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MIR-OPTICAL PARAMETRIC FLUORESCENCE: FROM PHOTON PAIRS TO PUMP DEPLETION

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ABSTRACT

Efficient, continuously tunable MIR optical parametric generation (OPG) is demonstrated in the wavelength range 2800 nm < λ_s, λ_i < 3400 nm using up to 94 mm long Ti:PPLN waveguides. Up to several mW of peak fluorescence power have been generated using pulsed pump sources in the 1540 nm < λ_i < 1580 nm wavelength range. The experimental results are compared with a fit parameter free theoretical analysis of OPG.

KEYWORDS

Nonlinear optics, parametric fluorescence, integrated optics, PPLN

INTRODUCTION

The generation of optical parametric fluorescence (OPF) in bulk nonlinear crystals is a well-known method for frequency down-conversion of coherent laser radiation [1]. It is mainly used for spectroscopy in the near (NIR) and mid (MIR) infrared. However, high conversion efficiencies can only be obtained in a pulsed mode of operation with relatively high peak power levels.

Contrary to bulk configurations nonlinear integrated optical waveguides promise conversion efficiencies, which can exceed those of bulk optical approaches by several orders of magnitude. Moreover, if quasi phase matching is used in periodically poled $LiNbO_3$ (PPLN) waveguides, the largest nonlinear coefficient d_{33} can be exploited and the spectral range of the OPF-emission can be adjusted by a corresponding periodicity of the ferroelectric grating. Recently, tunable optical parametric generation (OPG) in the wavelength range 1150 nm < λ_s, λ_i < 2300 nm has been reported using reverse proton exchanged PPLN waveguides [2].

In this contribution we report our progress to achieve continuously tunable, quasi phase matched MIR-OPF in the wavelength range 2800 nm < λ_s, λ_i < 3400 nm using up to 94 mm long Ti:PPLN waveguides. Besides an output (peak) power improvement of about 4 orders of magnitude in comparison with previous results [3], a theoretical analysis has been performed, which describes without any fit parameter OPG from the pW (spontaneous photon pair generation) up to the 100 W MIR OPF power level with strong pump depletion.

SAMPLE FABRICATION AND EXPERIMENTAL SETUP

Single-mode channel waveguides for the wavelength range 2800 nm < λ_s, λ_i < 3400 nm were fabricated on a 94 mm long, 12 mm wide and 0.5mm thick Z-cut optical grade $LiNbO_3$ (LN) substrate. The guides were prepared by the indiffusion of photolithographically delineated 160 nm thick Ti-stripes of 18, 20 and 22 µm width oriented parallel to the crystallographic X-axis as shown in Fig. 1. Subsequently, the periodic domain inversion was performed over a length of 92 mm using the electric field induced poling technique described in more detail in [4]. The periodicity of the domains ranges from 31.06 to 31.60 µm with duty cycles close to 1. The losses of these waveguides were investigated at λ = 3391.3 nm (He-Ne laser) with TM polarized light using the low-finesse resonator method [5]. Loss coefficients in the range 0.07–0.2 $dBcm^{-1}$ were measured.

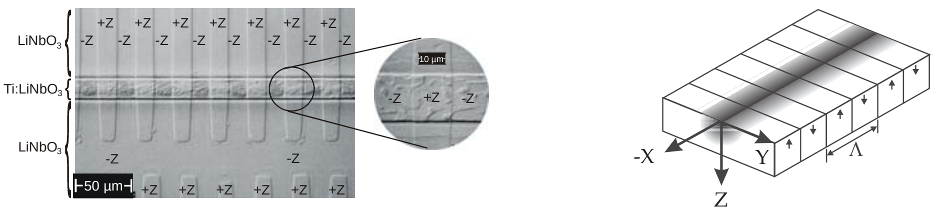

Fig.1: Top view of the (selectively etched) ferroelectric domain structure along a waveguide (left); orientation of the optical axes in the sample (right).

A schematic diagram of the experimental setup is presented in Fig. 2. As pump laser either a semiconductor distributed feedback (DFB) laser or an actively mode locked fiber laser (MLL) was used. The DFB-laser was operated at λ = 1552.7 nm in a cw-mode emitting up to 6 mW output power; the MLL could be tuned from λ = 1541 nm to 1564.5 nm emitting pulses of 6.4 ps width at 10 GHz repetition rate with up to 20 mW average power.

