Efficient Second Harmonic Generation in Matched Ti:PPLN Waveguide Resonators

R. Nouroozi, Y. H. Min, W. Grundkötter, V. Quiring, R. Ricken and W. Sohler

Angewandte Physik, Universität Paderborn, Warburger Str. 100, 33098 Paderborn, Germany
email: sol_rn@physik.uni-paderborn.de

Abstract: *Second harmonic generation in Ti:PPLN waveguide resonators is investigated as a means of enhancing the conversion efficiency. Using a matched resonator of 65 mm length a record conversion efficiency of 10.3 %/mW is achieved with 0.5 mW fundamental power at λ_f = 1531 nm.*

Introduction

Second harmonic generation (SHG) in waveguide resonators has been investigated in detail many years ago [1,2]; at that time phase matching was usually achieved by exploiting the birefringence of the waveguide material. This was a strong limitation for the possible wavelength combinations of a three wave nonlinear second order interaction. Moreover, it was not possible to exploit the largest nonlinear coefficient. With the advent of periodically poled substrate materials quasi phase matching became possible. It proved to be a very versatile method allowing nearly arbitrary wavelength combinations and the exploitation of the largest nonlinearity. In the meantime single pass SHG and other parametric interactions have been demonstrated in periodically poled materials with excellent efficiencies for wavelengths in different spectral ranges from the UV to the infrared [3,4]. Moreover, quasi phase matched SHG is exploited in a number of devices using cascaded $\chi^{(2)}:\chi^{(2)}$ interactions for all-optical signal processing such as wavelength conversion and optical time-division multiplexing [5,6].

It is surprising that up to now SHG in periodically poled waveguide resonators has not yet been studied though power enhancement and the higher nonlinearity promise a significant enhancement of the conversion efficieny.

Several nonlinear substrate materials can be used to develop periodically poled waveguide resonators. Among them ferroelectric crystals such as Potassium Titanium Oxide Phosphate (KTP), Lithium Tantalate, and Lithium Niobate (LN) are the preferred candidates. We are using the standard Ti-indiffusion technique to fabricate optical channel guides of excellent quality in Periodically Poled Lithium Niobate (PPLN). Very good homogeneity of all waveguide properties can be achieved over a length of up to 95 mm enabling quasi phase matched nonlinear interactions of high efficiency. Moreover, the low propagation losses of Ti:PPLN guides (down to 0.05 dB/cm around λ = 1550 nm) allow the development of high Q waveguide resonators as already exploited e.g. in different types of optical parametric oscillators [7].

In this contribution SHG in matched Ti:PPLN waveguide resonators for the fundamental wave is reported. The realization of this concept, which leads to the maximum intracavity power enhancement and, therefore, to the maximum conversion efficiency, is experimentally demonstrated. A record conversion efficiency of 10.3 %/mW has been achieved with 0.5 mW fundamental power at λ_f = 1531 nm.

Modelling

The theory of SHG in (Fabry-Perot-type) waveguide resonators has been presented long time ago [2]. Only resonances of the fundamental wave have been considered up to now. The key results will be mentioned here again, to highlight the advantages of SHG in waveguide resonators. The main advantage is the large intracavity enhancement of the fundamental power, if low loss waveguides and appropriate mirrors are used. This enhancement can be described by a resonance factor f with:

$$f = \frac{1 - R_f}{\left[1 - (R_f R_r)^{1/2} \exp(-\alpha_\omega l)\right]^2} \qquad (1)$$

R_f and R_r are the reflectivities of the front and rear mirror of the resonator, respectively; α_ω is the loss coefficient describing the propagation loss of the fundamental wave; l is the sample length.

If no transmitted fundamental power is needed R_r can be set to 1. Then R_f is determined by the condition for maximum power enhancement or maximum f yielding:

$$R_{fm} = R_r \exp(-2\alpha_\omega l) \qquad (2)$$

Such a front mirror reflectivity leads to zero reflectivity at maximum resonance; all the input power is used for intracavity power enhancement limited by (scattering) losses alone. The maximum enhancement factor of such a “matched” resonator is given by:

$$f_m = \frac{1}{1 - R_{fm}} \rangle 1 \qquad (3)$$

This power enhancement leads in the nondepleted pump approximation to a corresponding enhancement of the conversion efficiency for SHG:

$$\eta_{res} = \eta f^2 \qquad (4)$$

with the single pass, nonresonant efficiency η.

