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CONTINUOUS-WAVE MID-INFRARED OPTICAL PARAMETRIC OSCILLATORS WITH PERIODICALLY POLED Ti:LiNbO$_3$ WAVEGUIDE

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The operation of the first mid-infrared, continuous-wave, doubly resonant integrated optical parametric oscillators is demonstrated. A pump threshold as low as 14 mW, an output power of up to 7.8 mW, and a continuous tuning range from 2804 to 3379 nm have been achieved.

Introduction

Integrated optical parametric oscillators (IOPOs) in LiNbO$_3$ have been identified as most attractive tunable nonlinear frequency converters [1] with many applications mainly in environmental sensing and process monitoring.

The first near-infrared (NIR) devices have been demonstrated in low-loss Ti-diffused LiNbO$_3$ waveguides. They used birefringent phase matching with thresholds of 7.6 W in singly resonant [2] and 26.5 mW in doubly resonant [3] configurations. However, the material system limited their operation to temperatures between 200 and 300 °C and to pump wavelengths near 600 nm, too short to permit diode pumping.

Using periodically poled waveguides and exploiting quasi-phase matching room temperature operation should become possible together with a considerably lowered threshold. Furthermore, the adjustment of the periodicity of the domain grating should allow to determine a nearly arbitrary wavelength range of the IOPO output.

The first NIR-IOPO using quasi-phase matching was demonstrated in 1994 with a threshold of 5.5 W [4]. This device suffered from a non ideal ferroelectric domain pattern and high propagation losses in annealed-proton-exchanged (APE) waveguides. By using electric field poling the domain quality was enormously enhanced. Thereby, singly resonant NIR-IOPOs with APE-waveguides could be demonstrated with thresholds of 1.6 W [5].

In this contribution, we report for the first time continuous-wave, mid-infrared, doubly resonant optical parametric oscillators with periodically poled Ti:LiNbO$_3$ waveguides of very low oscillation threshold.

Experimental Set-Up

The experimental set-up is shown in Fig. 1. The pump source to operate the IOPOs was a tunable, single-frequency external cavity laser (1500 nm < λ_p < 1580 nm) in combination with a 27 dBm high power fibre amplifier.

The IOPOs consist of 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. Details on waveguide fabrication and domain inversion are given in [6]. The periodically poled waveguides have very low losses down to 0.03 $dBcm^{-1}$. The quality of the domain grating was characterized by difference-frequency generation [6]. It yields a maximum conversion efficiency of 105 $\%W^{-1}$ and an effective interaction length of 68 mm.

To achieve doubly resonant optical parametric oscillation we used mirrors 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 % in the 1500 to 1580 nm spectral range). The subtending surfaces of the saphire substrate are anti-reflection coated for λ_P, λ_S and λ_I.

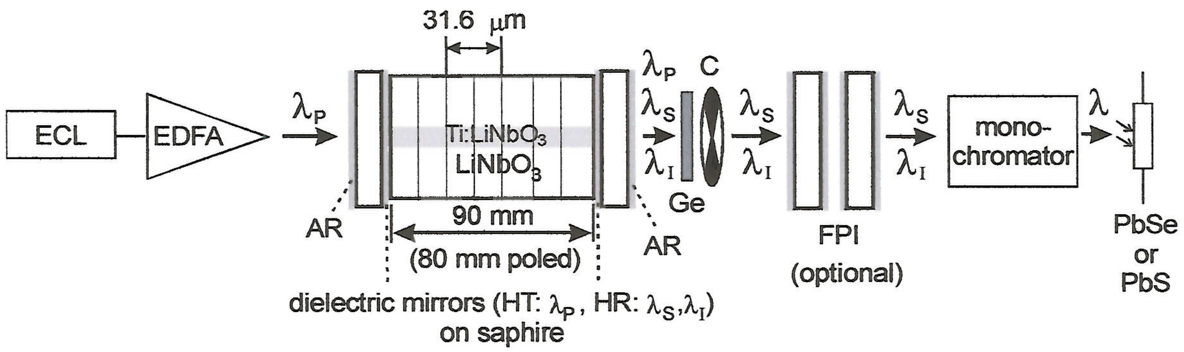

Fig. 1: Experimental set-up: ECL (external cavity laser), EDFA (erbium doped fibre amplifier), C (chopper), Ge (germanium filter), FPI (Fabry-Perot interferometer), PbS (lead sulfide photoconductive detector), PbSe (lead selenide photoconductive detector), lenses not shown.

At the IOPO input side an anti-reflection coated (λ_P) quartz lens (f = 10 mm) was used to couple the pump beam in the waveguide. A CaF_2 lens (f = 8.3 mm) was employed at the output side. Blocking of the transmitted pump radiation was done by a Ge filter. The tuning characteristic of signal and idler radiation was measured with a grating monochromator and a PbSe (or PbS) detector. With a Fabry-Perot interferometer inserted the fine tuning of the doubly resonant IOPO was observed.

Experimental Results and Discussion

The power characteristic of an IOPO with 20 µm wide waveguide is shown in Fig. 2. Signal and idler power behind the Ge filter was measured as function of the external pump power at the wavelength $\lambda_P = 1541.49$ nm (degeneracy point: $\lambda_P \approx 1556$ nm, see also Fig. 3). Optical parametric oscillation started at 14 mW; the corresponding transmitted pump power was only 6.5 mW. 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.

