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MID INFRARED INTEGRATED OPTICAL PARAMETRIC GENERATORS AND OSCILLATORS WITH PERIODICALLY POLED TI:LINBO$_3$ WAVEGUIDES

S. ORLOV, W. GRUNDKÖTTER, D. HOFMANN,
V. QUIRING, R. RICKEN, H. SUCHE AND W. SOHLER[*]
Universität Paderborn, Angewandte Physik, Warburger Str. 100,
D-33098, Paderborn, Germany

Abstract. The state of the art of quasi phase matched integrated optical parametric generators and oscillators is reviewed. The core of these devices is a periodically poled Ti:LiNbO$_3$ waveguide of propagation losses down to 0.03 dB/cm and a length up to 180 mm. These properties enable the development of efficient, tuneable, compact light sources for the mid infrared (2700 nm < $\lambda_{s,i}$ < 3500 nm) spectral range.

Keywords: nonlinear optics; parametric frequency conversion; lithium niobate; quasi-phase matching; optical parametric fluorescence; optical parametric oscillation

1. Introduction

The advent of the electric field assisted poling technique to fabricate periodically poled nonlinear ferroelectric materials such as LiNbO$_3$ resulted in a renaissance of (second order or $\chi^{(2)}$) nonlinear optics. Since then quasi phase matching has been used for nearly arbitrary wavelength conversion in devices like frequency doublers, difference and sum frequency generators, optical parametric generators (OPGs) and oscillators (OPOs). Moreover, periodically poled materials allowed to take advantage of the largest nonlinear coefficient and to achieve in this way a large improvement of the device efficiencies.

OPGs and OPOs are attractive devices to generate tuneable coherent radiation in a broad wavelength range for many applications mainly in spectroscopy, environmental sensing and process monitoring. In the past mainly bulk devices

[*] To whom correspondence should be addressed.

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have developed though a significant improvement of device efficiency, of stability with respect to ambient fluctuations and of beam quality can be expected by using integrated optical devices. Therefore, nonlinear waveguides fabricated in periodically poled materials like $LiNbO_3$ are attracting considerable interest as efficient frequency converters of (tuneable) laser radiation. In particular Ti-diffused waveguides in periodically poled Lithium Niobate (PPLN) proved to be most attractive to develop OPGs and OPOs for the mid infrared (MIR) wavelength range due to their very low propagation losses (~0.03 dB/cm).

It is the aim of this contribution to review the state of the art of mid infrared quasi phase matched integrated OPGs and OPOs with periodically poled Ti:$LiNbO_3$ (Ti:PPLN) waveguides. In the next chapter waveguide and waveguide resonator fabrication and characterization are briefly described. Recent advances of microfabrication technology enable the fabrication of up to 180 mm long, homogenous, periodically poled Titanium-diffused waveguides in $LiNbO_3$. In chapter 3 the experimental setup is shown, which is used for the optical investigation of the nonlinear waveguide devices. Then the performance of OPGs is presented, which are simple, non resonant devices for wavelength conversion. In chapter 5 singly and doubly resonant OPOs are discussed. They mainly differ by their spectral fine tuning properties, threshold and conversion efficiency. Doubly resonant OPOs could also be operated in a special pulsed mode of operation (synchronous pumping) resulting in the generation of short MIR-pulses of high peak power.

2. Waveguide and Resonator Fabrication and Characterization

The waveguide fabrication starts with an indiffusion of a photolithographically defined Ti-stripe (Fig. 1, left). To get single mode waveguides in the mid infrared Ti-stripes of 18, 20, 22 μm width and 162 nm thickness are used. Indiffusion is performed into the –Z face at 1060 °C over 31 hours in an argon atmosphere; subsequently, a post diffusion follows at the same temperature in oxygen to reoxidize the material. We found that a subsequent electric field poling is not possible due to a shallow domain inverted layer on the +Z side of the sample. To obtain a single domain sample again this layer is removed by careful grinding. In order to get a periodic microdomain structure of excellent homogeneity a two step electric field poling technique has been developed. By a first poling step the spontaneous polarization of the whole substrate is reversed. In this way the waveguides come to the +Z-face preferred for periodic poling. As the growth of the microdomains always starts from the +Z-face the periodic electrodes are fabricated here on top of the waveguides. In this way the domains become more precisely defined in a surface layer including the waveguide. A periodic photoresist structure is formed on the sample surface and then immersed in LiCl dissolved in isopropylalcohol used as liquid electrode. Subsequently, periodic poling is accomplished by application of a high voltage to exceed the coercitive field strength of $LiNbO_3$ of about 21 kV/mm. The polishing process is controlled by monitoring the current flow through the crystal. Poling is stopped, when the charge corresponds to an empirically determined value to get a 50 % duty cycle of the domain pattern. The total length of the periodically poled region is up to 90 mm. Finally, thermal annealing at >120°C over 2 hours is performed to reduce the optical losses induced by electrical and mechanical stress.

