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Wavelength Conversion, Optical Parametric Amplification and Oscillation in Periodically Poled Ti:LiNbO$_3$ Optical Waveguides

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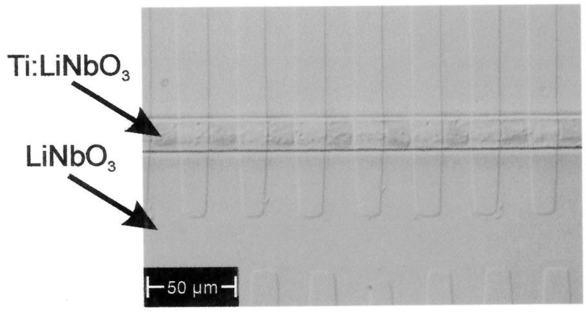
Abstract:
Quasi-phase matched quadratic nonlinear waveguide devices in periodically poled lithium niobate (PPLN) are reviewed with emphasis on Ti:(Er:)PPLN structures. In particular, difference frequency generators, optical parametric amplifiers and oscillators and combinations of lasers and nonlinear frequency converters are presented.

I Introduction

The recent demonstration of periodically poled optical waveguides in LiNbO$_3$ allows the development of very efficient quasi-phase matched second harmonic and difference frequency generators (wavelength converters), parametric amplifiers, all-optical ultra-fast switches, optical parametric oscillators and pulse compressors. Waveguide design and periodicity of the domain pattern determine the phase match wavelengths in the broad range from the visible to the mid-infrared ($\lambda \approx 4\mu m$). Moreover, Ti:LiNbO$_3$ devices can be combined with rare-earth- (in particular: Er-) doped amplifiers and lasers even in the same waveguide structure. There are numerous applications in the fields of optical communications, of all-optical signal processing and of spectroscopic analysis and monitoring of e.g. the environment. It is the aim of this contribution to review quasi-phase matched quadratic nonlinear waveguide devices in periodically poled lithium niobate (PPLN) with emphasis on Ti:(Er:) PPLN structures.

II Periodically Poled Ti:(Er:) LiNbO$_3$ Waveguides

To develop nonlinear integrated optical devices mainly proton exchanged LiNbO$_3$ waveguides were used up to now [1]. Recently, also the fabrication of up to 80mm long Ti:PPLN waveguides with periodicities around 17µm and 32µm was reported [2]. Even Ti:Er:LiNbO$_3$ waveguides, fabricated in an Er-diffusion-doped substrate, could be poled using the electric field technique. The domain pattern was investigated by chemically etching the waveguide surface revealing a nearly ideal 1:1 duty cycle (see Fig. 1). Moreover, the domain structure was studied by second harmonic generation- (SHG-) microscopy demonstrating a thickness of the domain walls below the resolution limit of the microscope.



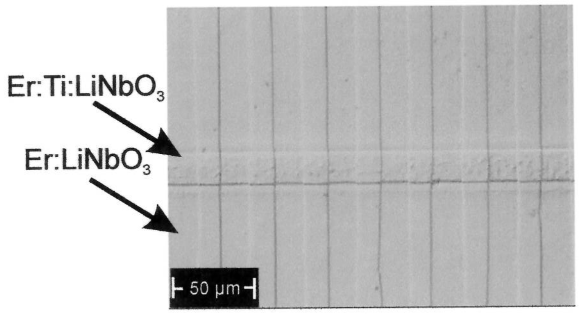


Fig. 1: Chemically etched surface of a periodically poled undoped (left) and Er-diffusion-doped (right) Ti:LiNbO$_3$ channel guide. The periodicity is 32µm.

The short period waveguides were designed as single-mode channels around λ = 1550nm for near-infrared (NIR) nonlinear interactions. They were tested as second harmonic generators using a tunable, single-frequency semiconductor laser as pump source. Measured and calculated characteristics (phase-matching curves) nearly coincide demonstrating the excellent homogeneity of the periodically poled waveguides. Their high quality with losses as low as 0.15dB/cm results in a normalized efficiency of 442 % W^{-1} (50mm long waveguide) or of 18 % $W^{-1}cm^{-2}$ [2].

The long period guides were single-mode channels around λ = 3400nm to allow mid-infrared (MIR) nonlinear interactions. The losses are as low as 0.03dB/cm, ideal for resonant structures.

III Wavelength Conversion (DFG) and Optical Parametric Amplification (OPA)

Waveguides of both periodicities were investigated as difference frequency generators (DFG).

The short period guides were studied as wavelength converters for the 1.5µm communication band using a Ti:sapphire laser as pump source ($\lambda_p \approx$ 780nm) and a tunable semiconductor laser as signal source (1500nm < λ_s < 1580nm). With 50mm long waveguides a device efficiency of 318 % W^{-1} or 13 % $W^{-1}cm^{-2}$ was measured [2].

