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Nonlinear Integrated Optics with Periodically Poled Waveguides in $LiNbO_3$

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The recent development of nonlinear integrated optics with waveguides in periodically poled $LiNbO_3$ (PPLN) is reviewed. Besides a whole family of near- and mid-infrared quasi-phase matched parametric frequency converters of excellent efficiency also devices for ultrafast all-optical signal processing are presented.

Keywords: nonlinear integrated optics, $LiNbO_3$, PPLN, SHG, SFG, DFG, OPA, OPF, OPO

Introduction

The advent of the electric field poling method to fabricate periodically poled, ferroelectric, nonlinear optical materials resulted in a renaissance of nonlinear optics. Since then quasi-phase matching has been used for efficient wavelength conversion in devices like frequency doublers, difference frequency generators (DFG) and optical parametric oscillators (OPO). Periodically poled Lithium Niobate (PPLN) proved to be not only one of the best materials for nonlinear bulk optics, but also the most attractive and suitable substrate material for nonlinear integrated optics. It is commercially available as high quality mono crystalline wafer of a diameter of up to 5" and has large nonlinear coefficients. Moreover, the electric field assisted poling technique is compatible with the two most important waveguide fabrication methods – (annealed) proton exchange and Ti-indiffusion. The development of nonlinear integrated optical devices did not only result in a considerable inprovement of device efficiency and stability in comparison with bulk frequency converters; also all-optical ultrafast functions like time-domain multiplexing, polarisation conversion, switching and sampling could be demonstrated with significantly reduced power levels (see e.g. [1]).

It is the aim of this tutorial to review the recent development of nonlinear integrated optics with waveguides in PPLN. The relevant microfabrication technologies are described as well as the poling technique to generate ferroelectric microdomain structures in $LiNbO_3$ (LN) of different crystalline orientation. Advanced microscopic and spectroscopic methods are used for the characterization of these structures.

It is of particular interest to fabricate microdomain structures also in Erbium-doped optical waveguides. This possibility allows to combine integrated optical amplifiers and lasers with quasi-phase matched nonlinear devices in the same structure. Self-frequency doubling lasers and amplifying difference frequency generators are corresponding examples.

Very long (up to 90 mm) waveguides have been developed in PPLN for the visible, near- (NIR, 1 $\mu m < \lambda < 2$ μm) and mid- (MIR, 2 $\mu m < \lambda < 5$ μm) infrared spectral ranges. They enabled the development of efficient second harmonic generators (SHG), sum- (SFG) and difference frequency generators (DFG), optical parametric amplifiers (OPA) as well as singly and low-threshold doubly resonant optical parametric oscillators (OPO) for different spectral ranges. Corresponding examples will be presented. The combination of harmonic generation and simultaneous difference-frequency generation led to the development of cascaded-difference frequency generators (cDFG) with more than 100 % efficiency and simultaneous parametric amplification. Moreover, spontaneous parametric fluorescence is used for the generation of entangled photon pairs, whereas stimulated optical parametric fluoresence (OPF) might become a useful source for widely tunable radiation.

Waveguide Fabrication and Characterisation

The two most popular techniques to fabricate waveguides in LN are the annealed proton exchange (APE) and the Ti-indiffusion. Both are used to get waveguides in PPLN. Usually APE-waveguides are fabricated in a (Z-cut) PPLN substrate, i.e. after the periodic domain inversion. They allow the propagation of an extraordinary wave (a TM-mode in Z-cut LN) only, as the APE increases the extraordinary, but lowers the ordinary index of refraction. APE-waveguides have a strong and broad absorption band around 2.7 µm wavelength, due to OH-vibrations. Therefore, they are mainly used for applications in the NIR and visible spectral ranges.

To fabricate Ti:PPLN waveguides, photolithographically defined Ti-stripes on the surface of a single domain Z-cut LN wafer are indiffused at high temperatures (e.g. 8.5 hrs @ 1060 °C). Afterwards, substrate and waveguide are poled together. Modes of both polarisations can be guided in Ti:PPLN channels (see also Fig. 1). They have very low losses (down to ~0.03 dB/cm) without the strong OH-absorption and can therefore be used in the MIR as well. However, their susceptibility to photorefractive effects is higher than that of APE-waveguides. Besides planar and channel guides also directional couplers and waveguide arrays have been developed as Ti:PPLN structures.

Ti:PPLN waveguides can also be fabricated in an Er-doped substrate to take advantage of the internal optical gain by optically pumped Er-ions. This effect cannot be exploited in APE-guides as the proton exchange reduces the lifetime of the upper laser level drastically (see e.g. [2]).