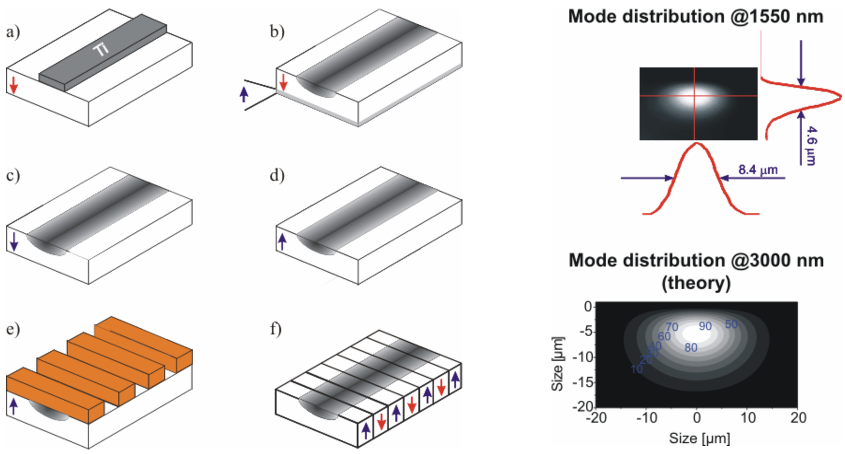

Fig. 1. Left: Fabrication of periodically poled Ti.$LiNbO_3$ waveguides: a) photolithographic definition of a Ti-stripe and in-diffusion afterwards; b) removal of a domain inverted layer on the +Z face; c) reversal of the spontaneous polarization of the sample as a whole; d) definition of the periodic electrode; e) electric field poling; f) thermal annealing. Right: Measured (λ=1550 nm) and calculated (λ=3000nm) mode distributions.

The technique described above allows fabricating straight waveguides with a length of up to 95 mm (limited by the wafer diameter of up to 4 inches). However, as the efficiency of all nonlinear frequency conversion processes strongly growths with the interaction length longer, periodically poled waveguides of excellent homogeneity are highly desirable. Therefore, we recently developed a technique to fabricate such waveguides as bent structures with a radius of curvature from 20 to 36 mm. These bent guides of up to 180 mm length were prepared by the indiffusion of photolithographically delineated 160 nm thick Ti-stripes of 18 µm width with two straight parts of 37 mm length oriented parallel to the crystallographic X-axis and a bent one to connect them forming a “U” as shown in Fig. 2. Subsequently, the periodic domain inversion was performed such that the domain orientation is always parallel to the crystallographic axes; the poling period is 31.6 µm.

After polishing the end faces the waveguides were characterized. In particular, the propagation losses were determined with the low finesse method[1] using a He-Ne laser (λ = 3394 nm); in some waveguides the losses are as low as 0.03 dB/cm. Moreover, the near field distribution of the fundamental mode was measured with a camera in the near infrared (see Fig. 1, right).

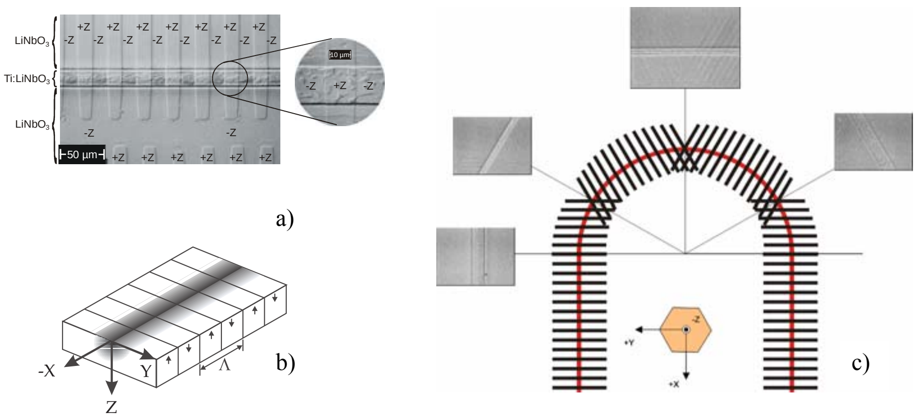

Fig. 2. a) Top view of the (selectively etched) ferroelectric domain structure along a straight waveguide; b) Orientation of the optical axes in the sample; c) Top views of parts of the (selectively etched) ferroelectric domain structure oriented parallel to the crystallographic axis.

To set up resonators external dielectric mirrors on a sapphire substrate have been clamped to the waveguide end faces (Fig. 3, left). Alternatively, using ion beam assisted evaporation dielectric MIR-mirrors with up to 12 layers of SiO_2 and TiO_2 of optimized thickness have been deposited on the waveguide end faces. An example of a corresponding spectral mirror characteristic is shown in Fig. 3 on the right; the reflectivity above 2700 nm wavelength approaches 99 %, whereas in the pump band around 1550 nm a residual reflectivity < 20 % remains. Depending on waveguide parameters, pump wavelength and mirror characteristics singly or doubly resonant parametric oscillation is achieved[2].

