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All-Optical Signal Processing in Periodically Poled $LiNbO_3$ Waveguide Structures

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Abstract *Quasi-phasematched second order nonlinear optical interactions in periodically poled Ti:$LiNbO_3$ channel waveguides, directional couplers and waveguide arrays are exploited to develop efficient all-optical wavelength converters, parametric amplifiers, time division (de-) multiplexers, and space-, phase-, and polarisation-switches.*

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 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 [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 channel guides, but also in directional couplers and waveguide arrays. Applications in the field of optical communications are emphazised.

Wavelength conversion

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 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).

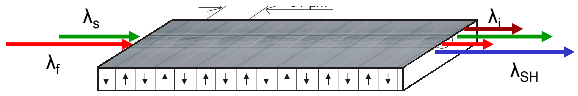

Fig. 1: Scheme of cSHG/DFG in a Ti:PPLN waveguide; a periodicity of about 17 µm is used for phase matched nonlinear interactions in the NIR.

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 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 °C. A conversion efficiency of –10dB was achieved in a spectral range of about 55 nm (FWHM) width [3].

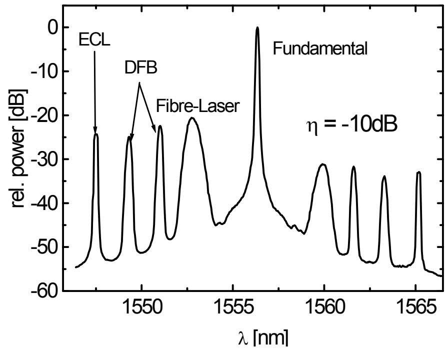

Fig. 2: Output spectrum of a Ti:PPLN wavelength converter for multi- channel operation by cSHG/DFG.

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 (see Fig. 3) [4].

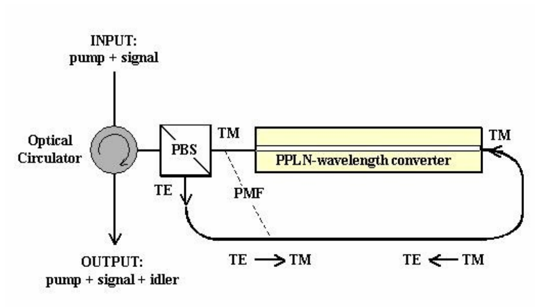

Fig. 3: Polarization independent Ti:PPLN wavelength converter.

One WDM-channel at λ = 1554.1 nm was demultiplexed after 300 km, wavelength converted in the Ti:PPLN device to λ = 1560.6 nm, amplified and multiplexed again into the fiber. Fig. 4 shows the spectra before and after wavelength conversion, demonstrating error free (BER < 10^{-13}) transmission with almost no penalty (< 0.5 dB).

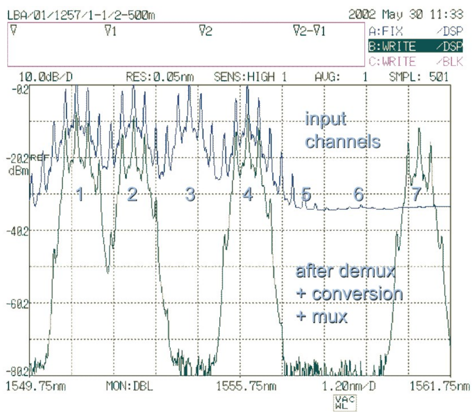

Fig. 4: Spectra before and after wavelength conversion of one out of four 40 Gbit/s channels of the Rome-Pomezia field trial of the European ATLAS-project.

Even optically tunable λ-conversion could be demonstrated by exploiting **cSFG/DFG** [5]. 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. 5 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 %.