By preferential etching of the surface the microdomain structure can be made visible (see Fig. 1). It can also be investigated by scanning SH-microscopy and spectroscopy of the Er-states in the domain walls.

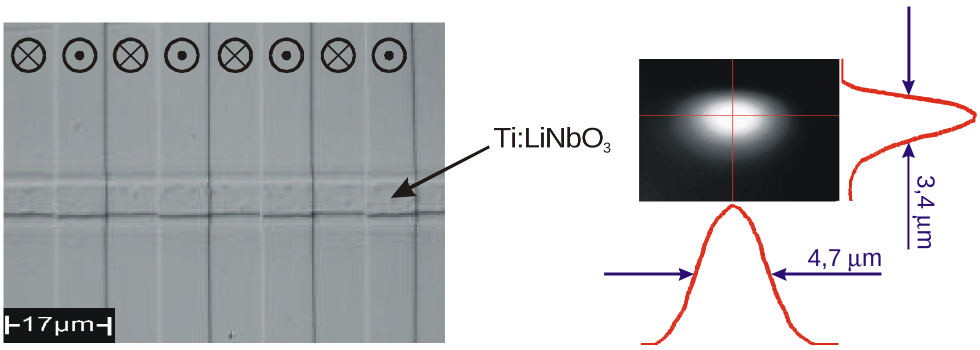


Fig. 1. left: Microphotograph of a selectively etched surface of a periodically poled sample with channel waveguides; the orientation of the optical axis of the different microdomains is indicated; right: TM polarized near field intensity distribution of a waveguide mode at about 1530nm wavelength.

Second Harmonic Generation (SHG)

Second Harmonic Generation (SHG) has been demonstrated in APE-PPLN as well as in Ti:PPLN waveguides with efficiencies exceeding 1%/mW. Its most important application is the generation of blue radiation using semiconductor lasers as fundamental source. The SHG-characteristic, i.e. SH-power as function of the fundamental wavelength, can also be used to assess the homogeneity of a nonlinear optical waveguide. By comparing the experimental response with the simulated one an effective interaction length can be derived which approaches the physical waveguide length in samples of best homogeneity of ferroelectric domain structure and effective index of refraction. Fig. 2 presents as example the SHG-characteristic of a nearly ideal, 55 mm long Ti:PPLN channel guide.

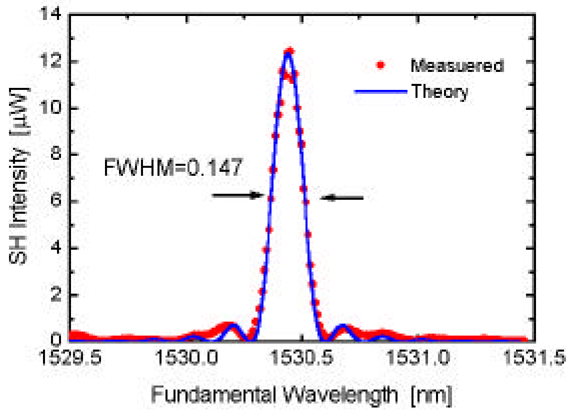


Fig. 2. SHG power vs. fundamental wavelength measured in a 55 mm long Ti:PPLN channel guide.

Self-Frequency Doubling Laser [3]

The combination of quasi phase-matched frequency conversion in amplifying or even laser active waveguides allows to develop a variety of new integrated optical devices. As an example a self-frequency doubling laser is described taking advantage of intracavity SHG in a periodically poled, Er-doped Ti:$LiNbO_3$ channel guide.

The experimental setup is schematically shown in Fig. 3.

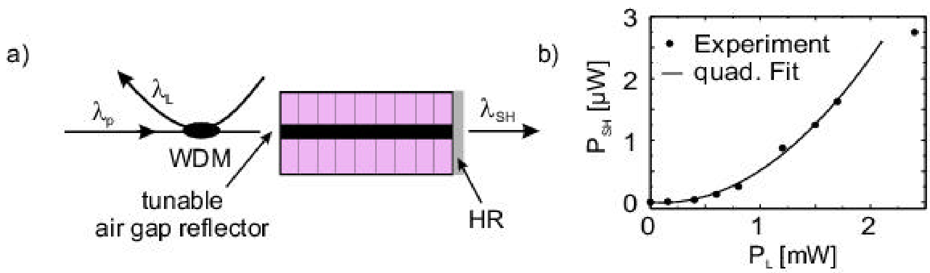


Fig. 3. a) Schematical setup for the investigation of intracavity self-frequency doubling in a periodically poled Ti:Er:$LiNbO_3$ laser. b) Measured second harmonic power as function of the laser output power at λ_L = 1531 nm.