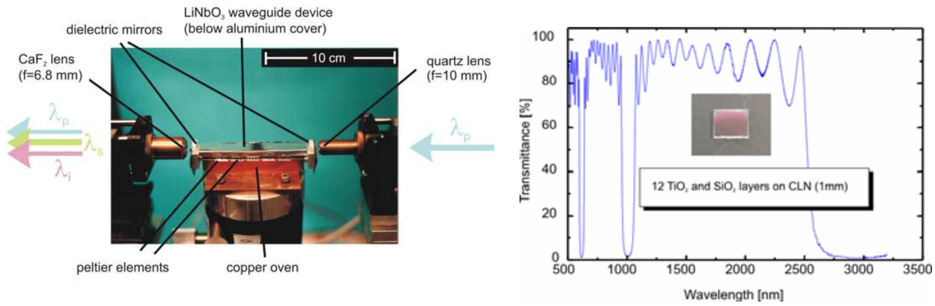

Fig. 3.: Left: Ti:PPLN sample in a holder with clamped external mirrors; Right: Transmisssion of the dielectric cavity mirrors of a doubly resonant MIR-IOPO versus wavelength.

3. Experimental Setup

A schematic diagram of a typical experimental setup to investigate OPGs and OPOs is presented in Fig. 4. As pump laser either an external cavity semiconductor laser (ECL) or a DFB-laser diode ($\lambda = 1552$ nm) or an actively mode locked fiber laser (MLL) was used. The ECL-laser could be tuned in the range $1535 < \lambda < 1620$ nm emitting up to 5 mW output power in a cw-mode of operation; the MLL could be tuned from $\lambda = 1541$ nm to 1564.5 nm emitting pulses of 6.4 ps width at 10 GHz repetition rate with up to 20 mW average power. The polarization controller was used to adjust TM polarization of the pump radiation to exploit the strongest nonlinear coefficient d_{33} of lithium niobate.

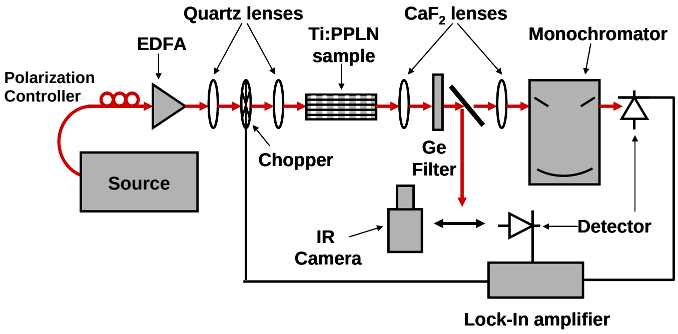

Fig. 4.: Schematical experimental setup to investigate integrated OPGs and OPOs.

The pump wave was amplified in an erbium doped fiber power amplifier (EDFA) to get an average output power up to 1.5 W. Coupling to an OPG or OPO with Ti:PPLN waveguide was done via bulk quartz lenses. The generated signal and idler radiations were measured with an IR detector (HgCdZnTe or

InSb); the resulting electrical signals could be amplified by a lock-in amplifier (in that case a mechanical chopper was inserted in the pump beam). A Germanium filter behind the sample was used to block the pump power. For spectral investigations a grating monochromator was used.

4. Optical Parametric Generators (OPG)

The generation of optical parametric fluorescence (OPF) in bulk nonlinear crystals is a well-known method for frequency down-conversion of coherent laser radiation[3]. It is mainly used for spectroscopy in the near (NIR) and mid (MIR) infrared. 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[4,5].

Using the setup as described above continuously tuneable, quasi phase matched MIR-OPF in the wavelength range 2800 nm < λ_s, λ_i < 3400 nm was generated in up to 94 mm long straight Ti:PPLN waveguides; their fabrication has been described in chapter 2. As the growth of the OPF power strongly depends on the interaction length also very long (up to 180 mm) bent Ti:PPLN waveguides were used for OPG. Calculated results presented in Fig. 5 demonstrate the huge growth of OPF power by increasing the waveguide length.

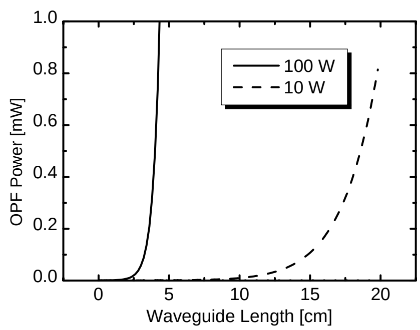

Fig. 5.: OPF (λ_s = 2849 nm; λ_I = 3400 nm) output power as function of the waveguide length; parameters are the coupled pump power levels (λ_p = 1550 nm).