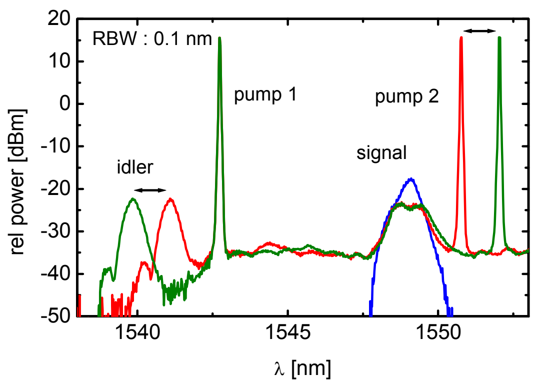

Fig. 5: Output spectra showing all-optical tuning of the idler by the wavelength of pump 2 exploiting cSFG/DFG.

Optical parametric amplification

Cascaded difference frequency generation (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. 6 presents 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 (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.

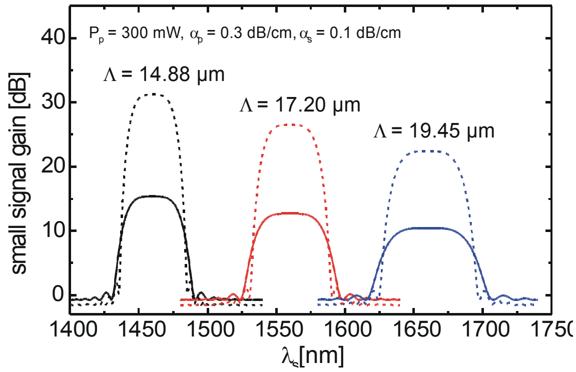

Fig. 6: Calculated small signal gain as function of the wavelength for three different periodicities of the microdomain structure of Ti:PPLN channel guides of 80 mm (solid line) and 160 mm (dashed line) length.

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 cSHG/DFG [6]. It is remarkable, that in the experimental setup (Fig. 7) 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 difference frequency generator. By an appropriate adjustment of the relative delay of signal and pump pulses a specific OTDM-channel can be demultiplexed (Fig. 8).

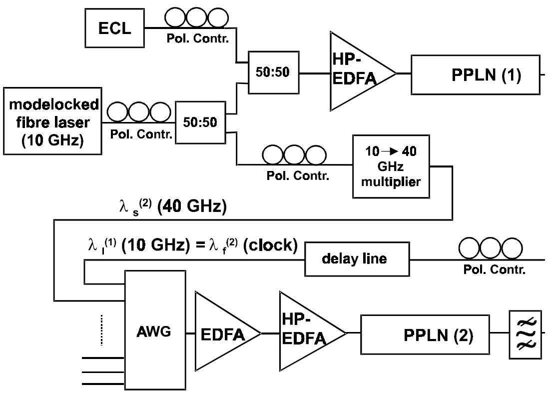

Fig. 7: Experimental setup to demonstrate demultiplexing of OTDM-channels with simultaneous wavelength conversion.

As another example selective OTDM-channel dropping was demonstrated exploiting SFG [7].

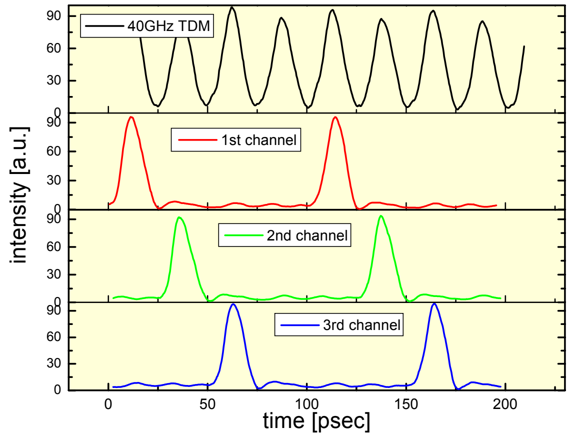

Fig. 8: Selective dropping of individual 10 GHz OTDM channels (lower traces) from the 40 GHz OTDM signal (upper trace).

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 [8]. Fig. 9 shows as example wavelength selective switching of a simulated WDM channel.