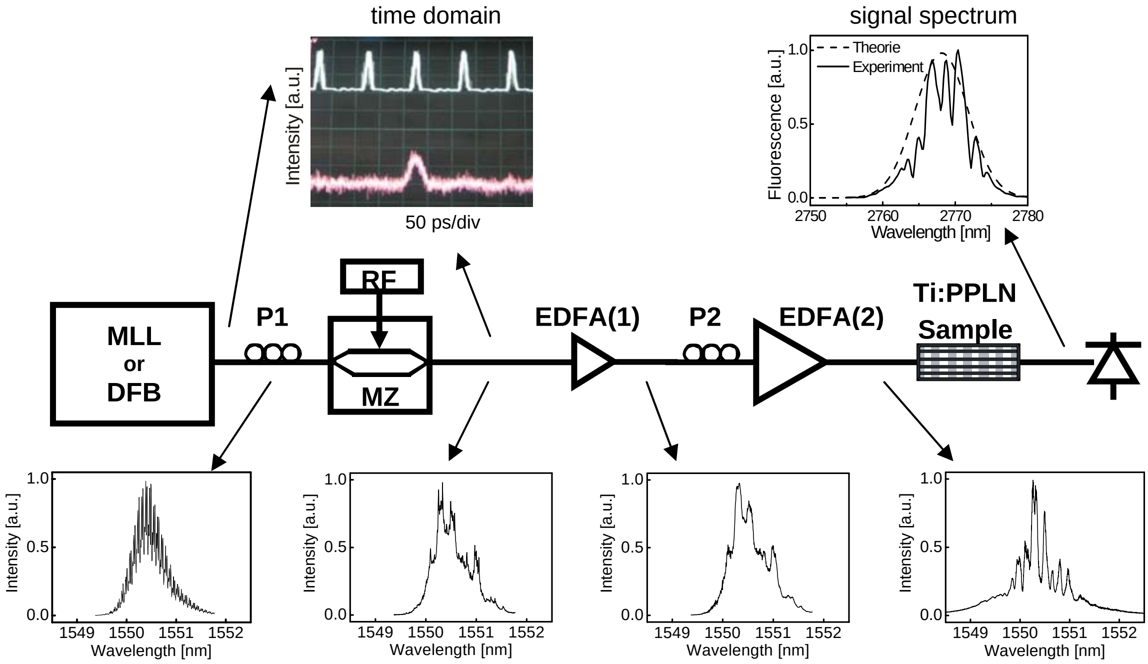

Fig.2: Experimental setup. MLL – mode locked laser; P1, P2 – Polarization controller; MZ – Mach-Zehnder integrated optical modulator; RF – radio frequency generator; EDFA(1) – Erbium doped fiber preamplifier; EDFA(2) – Erbium doped fiber power amplifier; D – detector (HgCdZnTe or InSb). MLL-pulses before and after pulse picking by the modulator are presented in the time domain in the upper left part. Corresponding spectra are displayed in the lower row of diagrams. A typical measured (solid line) and calculated (dashed line) signal spectrum is shown in the right upper part.

A LN Mach-Zehnder modulator was used to generate pulses of 25, 50, and 100 ns duration at a repetition of 1 MHz, if the cw DFB-laser was chosen as light source. If the MLL was used the modulator operated as a pulse picker transmitting every 8^{th}, 16^{th}, and 32^{nd} pulse, respectively, of 6.4 ps width only (see the photograph in Fig.2). The generated or transmitted pulses were amplified in two stages: first in an erbium doped fiber preamplifier of average output power up to 10 mW and then in an erbium doped fiber power amplifier of an average output power up to 1.5 W. This scheme should allow to reach peak power levels up to 60 W with 25 ns pulses and up to 720 W with 6.4 ps pulses according to the corresponding duty cycles. This concept worked reasonable with the DFB-laser; up to 10 W peak power (of 25 ns pulses) could be coupled to the PPLN waveguide. Using the MLL, however, strong pulse distortions occured, which were observed in the spectral domain (see the lower part of Fig.2 with the spectral characteristics of the pump radiation after each device in the chain). The pulses could not yet be analyzed in the time domain with the required resolution to be able to quantify the peak power levels achieved. Therefore, the data deduced from the simple duty cycle argument were taken in the discussion below; these power levels are definitively too high. The output pulses from the high power EDFA were coupled to the end face of the Ti:PPLN sample either by fiber butt coupling or via a bulk coupling optics. The polarization controller P2 was used to adjust TM polarisation to exploit the strongest nonlinear coefficient d_{33} of LN [2,3]. The generated signal and idler radiations were measured with an IR detector (HgCdZnTe or InSb) assisted by lock-in technique. For spectral investigations of the fluorescence a grating monochromator was used.