Another theoretical analysis has been performed, which describes without any fit parameter the OPF output power from the fW (spontaneous photon pair generation) up to the 100 W level (strong pump depletion) as function of the pump power (see also Fig. 8).

Fig. 6 shows as an example 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[6]. The coupled (cw) pump power was approximately 700 mW. The MIR-OPF was continuously tunable from 2819 to 3394 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, selected spectral characteristics are given in Fig. 5 together with the calculated responses; the differences originate from residual, small waveguide inhomogeneities. All peaks become broader with increasing pump wavelength in good agreement with modelling results.

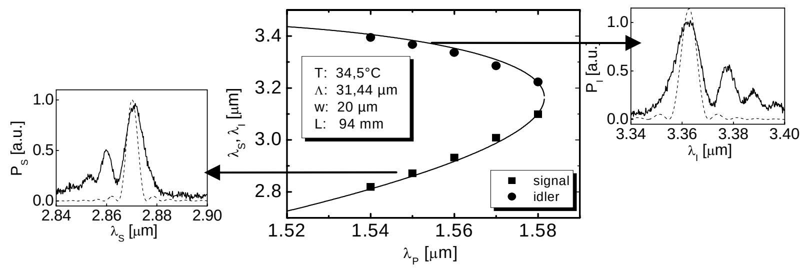

Fig. 6. Measured and calculated tuning characteristics of OPF as signal and idler wavelengths versus the pump wavelength in cw-operation (middle diagram) and signal (left graph) and idler (right graph) spectra for the pump wavelength 1548.5 nm as an example.

Measured and calculated data of the total OPF output power (signal and idler) are presented in Fig. 7 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[7]. 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.

To increase the (peak) power levels and in this way the conversion efficiency a MLL with 6.4 ps pulses of different duty cycles (1:18, 1:125, 1:250, 1:500 and 1:10000) were used; the pulses were (in the last case stretched), amplified by an high power EDFA, (and compressed again) as shown in Fig. 3. The experimental results are plotted in Fig. 8 as total (signal and idler) OPF output peak power versus coupled pump peak power using the optimistic data deduced from

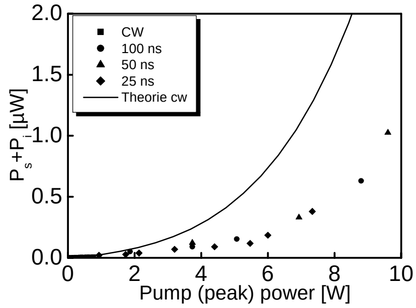

Fig. 7. Total OPF output peak power versus coupled pump power (DFB laser, λ_p=1552 nm) in a pulsed mode of operation (1 MHz repetition rate) for different pulse width (dots) compared with a theoretical calculation (solid line).

the 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[8].

The predicted high conversion efficiency with strong pump depletion has not yet been achieved due to large pulse distortions in the EDFA; the true pump peak power levels are considerably smaller than plotted in the Fig. 8 and also the spectrum of the high power pump pulses is far away from being transform limited. Nevertheless, there is a good chance to get OPF up to pump depletion if better defined pulses are used.

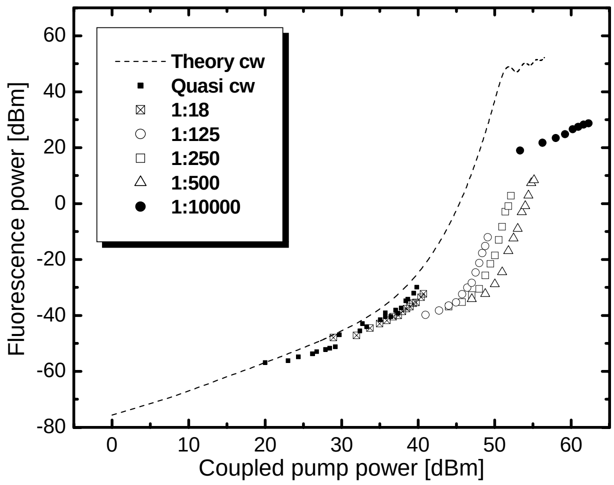

Fig. 8. Total OPF output (peak) power versus coupled pump (peak) power in a pulsed mode of operation (6.4 ps pulses of different duty cyle as given in the inset) compared with results of a theoretical analysis (dotted line).

5. Optical Parametric Oscillators (OPOs)

As seen above the OPF power grows (by parametric amplification) in an OPG along the interaction length in the waveguide sufficient pump power provided. At relatively low pump power levels the parametric gain (over-) compensates the inherent (absorption and scattering) propagation losses of an optical mode. In this case optical feedback, as provided by a resonator, can give rise to optical parametric oscillation sufficiently high mirror reflectivities provided. Above oscillation threshold a further growth of signal and idler waves continues with increasing pump power level until depletion of the pump wave and resulting gain saturation set in.

