Laser written waveguides in KTP for broadband Type II frequency doubling

Fredrik Laurell, Carlota Canalias
Department of Applied Physics, KTH,
Albanova, Roslagstullsbacken 21,
106 91 Stockholm, Sweden
fl@laserphysics.kth.se

Thomas Calmano, Sebastian Müller, Günter Huber
Universität Hamburg, Institut für Laser-Physik, Luruper
Chaussee 149, 22761 Hamburg, Germany
tcalmano@physnet.uni-hamburg.de

Abstract— **Femto-second laser writing was used to fabricate waveguides in KTP with losses below 0.8 dB/cm. They were used for efficient broad bandwidth, Type II frequency doubling of cw Ti-sapphire laser radiation at 1080.4 nm.**

Keywords; laser written waveguides, low loss, broad bandwidth, KTP, type II frequency doubling

I. INTRODUCTION

$KTiOPO_4$ (KTP) is widely used in nonlinear optics thanks to its large nonlinear optical coefficients, good mechanical properties and strong optical damage resistance. Its extra-ordinary wide phasematching bandwidth for noncritical Type II frequency doubling with fundamental wavelengths around 1 µm has made it the material of choice for green laser [1]. High quality waveguides has been fabricated in KTP by Rb ion-exchange [2] and spontaneous domain reversal of the ion-exchanged region can be obtained, which has been utilized for fabrication of segmented waveguides for very efficient quasi-phase matching (QPM) [3]. However, these waveguides have reproducibility and stability problems [4]. Recently laser written waveguides were made in periodically poled KTP and used for frequency doubling [5],[6]. These were stable with circular mode-fields and used for fs-laser frequency doubling. However, the losses were much higher than for ion-exchanged waveguides, the phasematching bandwidth was narrower and the normalized conversion efficiency was far from ideal.

Three dimensional micro-structures can be fabricated in several dielectrics utilizing nonlinear absorption processes with focused femtosecond lasers [7]. Channel waveguides are made by focusing the laser radiation inside the sample, while the sample is translated. Simple straight waveguides as well as more complex passive structures as splitters and couplers have been made this way [8],[9]. Active devices like lasers and amplifiers have been obtained in rare-earth doped glasses, and crystalline hosts like Nd:YAG and Yb:YAG. The low loss has made it possible to obtain lasing with high slope efficiency (75%) and an output power of nearly 0.8W [10].

In this paper we present a modified laser waveguide writing procedure, which provide low loss, single-mode waveguides in KTP. These were used for Type II frequency doubling and provided broadband phasematching with close to ideal efficiency.

II. WAVEGUIDE FABRICATION

A set of x-propagating channel waveguides were produced in a z-cut flux grown KTP crystal (10×5×1 mm^3). Laser pulses at 775 nm with a pulse duration of 150 fs, and a repetition rate of 1 kHz were focused 150 µm below the polished surface of the crystals using an aspheric lens (N.A.=0.55). The crystal was translated transversally in the focused beam (spot size, 2 µm ($1/e^2$)) with a motorized translation stage at a velocity of 25 µm/s. The threshold for material modification was about 0.6 µJ and a pulse energy of 2.5 µJ was used to form the tracks/waveguides described below. Several different pairs of parallel tracks were inscribed in the sample and the distance between two adjacent tracks was changed between 16 µm and 25 µm to obtain waveguides with different width. After polishing the final length of the sample was 9.5 mm.

III. WAVEGUIDE CHARACTERISATION

The characteristic of laser written waveguides is the guiding next to the damaged region caused by a stress induced refractive index change [8]. When two tracks of damage are written into the crystal, see Fig. 1, guiding can be obtained in six positions around the tracks where the strongest confinements are in position a and b. The damaged regions were in

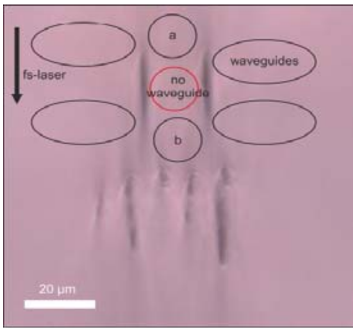

Figure 1 Bright-field microscope image of the end facet of the crystal where a pair of tracks with a distance of 18 µm was written.

this case approx. 21 μm in height and 3 μm in width. The modal properties depend on the track separation and the index modification. With a separation of 20 μm or less fundamental TE and TM modes could be guided, and when the tracks were placed further apart higher order transverse modes were guided. In Fig. 2 the TE near field for the two positions a and b can be seen when light from a HeNe laser was launched through the waveguide. In this case the track separation was 18 μm and the numerical aperture, N.A. =0.06.

