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Parametric Mid-Infrared Generation in Periodically Poled Ti:LiNbO$_3$ Waveguides

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Introduction

Integrated optical parametric devices in LiNbO$_3$ have been identified as most attractive tunable nonlinear frequency converters [1] with many applications mainly in environmental sensing and process monitoring. Using periodically poled waveguides and exploiting quasi-phase matching devices of high efficiency can be developed even for mid-infrared- (MIR-) operation allowing optical pumping with diode lasers.

In this contribution, we report quasi-phase matched difference-frequency generation (DFG), optical parametric fluorescence, and optical parametric oscillation of high efficiency in Ti:LiNbO$_3$ waveguides. They have been fabricated in a Z-cut LiNbO$_3$ substrate with lengths up to 90 mm, widths between 15 and 30 μm, and with losses as low as 0.03 dB/cm. By electric field poling periodic domain structures with periodicities of 31.2 to 32.2 μm have been realized up to a length of 80 mm. The corresponding fabrication parameters are given in [2].

Difference-Frequency Generation

To perform the DFG experiments a tunable external cavity laser was used as pump and a He-Ne laser ($\lambda_S = 3391$ nm) as signal source [2]. The pump radiation was amplified by an erbium doped fibre amplifier up to 11 mW in the 1520 to 1580 nm spectral range. The transmitted pump power was blocked by a Ge filter. Due to the chopped pump radiation, only the amplified part of signal power was measured together with the generated idler power using an ac-coupled PbS or PbSe photoconductive detector and a lock-in amplifier.

The highest device conversion efficiency was $\eta = 105\ \%\mathrm{W}^{-1}$ ($\lambda_P = 1568$ nm, $\lambda_I = 2917$ nm). This figure is more than one order of magnitude higher than previous reported conversion efficiencies [3], [4], [5].

Optical Parametric Fluorescence

Due to the high parametric gain, possible in these waveguides at higher pump power levels, an investigation of spontaneous and stimulated parametric fluorescence in the MIR becomes possible. In this case an external signal source as used for DFG is not necessary.

The experimental set-up is sketched in Fig. 1. A Q-switched Ti:Er:LiNbO$_3$ waveguide laser ($\lambda = 1562$ nm, repetition rate $R = 2$ kHz, $\Delta\lambda = 5$ nm, $P_{Peak} = 500$ W) was used as pump laser [6]. On the output side of the periodically poled waveguide the transmitted pump was blocked by a Ge filter. Signal and idler wavelengths were measured using a monochromator and a PbS photoconductive detector.

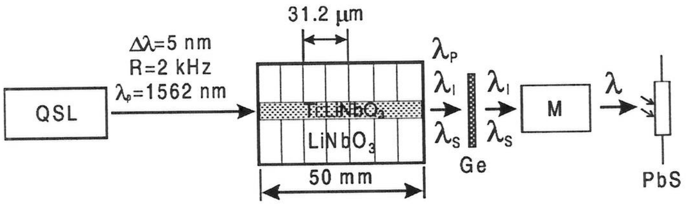

Fig. 1: Experimental set-up: QSL (Q-switched Ti:Er:LiNbO$_3$ waveguide laser), Ge (germanium filter), M (monochromator), PbS (lead sulfide photoconductive detector)

According to the tuning characeristic, spontaneous and stimulated parametric fluorescence is observed at $\lambda_S = 3297$ nm (signal) and at $\lambda_I = 2938$ nm (idler). As an example, a preliminary result is shown in Fig. 2. The evident difference between signal and idler power levels is due to the power instability of the pump laser. During the wavelength scan the pump power fell from about 500 W to about 300 W resulting in a much stronger decrease of the signal fluorescence due to its strong pump dependence (see inset of Fig. 2). The broad spectral width of the lines is determined by the low resolution of the monochromator enabling the measurement.

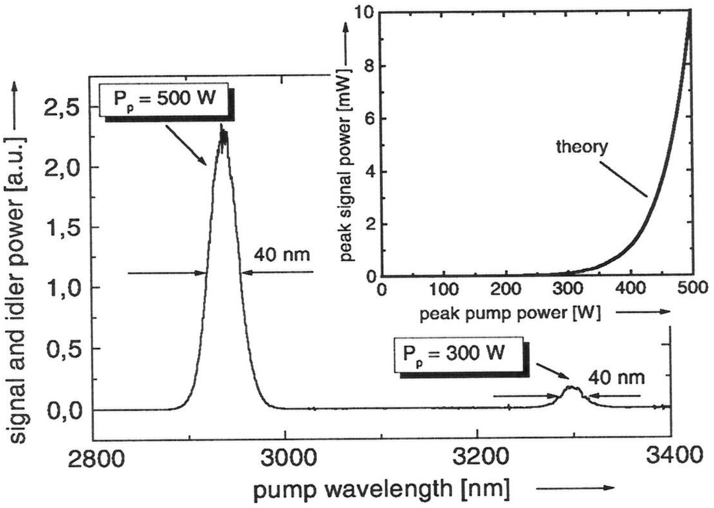

Fig. 2: Measured parametric fluorescence spectrum; inset: calculated signal peak power versus pump peak power

Optical Parametric Oscillation

The low losses of the periodically poled Ti:LiNbO$_3$ waveguides of long effective interaction length (up to 68 mm) enable the development of optical parametric oscillators of very low threshold [7]. Fig. 3 presents calculated results for the pump threshold as function of the reflectivity of the resonator mirrors for a single- (SP-) and double- (DP-) pump pass configuration of a doubly resonant oscillator (DRO).