Depending on the mirror characteristics singly (resonant for signal or idler only) and doubly (for both, signal and idler) resonant OPOs can be designed. They mainly differ by their spectral fine tuning properties, threshold and conversion efficiency. Even pump resonant (bulk) devices have already been demonstrated.

In comparison to their bulk counterparts integrated OPOs promise a substantially (up to two orders of magnitude) lower oscillation threshold, a higher stability with respect to ambient fluctuations and guarantied spatial single mode emission, if a single mode waveguide is used.

Moreover, there is a great potential to monolithically integrate (intra-cavity) components such as electro- and acousto-optical tuneable filters, phase and amplitude modulators, Bragg reflectors as wavelength selective mirrors, wavelength-dependent couplers to define separate cavities for signal and idler and even (tuneable) pump lasers in the same substrate. In particular the very low threshold levels, which can be achieved, underline the attractivity of an integrated optics approach. Fig. 9 presents the threshold pump power of singly and doubly resonant integrated OPOs as function of the mirror reflectivities; parameters are the waveguide propagation losses of the 80 mm long devices[9].

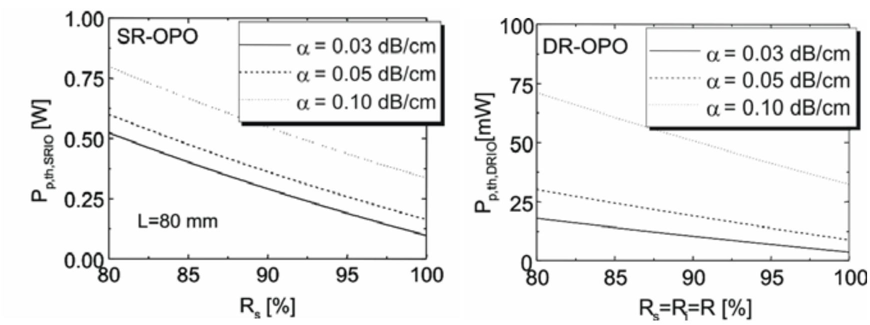

Fig. 9. Calculated threshold pump power of a SR-OPO (left) and of a DR-OPO (right) of 80 mm length as function of the reflectivity of the cavity mirrors.

In the following paragraphs we present singly and doubly resonant integrated OPOs for the mid infrared (MIR) spectral range (2700 nm < $\lambda_{s,i}$ < 3500 nm). They all have Ti:PPLN waveguides which are due to their low losses the preferred candidates for integrated MIR-OPOs. Doubly resonant OPOs could also be operated in a special pulsed mode of operation (synchronous pumping) resulting in the generation of short MIR-pulses of high peak power.

5.1. SINGLY RESONANT OSCILLATORS

Singly resonant (SR) integrated OPOs (SR-OPOs) are preferred in comparison with doubly resonant (DR) devices, if a high output power together with a high conversion efficiency (from the pump to the OPO-signal output) and stable, continuous wavelength tuning is required. On the other hand, the threshold power is higher.
Using an annealed proton exchanged waveguide a near-infrared device has been demonstrated with an oscillation threshold of 1.6 W[10]. On the other hand, low-loss Ti:$LiNbO_3$ waveguides allow to reduce the threshold considerably. The SR-OPO to be presented in the following 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. The substrate is periodically poled over a length of 80 mm with a domain periodicity of 31.3 µm.

Using dielectric mirrors on a sapphire substrate (R > 95% for 3200 nm < λ < 3800 nm, but R < 5% for 2650 nm < λ <2980 nm) in contact with the waveguide end faces the resonator of the SR-OPO has been realized. Fig. 10 presents on the left the power characteristics 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 modelling results. At a pump power level of 1.25 W the MIR emission (λ_s = 2883 nm, λ_i = 3364 nm) grows up to ~ 300 mW. Due to the singly resonant configuration of the oscillator the signal power always exceeds the idler power considerably. The output wavelength could be tuned within the range 2780 nm < λ_s, λ_i <3500 nm by changing the pump wavelength λ_p from 1530 nm to 1580 nm (see Fig. 10, right, expressed by corresponding frequencies). The linewidth of the emission can be below 170 MHz (the resolution limit of our Fabry-Pérot interferometer) corresponding to single frequency emission. Fine tuning of the emission over 4.5 GHz was possible by tuning the pump frequency by 2 GHz (see Fig. 10, right).