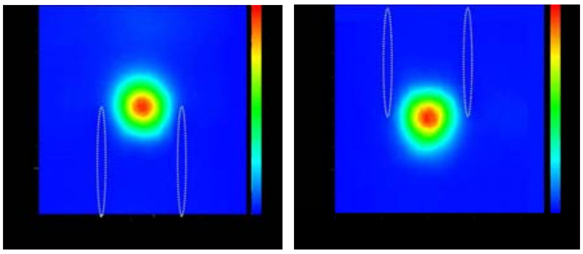

Figure 2.Near field intensity distribution at 633 nm for the two waveguides, a and b, in Fig 1. The tracks are indicated by white dotted lines.

The waveguide losses were quite low for all the waveguides written this way. A conservative upper limit for the single mode waveguides in Fig. 2 were estimated by coupling the HeNe laser through the waveguide and comparing launched and transmitted power. Taking the Fresnel reflections under consideration, but not the coupling losses gave a loss below 0.8 dB/cm for both the TE and the TM mode. A more accurate number must be determined with the interferometric technique developed by Regener and Sohler [12].

IV. FREQUENCY DOUBLING EXPERIMENTS

The waveguide was evaluated in a Type II frequency doubling experiment using a continuous wave Ti-Sapphire laser as the fundamental source. The condition for birefringent phasematching is obtained as,

$$\frac{1}{2}\left[n_z(\lambda_F) + n_y(\lambda_F)\right] = n_y(\lambda_F/2)$$

where the refractive indices are given by the Sellmeier's equations for KTP and d_{24} = 7.6 pm/V is the appropriate nonlinear coefficient [1]. This gives a bulk phasematching wavelength, λ_F, of just above 1080 nm at room temperature. As the index increase for these stress-induced waveguides is below 10^{-3} this means that the waveguide phasematching also should be obtained around this wavelength. Unfortunately this is in a wavelength region where the laser power has dropped to quite a low level. The Ti-sapphire radiation was rotated 45 degrees to simultaneously excite the TE_{00} and the TM_{00} mode and coupled into the waveguide with a 10x objective. The radiation at the output was collected with a 20x objective and imaged on a calibrated power meter. 7.3 μW of green light in the TE_{00} mode was generated with 8.0 mW at 1080.4 nm. It corresponds to a normalized efficiency of 11.5%/W, which is higher than what has been obtained previously using laser written waveguides in KTP, despite that those were done with QPM utilizing substantially higher nonlinear coefficients [5],[6].

Noncritical Type II phasematching for bulk KTP has a temperature bandwidth of 175°/cm [1]. A preliminary measurement of the bandwidth for our waveguides, when the sample was heated from room temperature to 80°, was in good agreement with this number. It should be compared to the temperature bandwidth for QPM frequency doubling, which is below 1°/cm in the same wavelength range.

V. CONCLUSIONS AND OUTLOOK

Femto-second laser writing was used to fabricate waveguides in KTP with losses below 0.8 dB/cm at 633 nm. Type II frequency doubling generated 7.3 μW of green light for 8.0 mW of input radiation at 1080.4 nm from a cw Ti-sapphire laser. This corresponds to a normalized conversion efficiency of 11.5%/W. The bandwidth for this process is so wide that no temperature control was required.

Further work, to be presented at the conference, will include frequency doubling using a high power, narrow linewidth, polarized, tunable, CW Yb- fiber laser as the source.

ACKNOWLEDGMENTS

We acknowledge support from the Linneus Center ADOPT financed by the Swedish Research Council, the Deutsche Forschungsgemeinschaft and the Joachim Herz Stiftung.

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