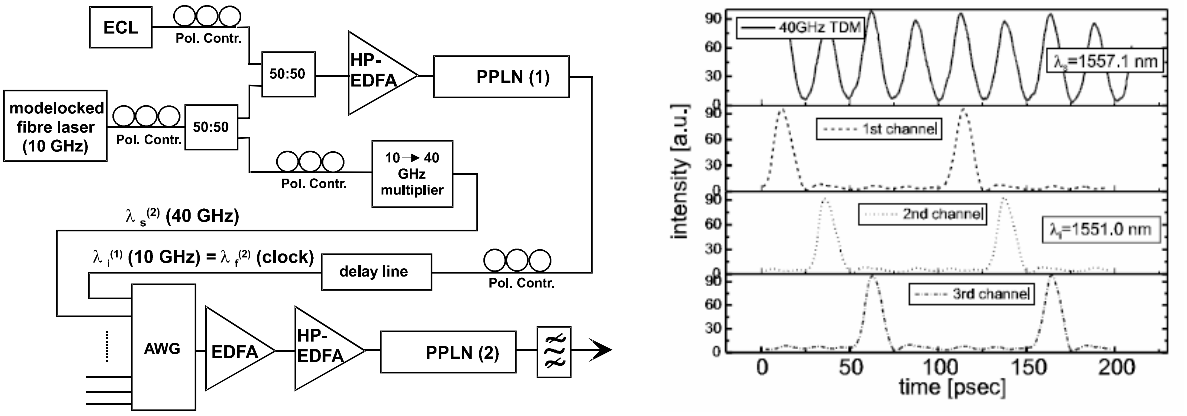

Figure 5: Left: Experimental setup to demonstrate demultiplexing of OTDM-channels with simultaneous wavelength conversion via cSHG/DFG. Right: Selective dropping of individual 10 GHz OTDM channels (lower traces) from the 40 GHz OTDM signal (upper trace).

5. ALL-OPTICAL SWITCHING

A π-phase shift is imposed to a signal by cSFG/DFG at high pump power levels after full signal depletion by SFG and regeneration by DFG. This process can be used to switch optically the phase of the signal; it is wavelength selective due to phase matching. cSFG/DFG was investigated in a polarisation interferometer using a Ti:PPLN waveguide as polarisation and wavelength selective phase switch. By controlling the input polarisation a polarisation rotation was achieved at the output with a pump power of 1120 mW. Using a polarisation beam splitter even spatial switching could be achieved with an extinction ratio of -20.2 dB [9]. Fig. 6 shows as an example wavelength selective switching of a signal at λ = 1554 nm from output channel 1 to output channel 2.

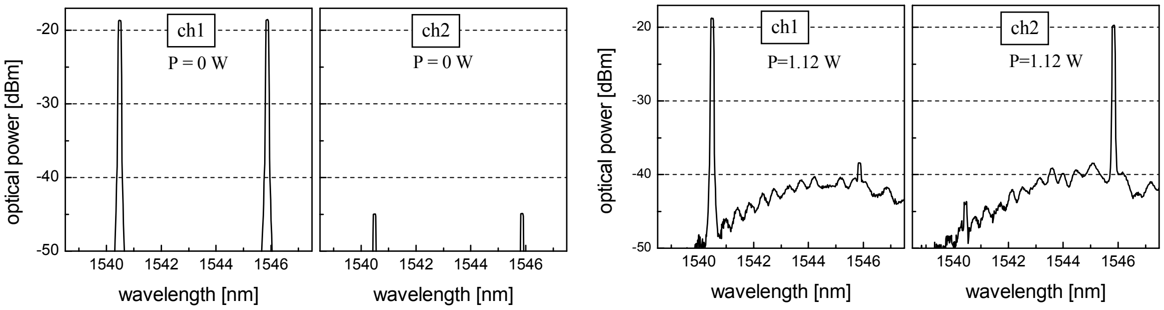

Figure 6: Wavelength-selective switching by exploiting cSFG/DFG in a Ti:PPLN waveguide. An optically induced phase shift of π leads to polarisation rotation exploited in a polarisation interferometer (see also text).

Moreover, all-optical spatial switching by DFG has been demonstrated in two-core Ti:PPLN directional couplers [10]. They are the basic modules of Ti:PPLN waveguide arrays with up to 101 coupled channels. Taking advantage of the unique diffractionless beam propagation in waveguide arrays [11] signal and generated idler can be switched by DFG with a control (pump) beam to different output positions of a waveguide array [12]. A signal is launched into several neighboring channels with a well-defined phase difference of π/2 thereby crossing the array at a certain angle as a diffractionless propagating beam. A high power control (pump) beam of approximately half the wavelength is launched into a single waveguide of the array propagating as strongly confined fundamental mode with negligible coupling to neighboring channels. At the intersection of signal and pump beams phase-insensitive parametric interaction results in both, amplification of the transmitted signal and generation of a deflected signal as well as of a frequency shifted transmitted and a deflected idler. The experimental results show good agreement with the theoretical predictions.

6. CONCLUSIONS

A variety of efficient nonlinear integrated optical devices for all-optical signal processing (wavelength conversion, parametric amplification, time division multiplexing, and all-optical switching) has been reviewed. They consist of Ti:PPLN waveguide structures (channels, directional couplers and waveguide arrays) of high effective nonlinearity and very low propagation losses. In the future longer (bent) waveguides will allow lower pump power levels.

ACKNOWLEDGEMENTS

We gratefully acknowledge partial support by the Deutsche Forschungsgemeinschaft (DFG) within the frame of the Paderborn research unit “Integrierte Optik in Lithiumniobat” and by the European Commission within the IST-program (projects ATLAS and ROSA).

REFERENCES

[1] J. Kurz et al., Proc. Contemporary Photonics Technology (CPT 2003), pp. 93-94, (2003)
[2] W. Grundkötter et al., Proc. European Conf. on Integrated Optics (ECIO`03), Prague, April 2003, vol **2**, invited lectures, pp. 143-152
[3] G. Schreiber et al., Appl. Phys. B **73** (2001), 501-504
[4] D. Caccioli et al., IEEE J. Select. Topics Quantum Electron. vol. **10,** no 2, pp. 356-362 (2004)
[5] S. L. Jansen et al., J. Lightwave Technol., vol. **24**, no.1, pp 54-64 (2006)
[6] Y. H. Min et al., Techn. Digest OFC 2003, FP4, vol **2**, pp. 767-768 (2003) and Y. H. Min et al., Proc. Coference Lasers and Electro-Optics (CLEO/Europe 2003), Munich, June 2003, paper EE2-2-WED
[7] H. Suche et al., Techn. Digest Int. Top. Meeting on Photonics in Switching (PS`02), July 2002, Jeju/Korea, pp.34-36 (invited)
[8] Y. L. Lee et al., IEEE Photon. Technol. Lett., vol. **15**, pp. 978-980 (2003)
[9] J.H. Lee et al., Proc. 11th European Conference on Integrated Optics (ECIO '03), Prague,April 2003, vol. **1**, p. 101
[10] R. Schiek et al., Appl. Phys. Lett., vol. **87**, 011109 (2005)
[11] T. Pertsch et al., Phys. Rev. Lett., vol. **88**, 093901 (2002)
[12] T. Pertsch et al., Optics Lett., vol. 30, no. 2, pp 177-179 (2005)