RESULTS AND DISCUSSION

Fig. 3 shows in the middle the tuning characteristics of the signal and idler waves generated in a straight, 94 mm long, 20 µm wide waveguide of 31.44 µm domain periodicity. The coupled (cw) pump power was approximately 700 mW. The MIR-OPF was continuously tunable from 2800 to 3400 nm by adjusting the pump wavelength from 1540 nm to 1580 nm. The calculated phase matching curve shows excellent agreement with the measured results. In waveguides of larger domain periodicity the tuning characteristics shifts as a whole to the left. The same happens, if broader waveguides or higher temperatures are used. Moreover, spectral characteristics of signal and idler for the pump wavelength λ_P = 1548.5 nm are given in Fig. 3 together with the calculated responses; the differences originate from residual waveguide inhomogeneities.

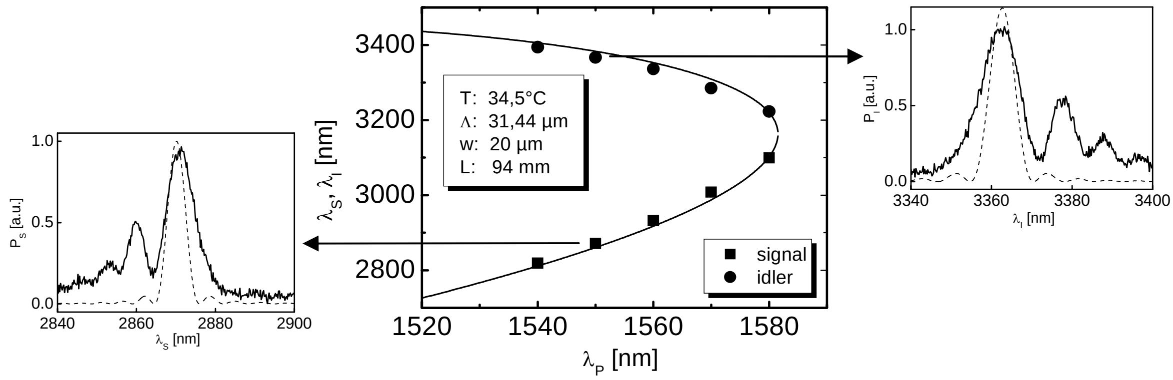

Fig. 3: Measured and calculated tuning characteristics of OPG as signal and idler wavelengths versus the pump wavelength in cw-operation (middle diagram) and signal (left graph) and idler (right graph) spectra for the pump wavelength 1548.5 nm as an example.

Measured and calculated data of the total OPF output power (signal and idler) are presented in Fig. 4 as function of the coupled pump power using the DFB-Laser as pump source (λ_p=1552 nm, λ_s = 2850 nm, λ_i = 3400 nm). The transition to a strong exponential rise (corresponding to high parametric amplification) at high pump power levels can be clearly observed. The theoretical response, which has been calculated without any fit parameter, predicts an even higher efficiency [5]. As only the fraction of the pump power, which is coupled to the fundamental mode, is responsible for phase matched OPG an even better agreement of experiment and theory can be expected by improving the mode selective coupling.