Modelling results show nearly the same pump threshold. However, the calculated characteristic has a much steeper slope than the experimental one. The reason of this behaviour will be investigated in the near future.

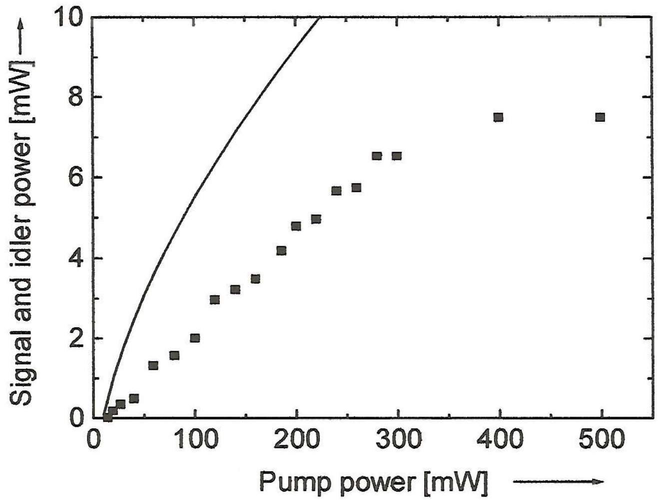

Fig. 2: Power characteristic: Signal and idler power as function of external pump power at $\lambda_P = 1541.49$ nm; $\Lambda = 31.6$ µm, w = 20 µm. Line corresponds to calculated results with 50 % estimated coupling efficiency.

The tuning behaviour of signal and idler radiation of three IOPOs of different waveguide width has been investigated by tuning the pump wavelength (Fig. 3).

The maximum continuous tuning range from 2804 to 3379 nm was achieved with the IOPO of 17.5 µm wide waveguide 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.

We have also investigated the fine tuning behaviour which is determined by the double resonance for signal and idler. A relative signal frequency is plotted in Fig. 4 as function of the pump frequency detuned from $\lambda_{P0} = 1540$ 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. This behaviour of doubly resonant oscillators is well-known.

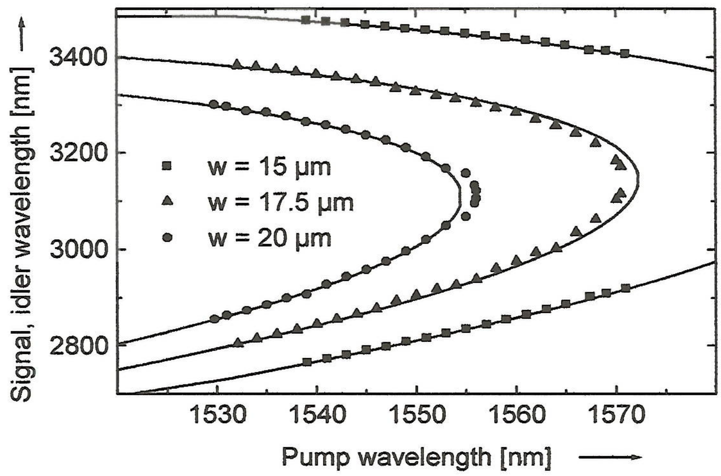

Fig. 3: Tuning characteristic: Signal and idler wavelength as a function of pump wavelength for three oscillators with different waveguide width (15, 17.5, 20 µm), but identical domain periodicity of $\Lambda = 31.6$ µm. Theoretical curves are fitted to the experimental results.

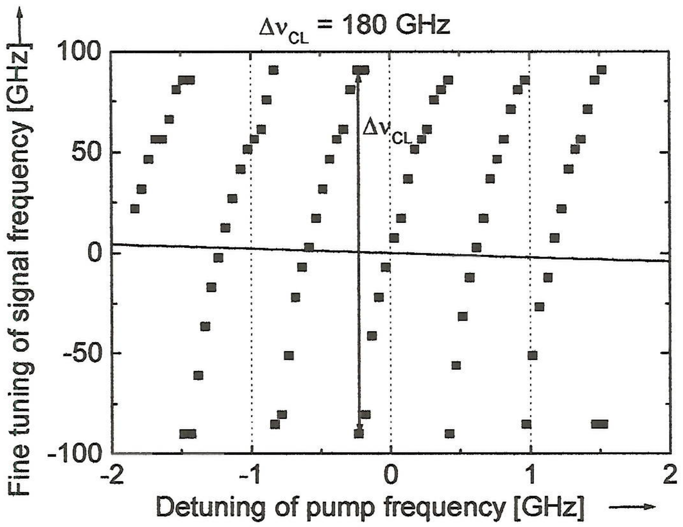

Fig. 4: Fine tuning characteristic: Relative signal frequency (λ_{S0} = 2920 nm) as function of detuned pump frequency (λ_{P0} = 1540.00 nm); Λ = 31.6 µm, w = 20 µm. Line corresponds to a small section of the tuning characteristic of Fig. 3.

Conclusions

We have demonstrated for the first time continuous-wave, mid-infrared, doubly resonant integrated optical parametric oscillators with 90 mm long Ti:$LiNbO_3$ waveguides (80 mm periodically poled). They have an extremely low threshold (14 mW). Up to 7.8 mW MIR-power could be generated with 500 mW pump power. The overall MIR tuning range was 700 nm around the degeneracy wavelength of 3100 nm.

Based on these results we anticipate the development of singly resonant MIR IOPOs with thresholds in the 100 to 200 mW range.

Acknowledgement

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