As shown in [2], η_{res} is only weakly dependent on the length of a matched resonator, but strongly on the propagation losses α_ω. Fig. 1 shows this dependence as f^2 versus α_ω for parameters as used in our experiments (λ = 1550 nm; l = 65 mm); note, that the reflectivity of the front mirror is continuously adjusted according equation (2). It is seen that an improvement of the conversion efficiency for SHG of more than 100 can be expected low loss waveguides assumed! Therefore, matched waveguide resonators are most attractive devices for efficient second harmonic generation.

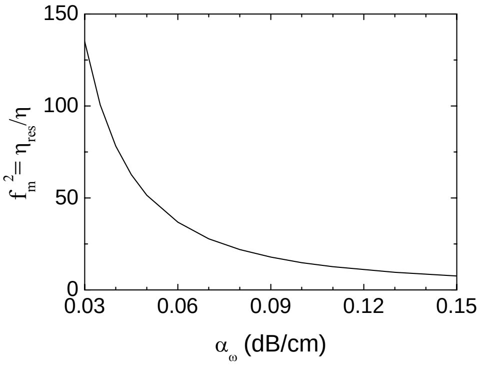

Fig. 1: Calculated ratio of SHG efficiency η_{res} in a matched resonator and efficiency η of a single pass nonresonant device as function of waveguide propagation losses α_ω at the fundamental wavelength.

Fabrication and experimental setup

In a first step 65 mm long single mode channel waveguides have been fabricated in a 0.5 mm thick Z-cut LN substrate. Photolithographically defined, 7 µm wide, vacuum-deposited Ti-stripes of 98 nm thickness have been indiffused (8.5 h @ 1060°C) to form the optical waveguides. They have been aligned parallel to the X-axis of the crystal. In the second step, the sample has been periodically poled by the electric field assisted poling technique using liquid electrodes. The periodicity of the microdomain structure is 16.6 µm allowing quasi-phase-matched SHG at 1531 nm fundamental wavelength. In the third step, the end faces of the waveguides have been polished perpendicular to the waveguide axis. Finally, dielectric end face mirrors of special properties have been prepared by vacuum-depositing. On one hand, both, input and output mirrors, should have a negligeable reflectivity at 765 nm wavelength, but a high reflectivity at 1530 nm. To be specific, according to theoretical results the reflectivity of the input (output) mirror should be 76% (> 99%) to get a matched resonator for most efficient SH-generation by maximum intracavity fundamental field enhancement. Modelling calculations show that 5 (6) pairs of SiO_2 and TiO_2 layers will form dielectric multilayer mirrors of the required spectral properties. Fig. 2 presents the measured transmission of input and output mirrors. The resulting reflectivities are 3% (at λ = 765 nm) and 74% (at λ = 1530 nm) for the input mirror; the corresponding data for the output mirror are 3% and 99%.

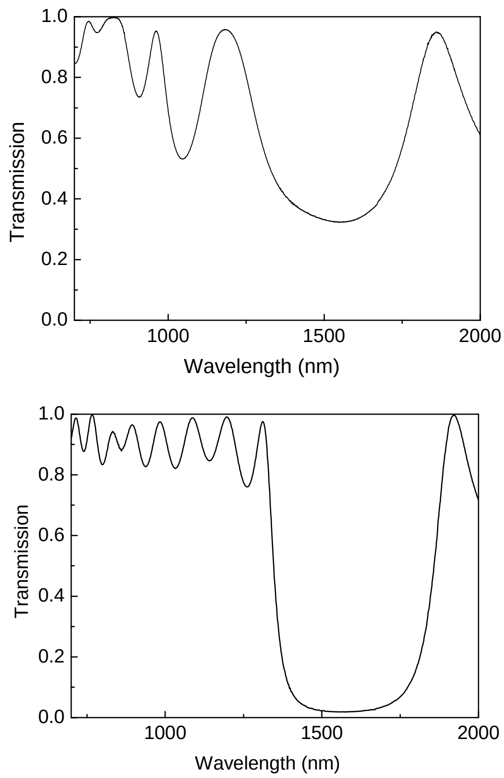

Fig. 2: Simulated and measured transmission spectra of the input (above) and output mirror (below) of the matched waveguide resonator.