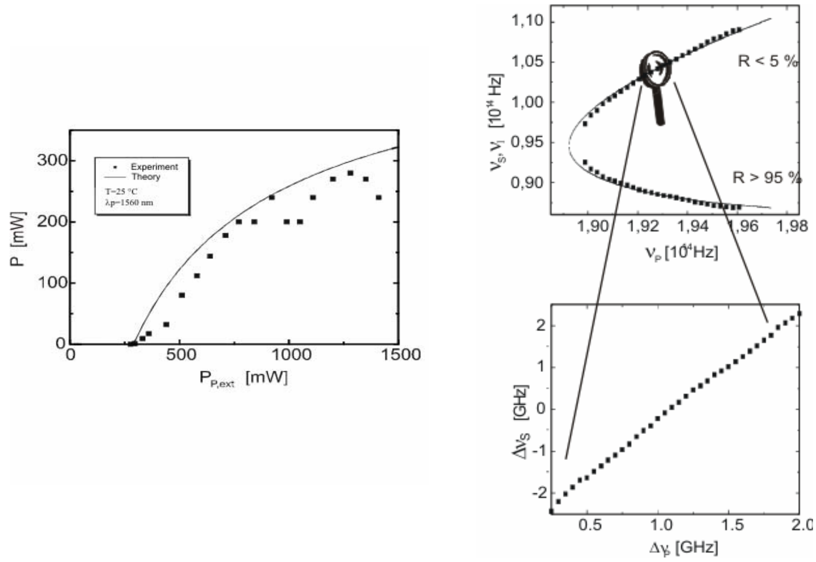

Fig. 10. Calculated (solid line) and experimental (dots) power characteristics of a singly resonant OPO with external mirrors as an average MIR output power versus the average pump power (left) and coarse and fine tuning characteristics (right).

5.2. DOUBLY RESONANT OSCILLATORS

In contrast to SR-OPOs doubly resonant devices (DR-OPOs) can have an extremely low threshold as already shown in Fig. 9. This property should allow pumping with semiconductor laser diodes in the future. On the other hand, DR-OPOs have a more complicated, sawtooth like fine tuning characteristics, which results from the resonance condition for both, signal and idler waves simultaneously.

5.2.1. *Continuous Pumping*

The DR-OPOs to be presented have 89.5 mm long straight Ti:$LiNbO_3$ waveguides in a 0.5 mm thick Z-cut, X-propagation $LiNbO_3$ substrate. The waveguide losses are as low as 0.03 dB/cm measured at λ = 3391 nm. The substrate is periodically poled with a domain periodicity of 31.3 μm. To set up the resonator either external mirrors in contact with the waveguide end faces or vacuum deposited end face mirrors have been used.

The external mirrors had reflectivities > 95 % in the wavelength range 2800 nm < λ < 3400 nm defining in this way the doubly resonant regime of the OPOs. The best device had a threshold of only 14 mW incident pump power (λ_p = 1541.5 nm), corresponding to about 10 mW coupled to the fundamental waveguide mode. A continuous tuning range of 2804 nm < λ < 3379 nm has been demonstrated in a DR-OPO of 17.5 µm waveguide width by changing the pump wavelength from 1532 nm to 1570 nm (see Fig. 11); the maximum output power was about 8 mW. The fine tuning behaviour is not only determined by energy conservation and quasi phase matching, but also by the double resonance condition for signal and idler. This leads to a sawtooth spectral dependence of about 180 GHz spectral width for e.g. the signal frequency as function of the pump frequency.

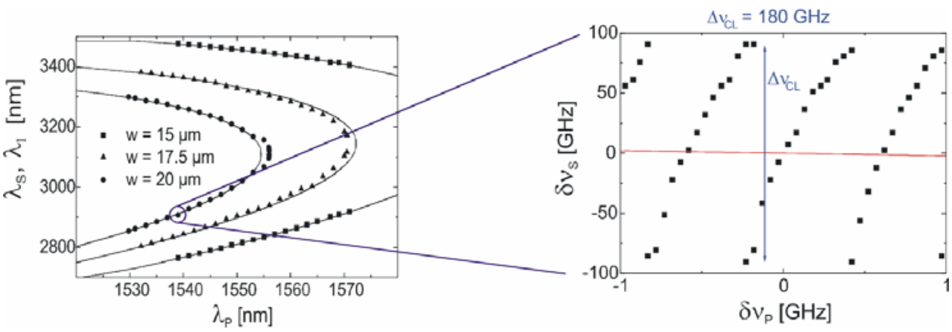

Fig. 11. Calculated (solid line) and experimental (dots) tuning characteristics of a doubly resonant OPO with external mirrors as MIR output wavelengths versus the pump wavelength (left) and fine tuning characteristics (right).

Vacuum-deposited end face mirrors have some advantages compared to external ones: no mirror adjustment is needed, the device becomes more compact and stable. However, coating the end faces with relatively thick, dielectric mirrors consisting of up to 12 SiO_2 and TiO_2 layers proved to be difficult as good homogeneity is required up to the sharp waveguide edge.

