A fs-laser written waveguide in periodically poled $Rb:KTiOPO_4$ for efficient second harmonic generation

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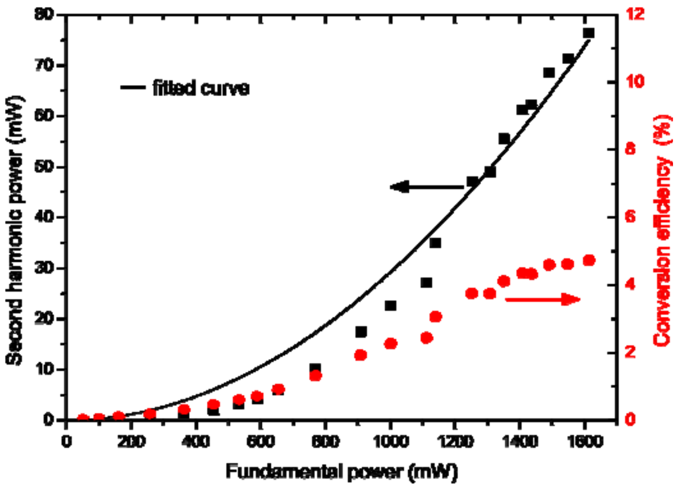
Abstract: A femtosecond Ti:sapphire laser was used to inscribe low loss waveguides with the double-track method in a 9.5 mm long periodically poled $Rb:KTiOPO_4$ sample. 76mW of stable blue light was obtained in a second harmonic generation experiment using a fundamental power of 1.6W from a continuous wave Ti:Sapphire laser at a wavelength of 943.18 nm resulting in a normalized conversion efficiency of 4.6%$W^{-1}cm^{-2}$.

Introduction: Three dimensional microstructures can be formed in transparent dielectrics by intense laser radiation. Fs-laser radiation focused underneath the material surface creates a refractive index modification or micro destruction[1]. By proper choice of the fabrication parameters and the arrangement of the modifications, waveguiding structures in passive and active glasses as well as in crystals have been realized[2]. The so called "double-track method" in which waveguiding is appearing between the tracks has in most cases given waveguides with the lowest loss in crystalline materials[3].
With the advent of periodic poling (PP) efficient quasi-phasematching (QPM) has become a versatile technique in nonlinear optics. PP-crystals from the $KTiOPO_4$ (KTP) family are preferred for the generation of visible light thanks to their strong resistance to optical damage and the possibility to pole dense gratings of high quality. Rb doped KTP (RKTP) is the latest introduced material in this class where the slight Rb-doping facilitates the periodic poling, and reduces the linear absorption[4]. Ion-exchanged waveguides in $KTiOPO_4$ (KTP) have been extensively used in nonlinear applications[5]. However, at high power operation the electric field drives the diffused ions deeper into the substrate and the effective mode indices changes, which also shifts the phase matching condition. This is detrimental in most cases[6].
Laser writing is a potentially interesting, novel, alternative to ion-exchanged, ion-implanted and diffused waveguides for nonlinear optical applications. Fs-laser inscribed waveguides in PPKTP were first demonstrated by Campbell *et al.*[7]. They achieved 0.22%W^{-1} normalized conversion efficiency in first order QPM second harmonic generation (SHG) of 980 nm and 0.02%W^{-1} third order QPM of 800 nm radiation. In our recent work we introduced the double-track writing method and obtained low loss waveguides in KTP and used those for broad bandwidth type II SHG generating 1.3 mW of green light[7]. In this work we applied the writing method to PPRKTP and demonstrate efficient blue light quasi-phasematched SHG without any long term drift as previously observed with ion-exchanged KTP waveguides[6].