The experimental setup to investigate SHG in the matched Ti:PPLN waveguide resonators is shown in Fig. 3. The sample is mounted on a thermoelectric cooler/heater, which allows a temperature stabilisation of about ± 1°C. A semiconductor Extended Cavity Laser (ECL) is used as tuneable coherent light source of about 150 kHz instantaneous linewidth. It can be continuously tuned in a small wavelength range enabling to sweep over some cavity resonances. The light is fed into the sample via a 10/90 fiber coupler to monitor the reflected fundamental power by a Ge-photodiode. The generated SH output power is measured by a Silicon photodiode, which is sensitive at the SH-wavelength only.

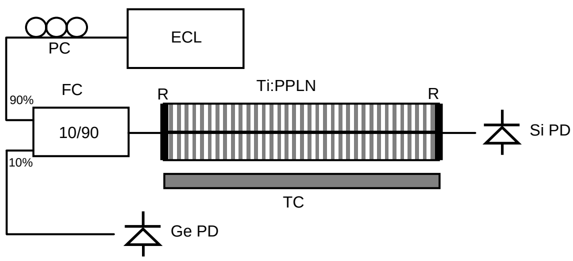

Fig. 3: Experimental Setup: ECL-tuneable, semiconductor Extended Cavity Laser; PC-polarization controller; FC-fiber coupler; R_1 and R_2-dielectric end face mirrors; TC-thermoelectric cooler/heater; PD-photo diode.

Results and discussion

Fig. 4 presents the measured reflected fundamental power versus wavelength around the expected phase match wavelength of 1531 nm; the input power was 0.5 mW. Using experimentally determined waveguide parameters (R_{in} = 74%, R_{out} = 98.6%, α = 0.084 dB/cm, l = 65 mm) also simulated results are given. As predicted for matched resonators the reflected power nearly drops to zero in a resonance due to maximum fundamental power enhancement. The agreement of theoretical and experimental results is relatively good; only the measured drop in the resonances is somewhat smaller than calculated.

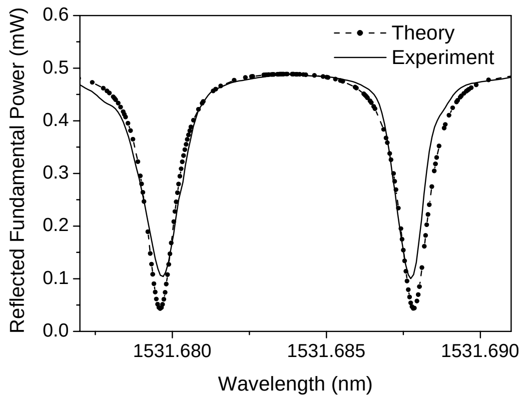

Fig. 4: Measured and calculated reflected fundamental power versus wavelength for an input power of 0.5 mW

In Fig. 5 the generated SH-power (at $\lambda \sim 765$ nm) is shown as function of the wavelength of the fundamental radiation. Again, the fundamental power in front of the waveguide resonator is 0.5 mW. SHG can be observed in a large number of cavity resonances (not completely resolved). The envelope of the SH-power reflects the phase match properties of the waveguide. Due to inhomogeneities, which might be arise from inhomogeneities of the substrat or /and of the fabrication process, not a sinc^2-response is observed. The wavelength of the laser can be stabilized to a single resonance by a proper feedback to the laser power supply.