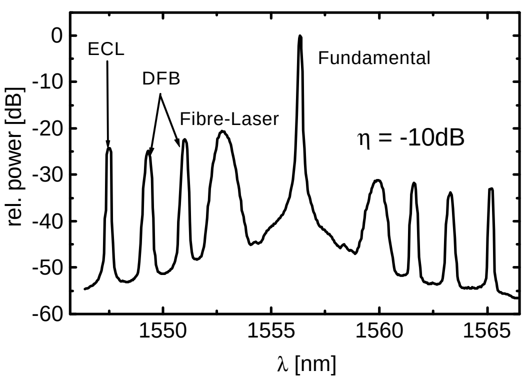
A fiber-optic wavelength division multiplexer (WDM) is used to couple up to 135 mW of pump radiation of a high power semiconductor laser diode at 1480 nm center wavelength into the Ti:Er:$LiNbO_3$ waveguide resonator. The input mirror is a tunable, low finesse Farby-Perot etalon, formed by the end face of the optical fiber and the polished, uncoated front face of the waveguide. The fiber is mounted on a piezo-driven translator allowing to adjust the thickness of the air gap and in this way the effective (wavelength dependent) reflectivity of the etalon between 5 % and 30 % ("tunable air gap reflector"). Due to its wavelength dependence the preferred laser wavelength can be selected among emission at λ_L = 1531 nm, 1546 nm, 1575 nm and 1602 nm. The output mirror is a dielectric multilayer (12 layers) high reflector (HR) vacuum-deposited on the polished rear waveguide end face with a broadband reflectivity of > 95 % in the wavelength range 1480 nm < λ < 1800 nm. Around 765 nm wavelength the mirror transmission was high, exceeding 80 %.

To get quasi-phase-matched SHG in the periodically poled (Λ = 17 µm) waveguide at room temperature the laser emission wavelength has to be adjusted to λ_L = 1531 nm. In this configuration the laser threshold is at 87 mW coupled pump power. Due to waveguide losses the slope efficiency is poor allowing only up to 2.4 mW of output power. Simultaneously, frequency doubled radiation at λ_{SH} = 765.5 nm is generated and emitted in both, forward and backward directions. Up to 2.7 ìW of SH-power was measured in forward direction with a quadratic dependence on the fundamental laser power (see Fig. 3). By using a narrow bandwidth fiber Bragg grating of high reflectivity instead of the “air gap reflector” up to 20 µW of SH-power has been observed. Nevertheless, there is still a large potential for a further improvement of this type of integrated self-frequency doubling laser.

(Cascaded) Difference Frequency Generation (cDFG) [4]

In cDFG a strong fundamental wave at λ_f is used to generate via SHG a pump wave at $\lambda_p = \lambda_f /2$. Simultaneously, this pump wave interacts with a signal wave at λ_s to generate an idler wave at λ_i with $\lambda_i^{-1} = 2\lambda_f^{-1} - \lambda_s^{-1}$. cDFG in PLLN waveguides proved to be very attractive for several applications in optical communications such as wavelength conversion, dispersion compensation, all-optical switching, but also for spectroscopy in the mid infrared (MIR) spectral range.

As an example, Fig. 4 presents simultaneous multi-wavelength 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 pulses at 10 GHz repetion rate) at ITU-wavelengths. The amplified fundamental and the signal radiation(s) were multiplexed using an arrayed waveguide grating (AWG) of 200 GHz channel spacing with about 3dB insertion loss. 175 mW of fundamental power and 10 mW of signal power were fed to the input pigtail of the Ti:PPLN-wavelength converter operated at 188.5°C. The TM-polarization was adjusted using polarization controllers. A conversion efficiency of –10dB was achieved. By switching individual signal channels on and off no measurable change of the efficiency was observed. There was also no difference in conversion efficiency for cw- and pulsed channels. The conversion bandwidth is about 55 nm (FWHM).



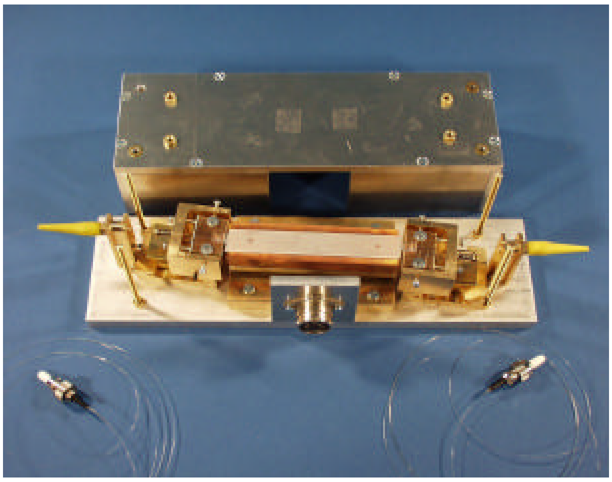


Fig. 4. (left) Output spectrum of the Ti:PPLN-wavelength converter for multi-channel conversion; (right) Packaged and fiber-pigtailed device, allowing high temperature operation.