The total output power (signal and idler) versus pump power of the first integrated DR-OPO with dielectric end face mirrors is shown in Fig. 12; the waveguide parameters are given in the inset. The pump wavelength is λ_P = 1565 nm, resulting in a signal (idler) wavelength of 2988 nm (3286 nm). The oscillation threshold is 150 mW, whereas the corresponding theoretical result predicts a threshold of 50 mW (see Fig. 12). However, if we take into account that the calculated output power is plotted versus the coupled pump power (coupled to the fundamental mode), but the measured output is plotted versus the incident pump power (the coupling coefficient to the fundamental mode can only be estimated to be around 50 %) a relatively good agreement is found between experimental and theoretical results.

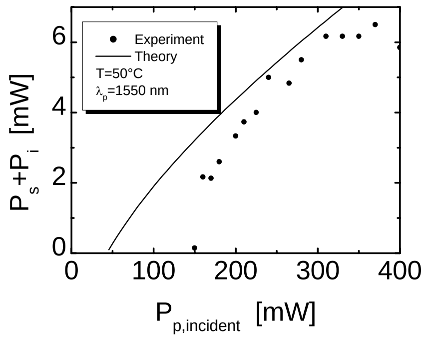

Fig. 12. Sum of signal (λ_s = 2988 nm) and idler (λ_i = 3286 nm) output power of the first IOPO with dielectric mirrors vacuum deposited on the waveguide end faces as function of the incident pump power (λ_p = 1565 nm).

5.2.2. *Synchronously pumped devices*

If an OPO is pumped periodically by short pulses - shorter than the round trip time within the cavity – short signal and idler pulses are generated and resonantly amplified after each round trip. This mode of operation is called synchronous pumping, applicable to SR-OPOs as well as to DR-OPOs. Again, the conversion efficiency and therefore the output power level depend on the type of OPO used (SR or DR).

We demonstrated synchronous pumping of a DR-OPO[11]. The amplified fibre MLL was used to get boosted 6 ps pump pulses of nearly 40 W peak power at a repetition rate of about 10 GHz resulting in an average power of 2 W. Though the group velocities of pump, signal and idler pulses are different in general, the special dispersion properties of $LiNbO_3$ (see Fig. 13, left) help to get resonant amplification inside the cavity. This is achieved, if the round trip time of either the signal or the idler pulses or approximately the average of both round trip times is equal to or a multiple of the repetition time of the pump pulses. As the repetition time of the pump pulses was nearly fixed to 100 ps, an OPO of the precise length of 6.805 mm or of an integer multiple of that number had to be designed. To have sufficient gain we fabricated a device of 6.805 cm length leading to 10 MIR pulses travelling inside the cavity simultaneously. A theoretical analysis reveals that the highest output power can be expected, if the time interval between two pump pulses (or their repetition time) matches exactly 10 times the round trip time of the idler or signal pulses[7]. This explains the two maxima shown in Fig. 13 on the right, where the calculated MIR output power is plotted versus the time interval between two pump pulses (or their repetition time), which can be adjusted by the repetition frequency of the mode locked pump laser. The modelling results are confirmed by experimental results plotted in Fig. 13b as well.

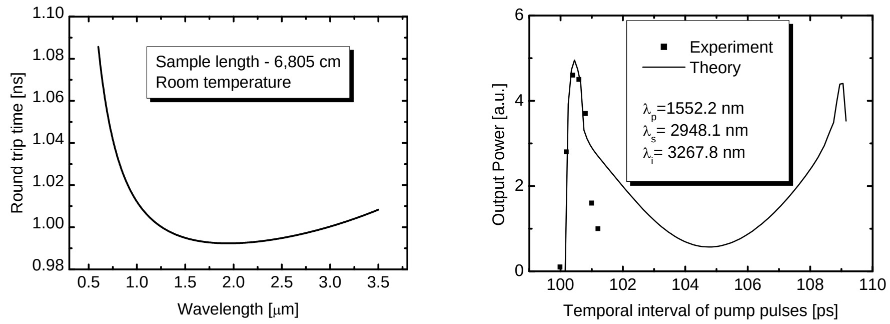

Fig. 13. Left: Pulse round trip time versus wavelength in $LiNbO_3$ waveguides of 6.803 cm length; Right: Calculated (solid line) and experimental (dots) power characteristics of a synchronously pumped DR-OPO with external mirrors as MIR output power versus temporal interval of pump pulses adjusted by the repetition rate of the mode locked pump laser.

Optical parametric oscillation was observed above a threshold of 300 mW (average) coupled pump power (λ_p = 1554.75 nm); at 600 mW more than 4 mW of MIR (average) power was generated. Fig. 14 shows on the left the power characteristics as signal and idler (average) power plotted versus the pump power. The results of modelling calculations using the parameters as in the inset give a similar dependence, but with a lower threshold (62 mW) and higher output power (see Fig. 14, right).