Experiment: A 1 mm thick RKTP crystal was periodically poled with a 6.03 μm period and a grating length of 8 mm. Prior to waveguide writing the bulk PPRKTP sample was characterized for SHG with a Ti:sapphire-laser. A maximum power of 0.45 mW at 180 mW launched IR radiation at 943.40 nm was measured after the sample, corresponding to a normalized conversion efficiency of 1.74%$W^{-1}cm^{-1}$ and an effective nonlinear coefficient, d_{eff} = 11pm/V.
For waveguide fabrication a chirped pulse femtosecond Ti:sapphire amplifier was employed. The radiation was focused 250 μm underneath the polished surface of an 11 mm long, 1 mm thick *z*-cut PPRKTP crystal. During the writing process, the crystal was translated along the *x*-axis with a velocity of 25 μm/s, using a motorized translation stage. Several waveguides were written with different track distances and pulse energies and finally the end faces were polished giving a device length of 9.5 mm. The waveguide, which later gave the highest SHG and conversion efficiency was written with a pulse energy of 3.2 μJ and a track distance of 18 μm. The losses were measured with a HeNe-laser at

632.8nm and a cw Ti:sapphire-laser at 940 nm. The lasers were vertically polarized to excite the TM modes. The combined incoupling and propagation losses for the above mentioned waveguide were 2.2 dB in the IR and 1.6 dB in the visible, respectively.
The Ti:sapphire laser was then used as the fundamental source for the SHG measurements. The sample was temperature controlled at room temperature. 76 mW of stable blue light were obtained for an incident fundamental power of 1610 mW at 943.18 nm (see Fig. 1). This corresponds to a conversion efficiency of η = 4.7% and a normalized conversion of η_{norm} = 4.6%$W^{-1}cm^{-2}$. The phase-matching bandwidth, 3.3 $^{\circ}$C, was the same as for the bulk measurement indicating a homogeneous waveguide.
In the figure a square-fit of the SH power vs. incident fundamental is depicted. One can see a slight deviation from a smooth fit at around 1.1 W of input power caused by thermally induced dephasing. To compensate for it a minor wavelength adjustment was done. The dephasing comes from the non-negligible absorption in the visible for RKTP[8], which leads to heating of the waveguide at high power and a small shift of the phase-matching wavelength. The phase-matching wavelength could be temperature tuned from 942.36 nm at 8.5°C to 945.35 nm at 65°C, i.e. by 0.053 nm/$^{\circ}$C. The mode sizes of the fundamental and second harmonic were both elliptically shaped with dimensions of 12.8 μm × 22.3 μm (IR) and 9.4 μm × 11.8 μm (blue), but with their center of gravity at almost the same spatial position, which is important for getting a good mode overlap and high conversion efficiency. The latter is in contrast with the case of SHG in annealed proton-exchanged waveguides in $LiNbO_3$, where the visible mode is strongly bound close to the surface, while the fundamental mode penetrates much deeper into the substrate, which reduces the overlap and hence ultimately limits the conversion efficiency.



Conclusions: Efficient and stable second harmonic generation into the blue spectral region has been demonstrated using a femtosecond-laser written waveguide in PPRKTP. The waveguide losses were estimated to be < 2.2 dB at 940nm and a maximum output power of 76 mW was obtained at 471.6 nm with an incident fundamental power of 1610 mW. The normalized conversion efficiency was η_{norm} = 4.6%$W^{-1}cm^{-2}$. Absorption of second harmonic led to heating of the waveguide and a weakly distorted phase-matching curve at maximum power. To a large extent this can be compensated for by slight cooling of the sample and it represents only a small reduction of the efficiency. If a waveguide with higher confinement could be fabricated and/or higher fundamental power used the SH power could hence be increased much further.
We believe that the waveguide fabrication process can be improved by optimizing the fs-laser writing parameters. A higher confinement, reduced waveguide loss and even better overlap between the fundamental and SHG modes are the primary properties to address. This new type of nonlinear waveguide device could have interesting applications, for example in biotechnology or quantum optics, if combined with a wavelength stabilized diode or fiber laser.

The authors are very grateful for the financial support by the graduate school 1355 "Physics with new advanced coherent light sources", the Linnaeus Center ADOPT, and the Swedish Research Council.

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