The excellent performance of this device enabled a transmission experiment using wavelength-converted data from a 4×10Gbit/s OTDM-transmitter as signal at 1561.1 nm wavelength. This experiment was done within the IST-ATLAS project in cooperation with Pirelli Labs., Milano. No BER-penalty between the back-to-back measurements of the converted and unconverted data was observed. After 500 km the penalty at BER=10^{-13} remained below 1dB for both, the converted and unconverted channel.

Optical Parametric Amplification (OPA) [5]

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 photo-refractive 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. 5 presents the calculated small signal gain in 80 mm and 160 mm long Ti:PPLN waveguides as function of the wavelength.

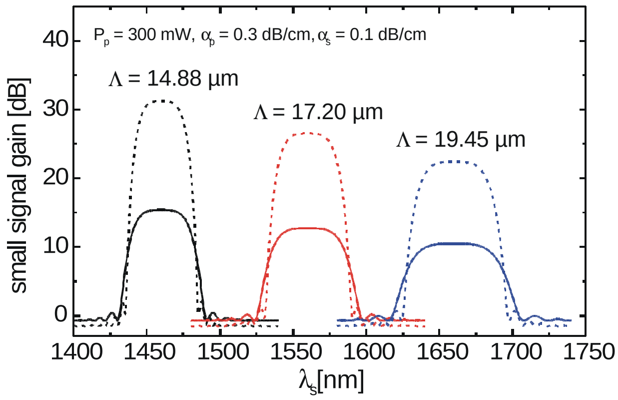


Fig. 5. Calculated small signal gain as function of the wavelength for three different periodicities of the microdomain structure; solid and dashed lines indicate the results for 80 mm and 160 mm long waveguides.

Experimentally, a cw-gain of up to 4 dB was observed in a 8.3 cm long s tructure with 765 mW coupled pump power (λ = 1558 nm). To reduce photorefractive effects the device was operated at 195 °C . If operated in a pulsed mode with 5 ps pulses at 10 GHz repetition rate a gain of 11.5 dB

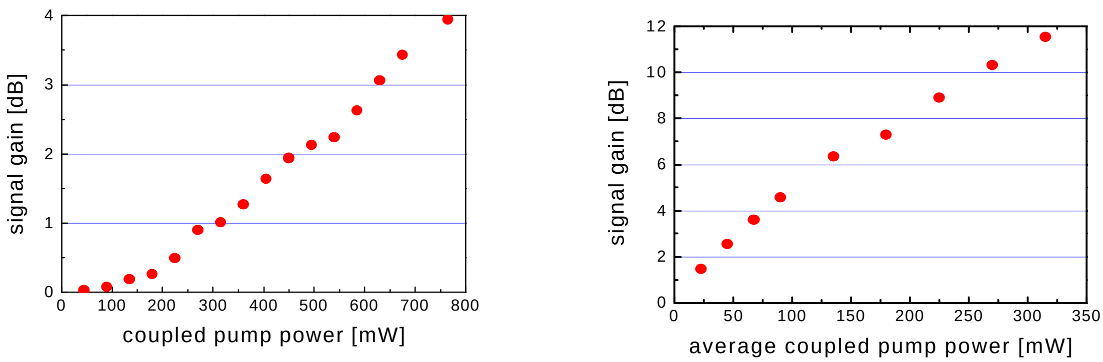


Fig. 6. Measured parametric gain as function of the coupled pump power at ë = 1558.5 nm for (left) cw and (right) pulsed pumping (5 ps; 10 GHz repetition rate). $ë_s$ = 1552.4 nm.

was achieved at 325 mW average power (see Fig. 6). The measured gain is still considerably smaller than the predicted one; the causes of this behavior are currently explored.

Cascaded Sum and Difference Frequency Generation (cSFG/DFG) [6]

Among various wavelength conversion schemes proposed, all-optical wavelength conversion based on cascaded sum and difference frequency generation (cSFG/DFG) in a Ti:PPLN channel waveguide is especially promising. It offers a broad tuning range, low spontaneous emission noise, and ultrafast operation speed.

