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ALL OPTICAL SIGNAL PROCESSING IN PERIODICALLY POLED TI:LINBO$_3$ CHANNEL GUIDES

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Abstract – *Quasi phasematched second order nonlinear optical interactions in periodically poled LiNbO$_3$ waveguides are exploited to develop efficient integrated optical devices for all-optical wavelength conversion, parametric amplification, time division (de-)multiplexing, phase- and polarisation-switching.*

INTRODUCTION

During the last years optical channel guides of excellent quality have been developed in Periodically Poled Lithium Niobate (PPLN), using the two most important waveguide fabrication methods – (annealed) proton exchange (APE) and Ti-indiffusion. APE:PPLN guides usually have a somewhat smaller cross-section, yielding a higher (normalized) efficiency of nonlinear optical interactions. Furthermore, their susceptibility to optically induced changes of the index of refraction is lower. On the other hand, Ti:PPLN channels can have very low losses down to 0.03 dB/cm in the mid infrared, where a strong OH-absorption (around λ=2.7 µm) limits the potential of APE-structures. The excellent homogeneity of Ti:PPLN guides of a length of up to 90 mm even allowed the development of waveguide arrays with up to 100 coupled channels. Moreover, in contrast to APE, Ti-indiffusion is compatible with Erbium (diffusion) doping; no lifetime reduction of the upper laser level is observed. As a consequence, Ti:Er:PPLN structures can be developed with a combination of integrated optical amplifiers and lasers with quasi phasematched nonlinear devices even in the same waveguide.

Optical channel guides in PPLN enabled the development of very efficient quasi phasematched quadratic nonlinear integrated optical devices for ultrafast all-optical signal processing. (Simultaneous multi-) wavelength conversion, dispersion compensation, parametric amplification, λ-selective time division (de-)multiplexing, phase- and polarisation-switching as well as spatial switching have been demonstrated [1,2]. Applications are mainly in the field of optical communications, but also in the field of optical instrumentation.

It is the aim of this contribution to review all-optical signal processing mainly in Ti:PPLN channel guides.

WAVELENGTH CONVERSION AND SPECTRAL INVERSION

All-optical wavelength conversion based on quadratic nonlinear interactions in Ti:PPLN channel waveguides offers a broad bandwidth or tuning range, respectively, quantum-limited noise, and ultrafast response and operation speed. Second Harmonic Generation (SHG), Difference Frequency Generation (DFG), cascaded DFG (cDFG), Sum Frequency Generation (SFG), and cascaded SFG and DFG (cSFG/DFG) have been exploited for efficient λ-conversion not only in optical communications in the near infrared (NIR), but also in spectroscopic analysis in the mid infrared (MIR) spectral range. Two examples are presented in the following.

λ-Conversion by cascaded Difference Frequency Generation (cDFG)

In cDFG 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. 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. 1(left) presents the simultaneous λ-conversion of the emission of two DFB lasers, of an extended cavity semiconductor laser (ECL) and of an actively mode-locked fibre 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 ^{o}C. A conversion efficiency of –10dB was achieved in a spectral range of about 55 nm (FWHM) width [3]. Even polarisation-independent operation was successfully demonstrated by the European IST-project ATLAS in a field trial of a 4 times 40 Gbit/s WDM-transmission over 500 km. It was achieved by using polarisation diversity in the same waveguide with the TM-(rotated TE-)component of the signal propagating to the right (left) accompagnied by counterpropagating fundamental (pump) waves in TM-polarisation [4].

Tunable λ-Conversion Exploiting cascaded Sum and Difference Frequency Generation (cSFG/DFG) [5]

Even optically tunable λ-conversion could be demonstrated by exploiting cSFG/DFG. 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 5.5 cm long channel guide of 16.6 µm microdomain 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. 1(right) 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 %.

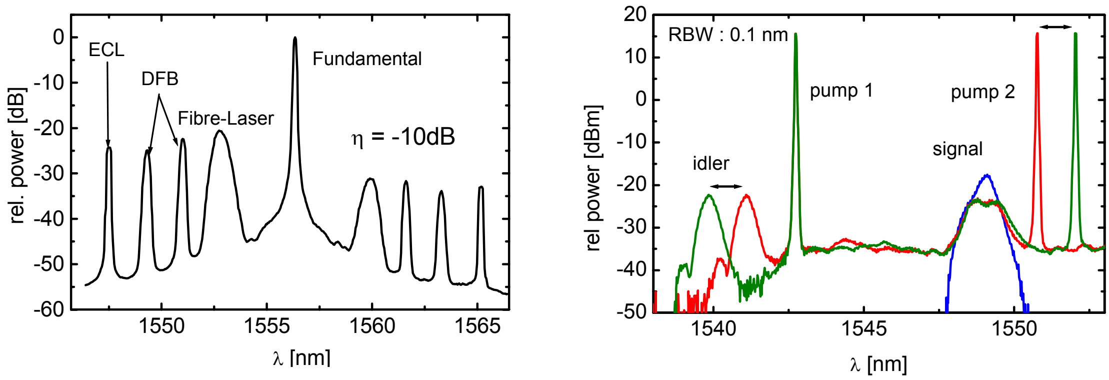

Fig. 1. (left) Output spectrum of a Ti:PPLN wavelength converter for multi-channel operation by cDFG. (right) Output spectra showing all-optical tuning of the idler by the wavelength of pump 2 exploiting cSFG/DFG.