Instead of a Ti:sapphire laser with all the problems to selectively excite a single pump mode at $\lambda_p \approx$ 780nm, a narrow linewidth semiconductor laser of $\lambda_f \approx$ 1560nm can be used, if necessary in combination with a high power erbium-doped fiber amplifier (EDFA). In this case the pump wave for DFG is generated inside the device by SHG; coupling to a single SHG-mode is guaranteed by the phase-match condition. In this "cascaded" process the overall DFG-efficiency is somewhat reduced. Nevertheless, -14dB or 4 % has been experimentally obtained as device efficiency in a 80mm long periodically poled Ti:LiNbO$_3$ waveguide at a coupled pump power of 155mW. The spectral bandwidth for wavelength conversion (at fixed fundamental and pump wavelengths) is 55nm in good agreement with theoretical predictions (see Fig. 2) [3].

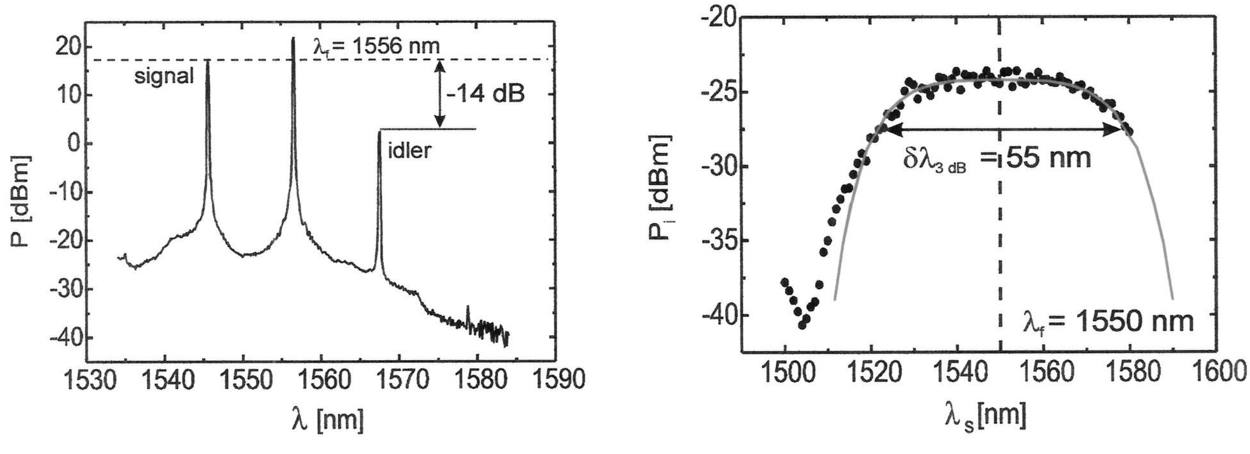


Fig. 2: Power spectrum of fundamental, signal and idler (difference frequency) waves (left); generated idler power versus signal wavelength (right).

DFG is always accompanied by optical parametric amplification (OPA) of the signal wave, as pump photons decay into one idler and one signal photon simultaneously (energy conservation). However, to be useful e.g. in optical communications, much higher efficiencies and therefore higher pump power levels are required.

Recently, with ~500mW coupled fundamental power the efficiency for cascaded DFG was enhanced to –1.8dB accompanied by an amplification of the signal wave of +2dB. Theory even predicts a gain of +14dB in a 80mm long "cascaded" OPA at the same power level; in a "direct" converter the gain should grow up to +19dB.

The $\chi^{(2)}$-nonlinear processes are extremely fast paving the way to all-optical switching. This was demonstrated using a harmonically modelocked Ti:Er:$LiNbO_3$ waveguide laser [4] as fundamental source (λ_f = 1561nm) for "cascaded" DFG/OPA. With fundamental pulses of ~6ps halfwidth somewhat short idler pulses were generated with an efficiency of 1.8%; in this way e.g. all-optical time division (de-)multiplexing (TDM) in combination with wavelength division (de-)multiplexing (WDM) can be achieved.

The long period waveguides were used as MIR-difference frequency generators mixing the radiation of a tunable extended cavity semiconductor laser (1500nm < λ_p< 1580nm), amplified by an EDFA, and of a mid-infrared He-Ne laser (λ_s = 3391nm) to generate the difference frequency (idler) radiation of a wavelength around λ_i = 2800nm. Using 80mm long waveguides a device efficiency of 105 % W^{-1} was achieved, by far the best result ever reported [5]. Such devices are ideally suited to develop compact efficient MIR-DFG spectrometers using semiconductor lasers as pump and signal sources.

IV Optical Parametric Fluorescence (OPF) and Oscillation (OPO)

Waveguides of both types as described above were also used to demonstrate the single-pass generation of spontaneous and stimulated parametric fluorescence. This fluorescence is induced by the quantum-mechanical zero point (vacuum) fluctuations of the electromagnetic field. Spontaneous optical parametric fluorescence (OPF) is an ideal means to measure the tuning characteristics of three wave $\chi^{(2)}$-processes. A tuning range of about 750nm (750nm) has been achieved in the NIR- (MIR-) spectral range by a variation of the pump wavelength. At higher pump power levels, stimulated PFG is obtained. Using a Q-switched Ti:Er:$LiNbO_3$ waveguide laser [4] with 5ns long pulses of about 500W peak power (λ_p = 1562nm) MIR-pulses (λ_s = 2930nm; $\lambda_i \approx$ 3300nm) were generated with a peak power of up to 10mW.