The principle of operation is shown in Fig. 7. Transform limited gaussian signal pulses (λ_s) of 5 ps width are superimposed with two cw pump waves (λ_{p1}, λ_{p2}) by a 10/90 coupler and launched together into the 5.5 cm long channel guide of 16.6 µm microdomain periodicity by fiber butt-coupling. The pulsed signal and the pump (λ_{p1}) generate sum frequency pulses (λ_{sf}) perfectly phase matched. At the same time, a second pump (λ_{p2}) interacts with the sum frequency wave (λ_{sf}) to generate idler pulses (λ_i) by DFG. This process is slightly phase mismatched, but the conversion efficiency is only slightly reduced in comparison to a phase matched interaction. The idler wavelength can be tuned by the wavelength of the second pump.

Fig. 7 shows the optical spectra for two different wavelengths of the second pump, measured with 0.1 nm resolution. The power levels of both pump waves were controlled to be equal (~275 mW); the coupled power of the signal was 1.6 mW. The conversion efficiency from the (transmitted) signal to the generated idler was measured to be –4.7 dB. When the wavelength of the second pump (λ_{p2}) was varied from 1533 nm to 1568 nm, the idler wavelength was tuned from 1524 nm to 1559 nm almost linearly. In this wavelength range, no significant change of the conversion efficiency was found. The theoretical calculation predicts a very wide tuning range of more than 100 nm. There is a broadening of the idler pulses due to group velocity mismatch (3 ps/cm) of about 28 %.

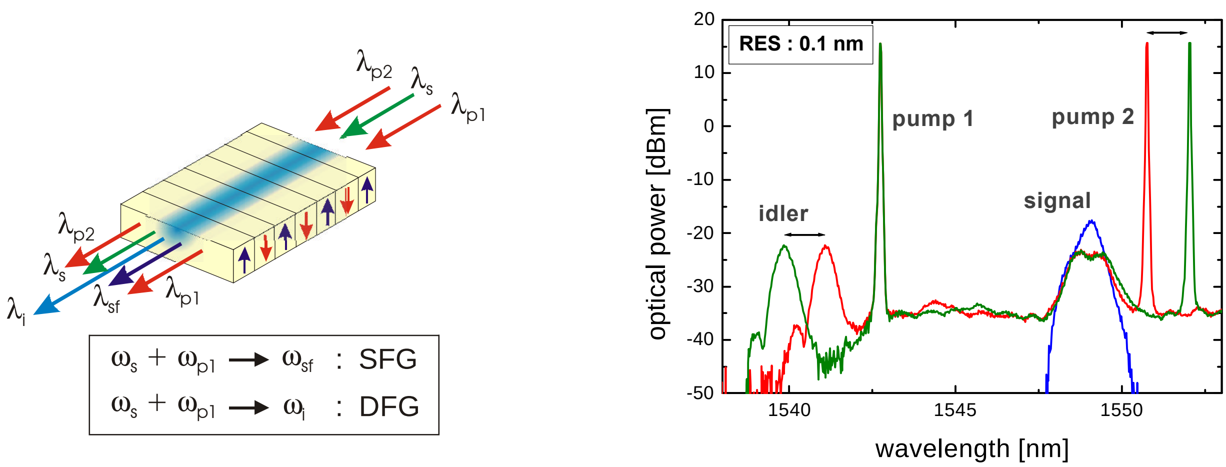


Fig. 7. (left) Schematic diagram of cSFG/DFG in a Ti:PPLN channel waveguide and (right) optical spectra of signal and idler showing the tuning of the idler by changing the wavelength of pump 2.

Optical Parametric Fluorescence (OPF) [7]

Optical Parametric Fluorescence (OPF) results from the spontaneous decay of pump photons into signal- and idler-photons by the influence of the zero-point fluctuations of the electromagnetic vacuum field. This process, which is described by energy- and wave-vectors conservation, can be stimulated and exploited to generate widely tunable radiation without the need of resonant structures. The spectral bandwidth of the emission strongly depends on parameters like pump wavelength, pump power and interaction length. Nonlinear waveguides are very attractive devices to generate in particular stimulated OPF because of the high intensity of the guided pump wave and the very long interaction lengths possible.

Fig. 8 shows as an example the tuning characteristics of the signal and idler waves generated in an 18 µm wide waveguide of 31.36 µm domain periodicity. The coupled (cw) pump power was approximately 300 mW. The MIR-OPF was continuously tunable from 2760 to 3000 nm (signal) and from 3360 to 3450 nm (idler). A gap remained near degeneracy due to the limited tuning range of the pump source. Moreover, selected spectral characteristics are given as insets; they all have one pronounced sidelobe, probably due to waveguide inhomogeneities. A calculated phase matching curve shows excellent accordance with the measured results. In waveguides of larger domain periodicity the tuning characteristics shifts as a whole to the left reducing the gap near degeneracy. The same happens, if broader waveguides or higher temperatures are used. The OPF-power grows exponentially at higher pump power levels.