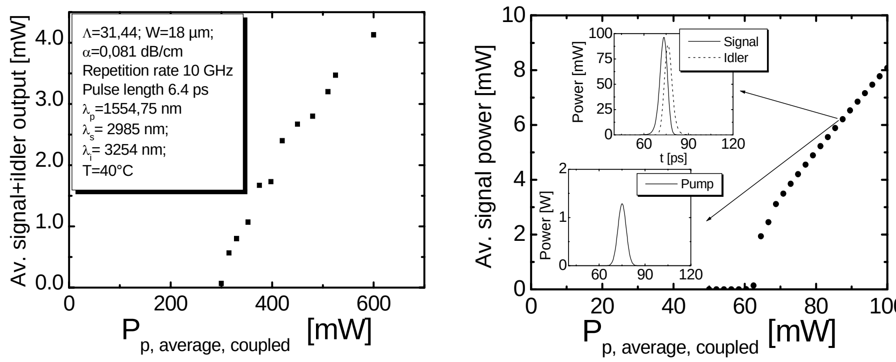

Fig. 14. Left: Measured power characteristics of the synchronously pumped OPO as average MIR output power versus the average pump power; Right: Calculated MIR power characteristics versus pump power and output pulses of pump, signal and idler as inset.

The MIR-pulses have not yet been investigated either with a fast detector nor with an autocorrelator. On the other hand, calculations predict that Gaussian pump pulses should result in nearly Gaussian signal and idler pulses of nearly the same width due to the small group velocity mismatch of the three pulses involved in the nonlinear interaction. Therefore, high MIR peak power levels can be expected (see the insets of Fig. 14, right).

It was possible to tune the output wavelengths in the range of 2850 nm < λ_s, λ_i < 3350 nm by changing the pump wavelength appropriately in the range 1545 nm < λ_p < 1565 nm.

6. Conclusions

The state of the art of quasi phase matched integrated optical parametric generators and oscillators was reviewed. The core of these devices is a periodically poled Ti:$LiNbO_3$ waveguide of propagation losses down to 0.03 dB/cm and a length up to 180 mm. These properties enable the development of efficient, tuneable, compact light sources for the mid infrared (2700 nm < $\lambda_{s,i}$ < 3500 nm) spectral range.

Continuously tuneable 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 tuneable lasers (ECL and fiber-MLL) have been used with emission in the wavelength range 1540 nm < λ_p < 1580 nm. The pump radiation was suitably modulated and amplified to generate MIR pulses of up to 1 W peak power.

A theoretical analysis without any fit parameter yielded the guided wave OPG characteristic as OPF power versus pump power from the fW (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 high pump peak power levels can be qualitatively explained by pump pulse distortions. Nevertheless, in comparison with bulk optics a pump power reduction of several orders of magnitude has been achieved.

Singly resonant cw-OPOs have been realized by using external mirrors with reflectivities > 95 % in the wavelength range 3200 nm < λ < 3800 nm (but < 5 % in the range 2650 nm < 2980 nm). The oscillation threshold of the best device is 275 mW incident pump power in good agreement with the modelling results. At a pump power of 1.25 W a MIR output (λ_s = 2883 nm, λ_i = 3364 nm) of 300 mW has been achieved. Due to the singly resonant configuration of the oscillator the signal power always exceeds the idler power considerably. The output wavelength can be tuned within the range 2720 nm < λ_s, λ_i < 3500 nm by changing the pump power wavelength from 1530 nm to 1580 nm; the linewidth of the emission might be below 170 MHz (our resolution limit) corresponding to single frequency emission.

Doubly resonant parametric oscillators have been set up with straight Ti:PPLN channel guides using external mirrors with reflectivities > 95 % in the wavelength range 2800 nm < λ < 3400 nm. The best device has a threshold of only 10 mW coupled pump power (λ_p = 1541.5 nm) in cw-operation. A continuous tuning range of 2804 nm < λ < 3379 nm has been demonstrated by tuning the pump wavelength from 1532 nm to 1570 nm; the maximum output power is about 8 mW. The fine tuning behaviour is determined by a sawtooth tuning characteristics of about 180 GHz spectral width as known from bulk OPOs. Also doubly resonant OPOs with dielectric mirrors vacuum-deposited on the waveguide end faces have been developed; their oscillation threshold is somewhat higher than with external mirrors.

Using a tuneable mode-locked fiber laser (10 GHz; 6.4 ps; 1545 nm < λ < 1565 nm) as pump source, short MIR-pulses (2850 nm < λ_s, λ_i < 3350 nm) have been generated by synchronous pumping of a specially designed 68.05 mm long, doubly resonant structure. The threshold (average) pump power is 300 mW (λ_p = 1554.75 nm); at 600 mW more than 4 mW of MIR (average) power is emitted. The results of modelling calculations indicate a great potential for further improvements.

More complex OPOs with additional intracavity components such as wavelength splitters and phase shifters will be developed in the future to obtain true continuous tuning.

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