OPTICAL PARAMETRIC AMPLIFICATION

Cascaded difference frequency generation (cDFG) 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. 2 presents the calculated small signal gain in 80 mm and 160 mm long Ti:PPLN channel guides as function of the wavelength.

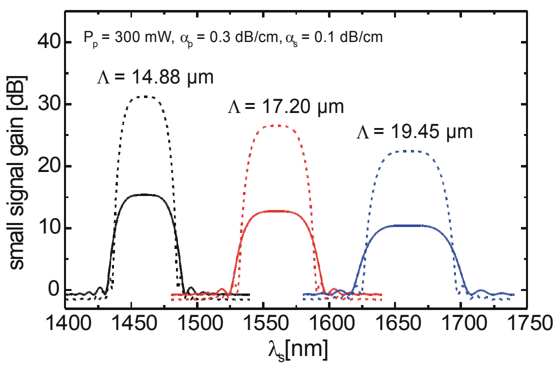

Fig. 2. Calculated small signal gain as function of the wavelength for three different periodicities of the microdomain structure of Ti:PPLN channel guides of 80 mm (solid line) and 160 mm (dashed line) length.

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). To reduce photorefractive effects the device was operated at 195 °C . In a pulsed mode of operation (5 ps; 10 GHz) a gain of 11.5 dB was achieved with 325 mW average power [2]. The measured gain is still considerably smaller than the predicted one; the causes of this behavior are currently explored.

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 fundamental (pump) pulses based on cDFG [6]. Another example is presented in Fig. 3 exploiting SFG for selective OTDM-channel dropping [7]. It is remarkable, that in the experimental setup (Fig. 3, left) two Ti:PPLN λ-converters have been used. The first one generated the λ-shifted pump pulses (5 ps;10 GHz), whereas the second converter served as sum frequency generator. By an appropriate adjustment of the relative delay of signal and pump pulses a specific OTDM-channel can be dropped (Fig. 3, right).

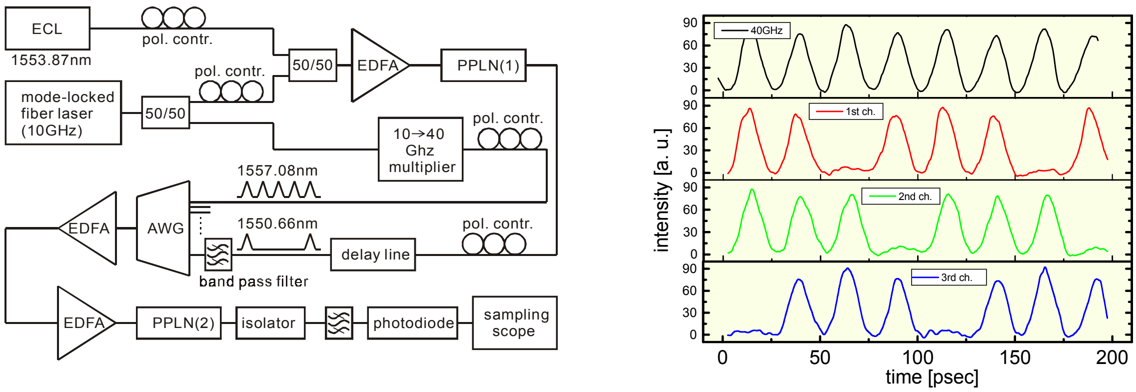

Fig. 2. (left) Experimental setup to demonstrate selective OTDM-channel dropping by SFG. (right) Selective dropping of individual 10 GHz OTDM channels (lower traces) from the 40 GHz OTDM signal (upper trace).

ALL OPTICAL PHASE- AND POLARISATION-SWITCHING

All-optical wavelength selective polarisation switching was demonstrated in a polarisation interferometer with a Ti:PPLN waveguide exploiting the π-phase shift of a signal induced by cSFG/DFG at a pump power level of 1120 mW. Using a polarisation beam splitter even spatial switching could be achieved. The extinction of the signal was measured to be –19.8 dB [8]. This scheme can be easily extended to an all-optical 2x2 spatial switch.

CONCLUSIONS

A variety of efficient integrated optical devices with Ti:PPLN channel guides has been presented for ultrafast all-optical signal processing. Applications are mainly in the field of optical communications. By developing more complex waveguide structures (e.g. waveguide arrays) with application specific engineered ferroelectric domain gratings further signal processing functions will become possible.

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