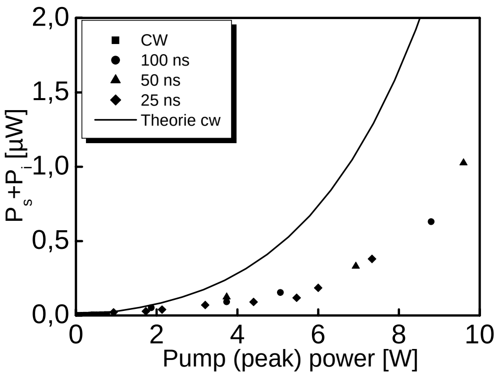

Fig.4: Total OPF output peak power versus coupled pump power (DFB laser, λ_p=1552 nm) in a pulsed mode of operation (1 MHz repetition rate) for different pulse width (dots) compared with a theoretical calculation (solid line).

The MLL with 6.4 ps pulses of different duty cycles (1:15, 1:120, 1:240 and 1:480) was used to increase the peak power levels and in this way the conversion efficiency. The experimental results are plotted in Fig.5 as total (signal and idler) OPF output peak power versus coupled pump power using the optimistic data deduced from the duty cycle. Nevertheless, OPF peak power levels of nearly 10 mW have been achieved. The measured results are compared with the results of a theoretical analysis, which is plotted over 10 orders of magnitude [6]. The predicted high conversion efficiency with strong pump depletion has not yet been achieved due to the mentioned pulse distortions; as a consequence, the pump peak power levels deduced (and used in the plot) are much too high. Nevertheless, there is a good chance to get OPG up to pump depletion if better defined pulses are used. The theoretical results demonstrate the large potential of integrated optics surpassing bulk results by several orders of magnitude.

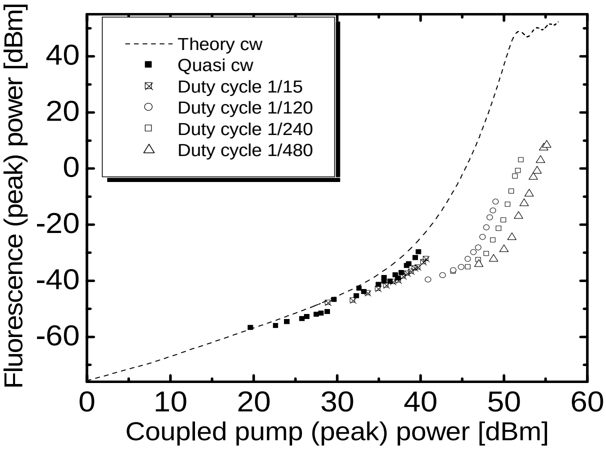

Fig.5: Total OPF output (peak) power versus coupled pump (peak) power in a pulsed mode of operation (6.4 ps pulses of different duty cyle as given in the inset) compared with results of a theoretical analysis (dotted line).

CONCLUSIONS

Cntinuously tunable MIR-OPF (2820 nm < λ_s, λ_i < 3400 nm) has been generated in Ti:PPLN monomode waveguides. As pump sources a DFB-laser and tunable lasers (ECL and fiber-MLL) have been used with emission wavelength in the range 1540 nm < λ_p < 1580 nm.

Pump pulses have been generated by a LN-modulator either by slicing 25, 50, or 100 ns long pulses out of the cw emission of the ECL or DFB-laser or by selecting every 8th, 16th or 32nd pulse only from the pulse train (6.4 ps; 10 GHz) of the MLL. The pump radiation has then been boosted in a sequence of EDFA preamplifier and power amplifier. Though this technique introduced strong pulse distortions, the pump power level achieved was sufficient to generate MIR-pulses of nearly 10 mW peak power in the Ti:PPLN device, an improvement of 4 orders of magnitude in comparison with previous results [3].

A theoretical analysis without any fit parameter yielded the guided wave OPG characteristics as OPF power versus pump power from the pW (spontaneous photon pair generation) to the 100 W MIR power level with strong depletion of the pump. The disagreement between theoretical and experimental results at nominally high pump peak power levels can be qualitatively explained by pulse distortions in the amplifier chain. A pulse stretching – amplifying – compressing procedure will be necessary to generate transform limited pump pulses of some 100 W peak power level. Nevertheless, the calculated OPG characteristics underlines the large potential of integrated nonlinear optics in comparison with bulk optics by a pump power reduction of many orders of magnitude. Ideal pump pulses assumed a useful integrated optical source for MIR-spectroscopy can be developed.

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