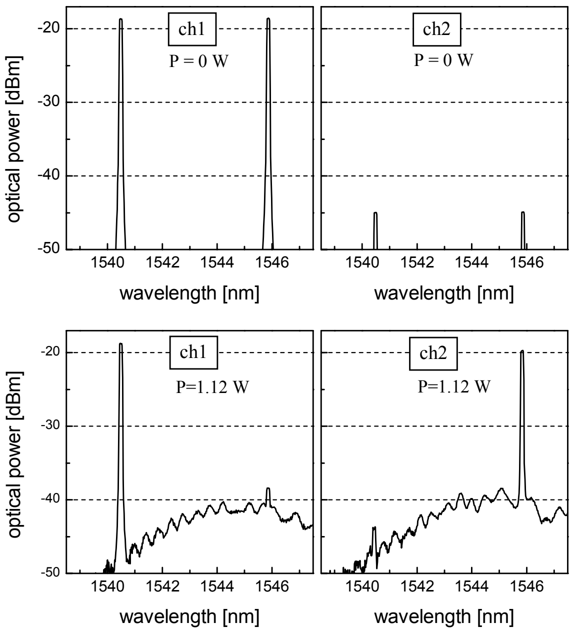

Fig. 9: Wavelength-selective switching by exploiting cSFG/DFG in a Ti:PPLN waveguide. An optically induced phase shift of π leads to polarisation rotation exploited in a polarisation interferometer.

Moreover, all-optical spatial switching by DFG in two-core Ti:PPLN directional couplers was demonstrated. They are the basic modules of Ti:PPLN waveguide arrays with up to 101 coupled channels (see Fig. 10)

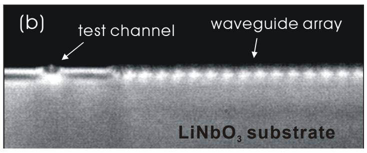

Fig. 10: Polished end face of a waveguide array of 101 coupled, single mode channel guides (only 15 neighboring channels are displayed).

Taking advantage of the unique diffractionless beam propagation in waveguide arrays [9] signal and generated idler can be switched by DFG with a control (pump) beam to different output positions of a waveguide array [10]. The schematical arrangement is shown in Fig. 11. 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.

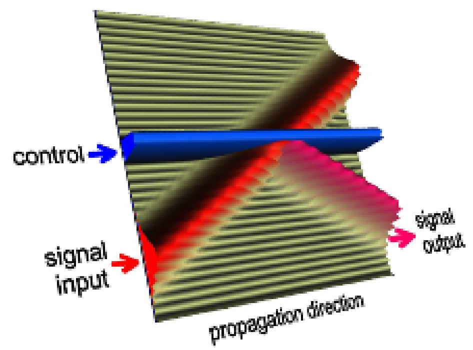

Fig. 11: Schematical diagram of parametric interaction in a waveguide array (see also the text).

Fig. 12 shows as an example the idler intensity distribution measured at the output face. About 8 channels have been excited by the signal at the input face (λ = 1550.7 nm). By DFG with the control beam (λ = 774.4 nm) two idler beams (λ = 1546.7 nm) are generated; one travels parallel to the transmitted signal beam, the other one is deflected under a small angle. The experimental results show a good agreement with the theoretical predictions.

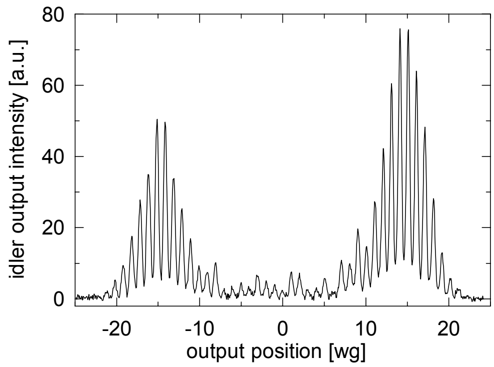

Fig. 12: Idler intensity distribution measured at the output face.

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 yield even higher device efficiencies. The power handling capabilities will be improved by using MgO-doped substrates. Moreover, nonlinear waveguides with engineered ferroelectric microdomains can also be developed in PPLN, which is doped by laser-active ions such as Erbium. This will allow to combine nonlinear devices, amplifiers, and lasers even in the same waveguide and to realise in this way a whole bunch of new all-optical functions.

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