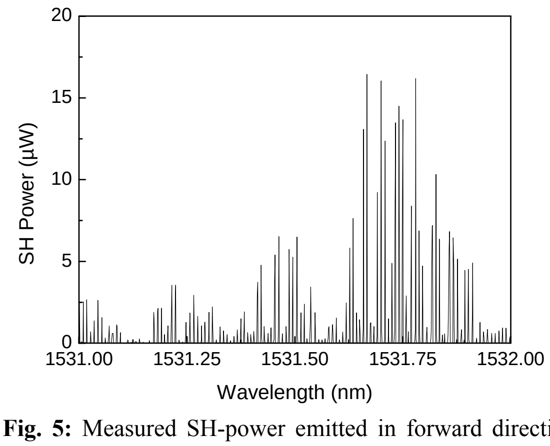

Fig. 5: Measured SH-power emitted in forward direction from a matched Ti:PPLN waveguide resonator versus fundamental wavelength around phase matching. Fundamental power is 0.5 mW.

The results of SHG in the two neighbouring resonances of highest efficiency are presented in Fig. 6. With only 0.5 mW of fundamental power, measured in front of the waveguide resonator (not coupled), a SH power of 25.8 µW was generated in forward direction. This corresponds to a record conversion efficiency of the device of 10300 %/W or 10.3 %/mW in reasonable agreement with the theoretical simulation. This impressive efficiency can even be doubled by using an appropriate input mirror of high reflectivity and appropriate phase for the SH-wave. A further improvement should be possible with a doubly resonant device, which is currently fabricated and investigated in our lab.

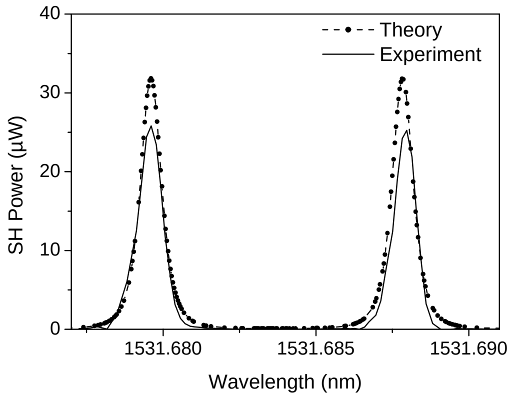

Fig. 6: Measured SH-power emitted in forward direction from a matched Ti:PPLN waveguide resonator versus fundamental wavelength around the two resonances of highest efficiency. Fundamental power is 0.5 mW.

Conclusions

In conclusion, SHG in Ti:PPLN waveguide resonators for the fundamental wavelength has been investigated. Theoretical modelling helped to identify matched resonators as optimum devices for maximum conversion efficiency. Based on these results corresponding Ti:PPLN resonators with appropriate dielectric mirrors have been developed. In a device of 65 mm length a record conversion efficiency of 10.3 %/mW has been achieved with 0.5 mW fundamental power at λ_f = 1531 nm.

A further improvement of the efficiency can be expected by devices, which are doubly resonant for fundamental and SH-waves simultaneously.

Acknowledgments

This work has been supported by the DFG (Deutsche Forschungsgemeinschaft) within the frame of the research unit "Integrated Optics in Lithium Niobate: New Devices, Circuits and Applications". The authors would like to acknowledge helpful discussions with H. Suche and S. Orlov.

References

1 R. Regener et al., *Digest of 1st European Conference on Integrated Optics* (ECIO), p. 19, 1981
2 R. Regener et al., J. Opt. Soc. Am. B, Vol. 5, No. 2, p. 267, 1988.
3 K. R. Parameswaran et al., Opt. Lett. Vol. 27, No. 3, p. 179, 2002
4 M. Fujimura et al., Electron. Lett., Vol. 28, No. 20, p. 1868, 1992
5 S. L. Jansen et al., J. Lightwave Technol., Vol. 24, No. 1, p. 54, 2006
6 C. Langrock et al., J. Lightwave Technol., Vol. 24, No. 7, p. 2579, 2006
7 G. Schreiber et al., Proc. SPIE, Vol. 4277, p. 144, 2001