Spontaneous parametric fluorescence represents the noise which starts optical parametric oscillation (OPO) in nonlinear waveguide cavities, if the pump power exceeds a certain threshold. Such (doubly resonant) OPOs have been developed for both the NIR- and MIR-spectral ranges by coating the end faces of waveguides of both types with dielectric multilayer mirrors (SiO_2/TiO_2). (for the MIR-devices commercial mirrors were used pressed against the waveguide end faces.) Due to the low losses of Ti:$LiNbO_3$ waveguides – especially in the MIR – high Q cavities could be fabricated leading to a low oscillation threshold of about 35mW of the NIR-OPO and of only 14mW of the MIR-OPO [6] (see Fig. 3, left). At higher pump power levels the OPO output power was increased up to several mW in cw-operation (see also Fig. 3, left). By optimizing the resonator design much higher output levels can be expected.

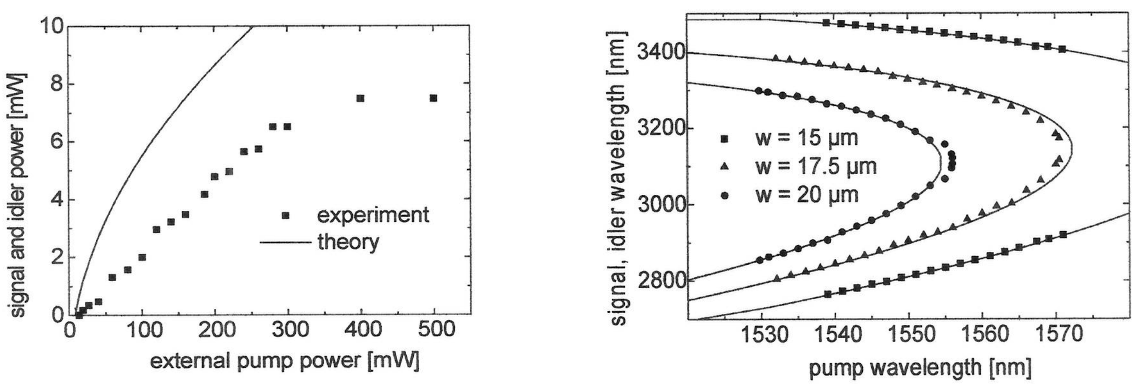


Fig. 3: Power characteristics (left) and tuning characteristics (right) of 80mm long Ti:$LiNbO_3$ MIR-OPOs of different waveguide width w and of Λ = 31,6µm domain periodicity.

The spectral tuning width of the OPOs was mainly determined by the width of the reflectivity band of the dielectric mirrors. In the NIR-device it extends from 1400nm to 1800nm, in the MIR-device from 2700nm to 3500nm. The tuning characteristic is not only determined by the periodicity of the ferroelectric domain pattern, but also by the waveguide width, which modifies the effective indices and in this way the phase match wavelengths (see also Fig. 3, right). The fine tuning behavior of the doubly resonant OPOs shows the well-known "saw-tooth" behavior according to the requirements of energy conservation, phase matching and simultaneous resonance of signal and idler waves. Singly resonant OPOs are the better choice for high resolution spectroscopy; corresponding devices are currently developed.

V Laser/Frequency Converter Combinations

As laser-active Ti:Er:$LiNbO_3$ waveguides can be periodically poled as well (see Fig. 1, right), integrated optical lasers (or amplifiers) and quasi-phase matched nonlinear frequency converters can be combined not only on the same substrate, but even in the same waveguide structure. This idea leads to a number of attractive concepts, only partly realized up to now.

The most straightforward device is a self-frequency doubling laser. A high conversion efficiency can be expected, if the resonator is designed to maximize the enhancement of the laser field. Even a doubly resonant device (resonant at laser and second harmonic wavelengths) should be possible. First experimental results of a self-frequency doubling laser have been reported recently [7].

The same principle can be applied to fabricate an amplifying difference frequency generator in a periodically poled Ti:Er:$LiNbO_3$ waveguide. By pumping the Er-ions a wavelength-dependent single-pass amplification up to 2dB/cm should be possible. Also this concept has been experimentally demonstrated recently.

Furthermore, a MIR-OPO can be designed with an intracavity Er-laser as pump. Currently, experiments are going on to realize such a device.

VI Conclusions

A variety of efficient nonlinear quasi-phase matched waveguide devices has been demonstrated with PPLN as substrate material. Now an optimization for specific applications is required to exploit the great potential of nonlinear integrated optics in optical communications, all-optical signal processing and spectroscopic analysis and monitoring.

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