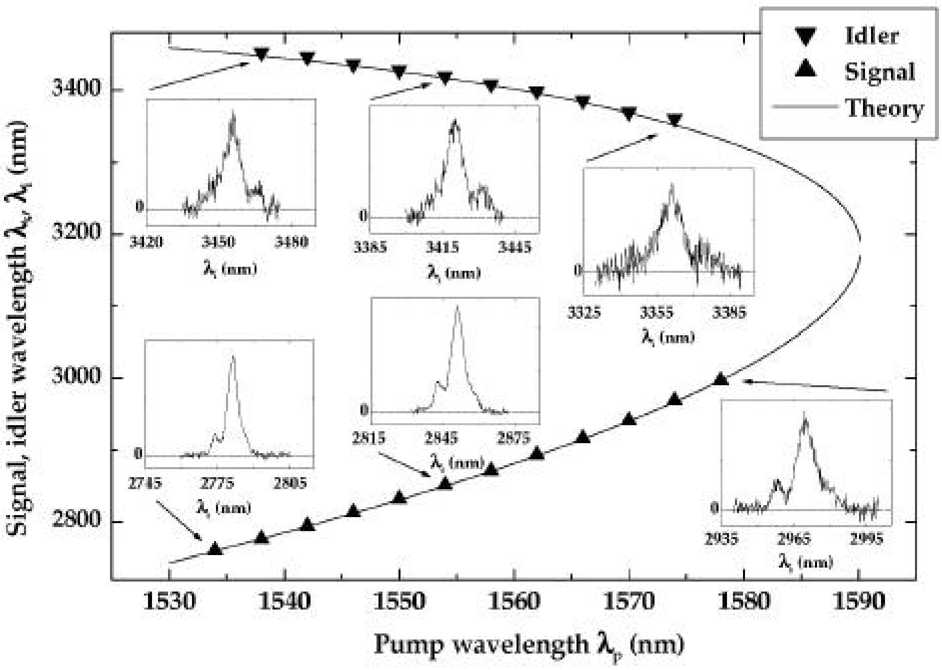


Fig. 8. Measured ( ) and calculated (--) tuning characteristics of OPF from an 18 µm wide waveguide with a domain period of 31.36 µm as signal and idler wavelengths versus the pump wavelength in cw-operation. Selected spectral characteristics of the fluorescence are shown in the insets.

Optical Parametric Oscillation (OPO)

Integrated optical parametric oscillators (IOPOs) are attractive devices to generate tunable coherent radiation in a broad tuning range. A schematic diagram is given in Fig. 9. Contrary to their bulk counterparts IOPOs promise a low oscillation threshold, low waveguide losses provided. Based on Ti:PPLN waveguides singly as well as doubly resonant IOPOs have been developed for the near- and mid-infrared spectral ranges with unprecedented properties. In the following three examples are presented.

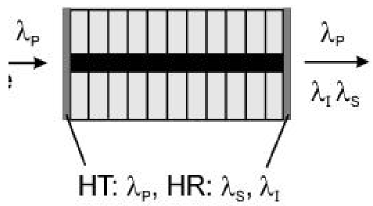


Fig. 9. Schematic diagram of a doubly resonant integrated optical parametric oscillator.

NIR Doubly Resonant Optical Parametric Oscillator (NIR-DR-IOPO) [8]

Using a periodic microdomain pattern with a period of ~17 µm over the total waveguide length of 80 mm a cw doubly resonant optical parametric oscillator was developed for the NIR spectral range. Typical waveguide losses are 0.1 B/cm. The endfaces of the samples are coated with dielectric mirrors of high transmission for the pump (~ 780 nm, T > 90 %) and of high reflectivity for signal and idler around 1550 nm wavelength (R > 95 %). Oscillation starts near degeneracy at a coupled pump power of 4.2 mW only. Fig. 10 shows on the left the measured output power of signal and idler $P_s + P_i$ as function of the coupled pump power $P_{p,c}$. The slope efficiency is ~ 3 %. Tuning of the IOPO is determined by the wavelength range of mirror reflectivity exceeding 87 %; it covers the wavelength range from ~1400 nm to ~ 1750 nm (Fig. 10 (right)).