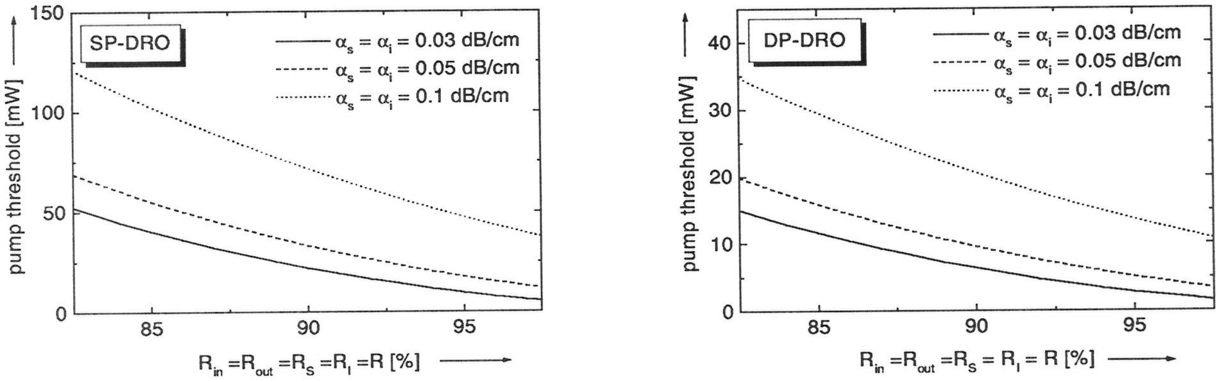

Fig. 3: Pump thresholds of continuous-wave mid-infrared single-pass (SP) and double-pass (DP) doubly resonant integrated optical parametric oscillators as function of mirror reflectivity; different waveguide losses used as parameters

To confirm these results experimentally an integrated optical parametric oscillator (IOPO) was set-up with 90 mm long Ti:LiNbO$_3$ waveguides (80 mm periodically poled with periodicities around 31 µm) in a 0.5 mm thick and 12 mm wide Z-cut, X-propagation LiNbO$_3$ substrate and of external dielectric mirrors in contact with the waveguide end faces. To achieve doubly resonant optical parametric oscillation we used mirrors optimized for high signal (λ_S) and idler (λ_I) reflectivity ($\approx$ 95 % in the 2800 to 3400 nm spectral range) and high pump transmission (80..92 % in the 1500 to 1580 nm spectral range). The IOPO was pumped by a tunable, single-frequency external cavity semiconductor laser (1500 nm $< \lambda_P <$ 1580 nm) in combination with a high power (up to 27 dBm) fibre amplifier.

The power characteristic of an IOPO with 20 µm wide waveguide is shown in Fig. 4 as signal and idler power versus external pump power together with the power-dependent pump transmission (depletion) at λ_P = 1541.49 nm (degeneracy point: $\lambda_P \approx$ 1556 nm). Optical parametric oscillation started at 14 mW; the corresponding transmitted pump power was only 6.5 mW due to a waveguide coupling efficiency of about 70 %. With rising pump power level also signal and idler power increased up to 6.5 mW at 300 mW pump power. At even higher levels the MIR-ouput saturates at about 7.8 mW. The measured threshold agrees well with modelling results. However, the calculated characteristic has a much steeper slope than the experimental one. Furthermore, the measured pump transmission (depletion) falls with increasing pump power much weaker than theoretically expected. Both discrepancies will be investigated in the near future.

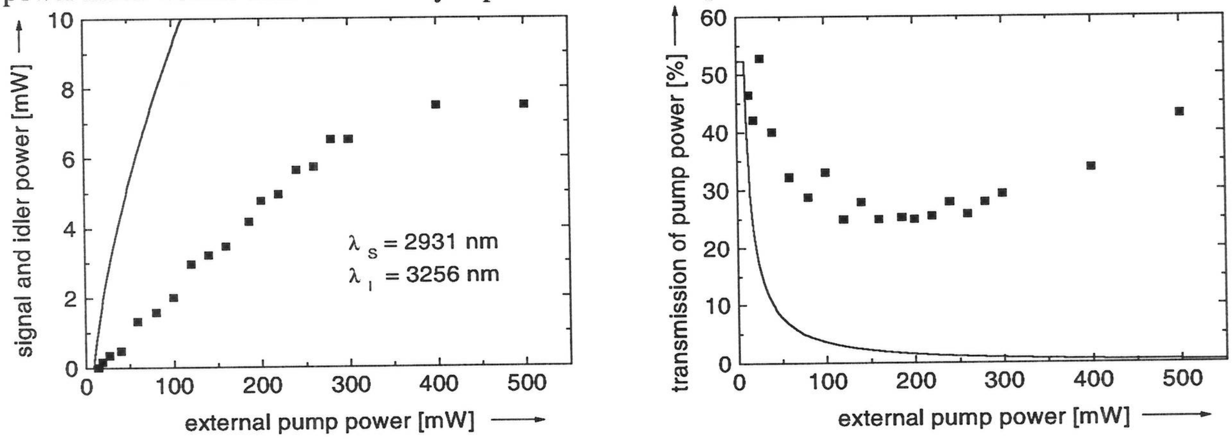

Fig. 4: Power characteristics: Signal and idler power (left) and pump transmission (depletion) (right) as function of external pump power at $\lambda_P = 1541.49$ nm; $\Lambda = 31.6$ µm; w = 20 µm. Full lines correspond to calculated results with about 70 % estimated waveguide coupling efficiency.

Conclusions

Mid-infrared radiation was generated by difference-frequency generation, optical parametric fluorescence and optical parametric oscillation with very high conversion efficiencies. A continuous-wave integrated optical parametric oscillator of very low threshold was demonstrated, more than two orders of magnitude lower than those of previously reported NIR-devices [8], [9].

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