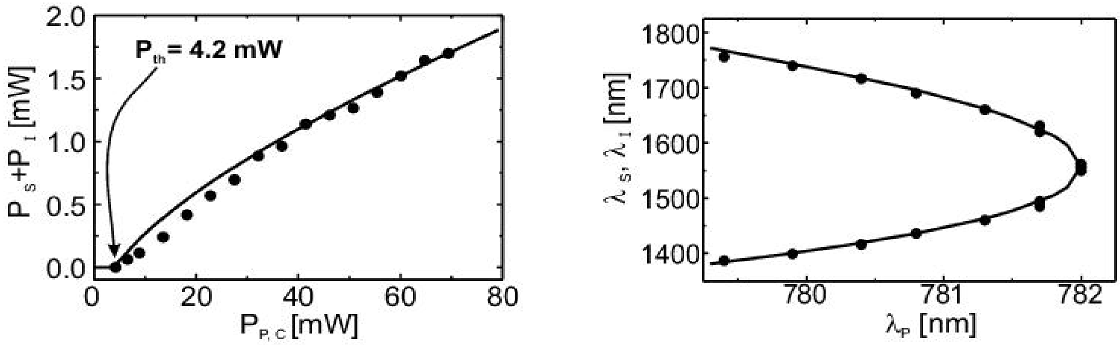


Fig. 10. Power characteristics (left) and tuning characteristics (right) of a doubly resonant NIR-IOPO.

MIR Doubly Resonant Optical Parametric Oscillator (MIR-DR-IOPO) [9]

The IOPO consists of a 90 mm long Ti:PPLN waveguide (80 mm periodically poled with a periodicity of ~31 µm) in a 0.5 mm thick and 12 mm wide Z-cut, X-propagation $LiNbO_3$ substrate with external dielectric mirrors in contact with the waveguide end faces. The periodically poled waveguide of excellent homogeneity has very low losses down to 0.03 $dBcm^{-1}$ in the MIR. To achieve doubly resonant optical parametric oscillation the dielectric mirrors are optimized for high signal (λ_s) and idler (λ_i) reflectivity (> 95 %) in the 2800 to 3400 nm spectral range and high pump transmission (80..92 %) between 1500 and 1580 nm wavelength. The IOPO is pumped by a tunable, single-frequency external cavity semiconductor laser (1500 nm < λ_p < 1580 nm) in combination with a high power (up to 27 dBm) fiber amplifier. Optical parametric oscillation starts at 14 mW (external) pump power. With rising pump power level also signal and idler power increases up to 6.5 mW at 300 mW pump power. At even higher levels the MIR-output saturates at about 7.8 mW. The measured threshold and output characteristic agrees well with modelling results.

The tuning behaviour of signal and idler radiation of three IOPOs of different waveguide width has been investigated using a grating monochromator and a Fabry-Perot interferometer (Fig. 11). The maximum continuous tuning range from 2804 to 3379 nm is achieved with the IOPO of 17.5 μm waveguide width and Λ = 31.6 μm domain periodicity by pump wavelength tuning from 1532 to 1570 nm. The overall tuning range is 2765 to 3476 nm determined by the spectral width of the high reflectivity band of the dielectric mirrors. The fine tuning behaviour is determined by the double resonance for signal and idler. As an example, a relative signal frequency is plotted on the right of Fig. 8 as function of the pump frequency detuned from λ_{p0} = 1540 nm. The signal frequency does not follow the exact phase-matching curve (straight line), but obeys a sawtooth-characteristics with a spectral width of about 180 GHz.

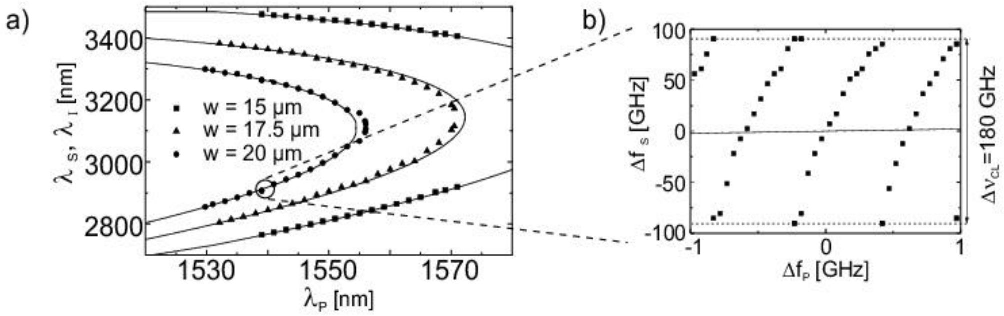


Fig. 11. Tuning characteristics as signal and idler wavelength versus the pump wavelength of three doubly resonant MIR-IOPOs of different waveguide width. Fine tuning characteristics at ëp = 1540 nm on the right.

MIR Singly Resonant Optical Parametric Oscillator (MIR-SR-IOPO) [10]

Singly resonant integrated optical parametric oscillators (SR-IOPO) are attractive candidates for efficient frequency conversion, nearly continuously tunable in a broad wavelength range without a sawtooth-characteristics as for a doubly-resonant device. Our SR-IOPO consists of a 90 mm long channel guide of 17.5 μm width in a Z-cut, X-propagation $LiNbO_3$ substrate. The waveguide losses are as low as 0.06 dB/cm measured at λ = 3391 nm. Using the electric field poling technique the substrate has been periodically poled over a length of 80 mm with a domain periodicity of 31.3 μm. Dielectric mirrors on a sapphire substrate (R > 95 % for 3200 < λ < 3800 nm, R < 5 % for 2650 < λ < 2980 nm) are in contact with the waveguide end face to form the resonator. A tunable narrow linewidth extended cavity semiconductor laser, amplified by a high power EDFA (33 dBm), is used as pump source to operate and to investigate the SR-IOPO. As an example, Fig. 12 (left) presents the power characteristic of the device in cw operation as signal plus idler power in forward direction versus the external pump power (λ_p = 1560 nm). The oscillation threshold is 275 mW in good agreement with the theoretical prediction, if a 60 % coupling efficiency is assumed. At 1.25 W pump power the mid-infrared emission (λ_s = 2883 nm, λ_i = 3364 nm) grows up to ~ 300 mW; this result corresponds to an overall slope efficiency of 30 %. Due to the SR-configuration of the oscillator the signal power always exceeds the idler power considerably. The SR-IOPO output can be tuned within the range 2720 nm < λ_s, λ_i < 3500 nm by changing the pump wavelength λ_p from 1530 nm to 1580 nm (see Fig. 12, right).

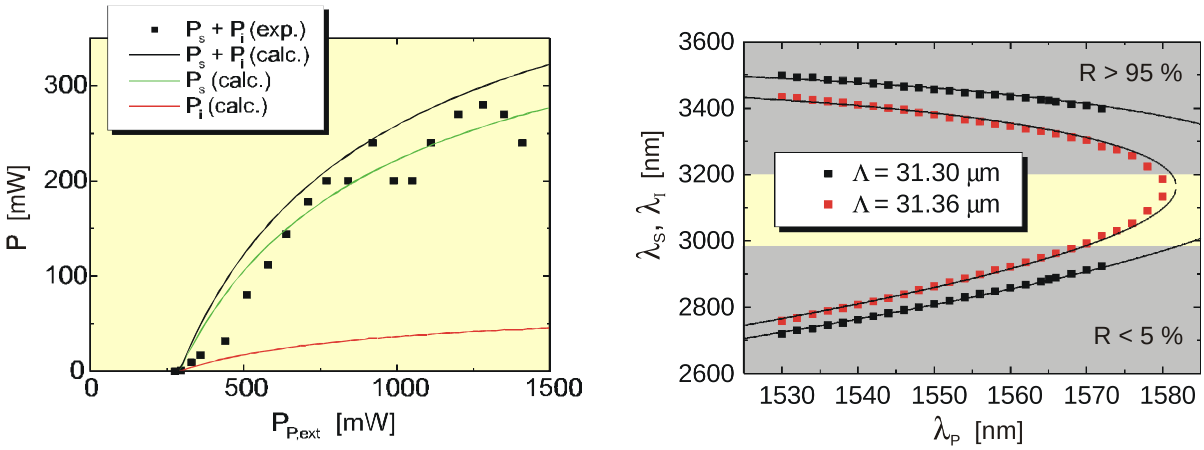


Fig. 12. Measured and calculated power characteristics of a SR-IOPO with 17.5 µm wide channel guide of domain period of 31.36 µm (left) and tuning characteristic of two SR-IOPOs of different domain periodicity as signal and idler wavelengths versus the pump wavelength in cw-operation.

Conclusions

The field of nonlinear integrated optics with waveguides in PPLN has been reviewed. A variety of all-optical frequency converters and signal processing devices with excellent properties has been presented. All these devices are based on single channel, straight waveguides in PPLN. It is a great challenge to develop devices with more complex nonlinear waveguide structures like waveguide arrays, engineered ferroelectric microdomains and even photonic bandgap structures in PPLN without and with doping by laser-active ions such as Erbium. They will allow to realise a whole bunch of new all-optical functions.

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