INTEGRATED OPTICS AND OPTICAL FREQUENCY CONVERSION

Second-Harmonic and Sum-Frequency Generation in $KNbO_3$ Waveguides

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Blue light generation by nonlinear optical interactions, such as second-harmonic generation (SHG) and sum-frequency generation (SFG) with diode lasers (e.g. AlGaAs and InGaAs) or diode-pumped solid-state lasers (e.g. Nd:YAG and Cr:LiSAF), is an attractive approach to realize a compact all solid-state blue laser. Potassium niobate ($KNbO_3$) is a particularly suited material for nonlinear frequency conversion. Phase-matched blue-light second-harmonic generation (SHG) and sum-frequency generation (SFG) is possible over a wide range of wavelengths. In bulk crystals, temperature tuning to achieve noncritical phase-matching is preferred because walk-off is eliminated in this case, and thus, a higher conversion efficiency can be achieved.

The use of channel waveguides eliminates the problem of walk-off for any of the possible phase-matching configurations because both waves are inherently guided along the same direction. A fabrication process based on planar ion-implantation, patterning of a mask by photolithography, and subsequent ion etching was developed. The channel waveguides with typical cross sections of 5 x 5 μm^2 fabricated by this process guide modes of both TE- and TM-polarizations which is required for phase-matching by natural birefringence.

A minimum attenuation coefficient of 2 $dBcm^{-1}$ was measured in these waveguides at a wavelength of 633 nm.

Noncritical phase-matched SHG in a 7 mm long waveguide yielded 10 mW of blue power at 438 nm with an incident laser power of 320 mW from a cw Ti:sapphire laser. The coupling efficiency is typically 80% for these channel guides. The corresponding normalized internal conversion efficiency is 30% $W^{-1}cm^{-2}$ which is the highest conversion efficiency reported so far for birefringence phase-matched SHG in a waveguide. We also investigated SFG in a $KNbO_3$ channel waveguide. 10 mW of blue power at 436 nm were generated using a cw InGaAs master oscillator power amplifier (MOPA) diode laser emitting at 982 nm and a Ti:sapphire laser tuned to 785 nm.

In conclusion, we demonstrated the suitability of these $KNbO_3$ waveguides for efficient frequency up-conversion to blue wavelengths. Theoretical modeling shows that optimized waveguides could yield a three times higher conversion efficiency. Therefore, we envision the generation of more than 30 mW of blue light by frequency doubling of 300 mW near-infrared diode lasers in $KNbO_3$ channel waveguides.

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Compact Diode-Pumped Blue Lasers

D. Fluck and T. Pliska

Frequency up-conversion of near infrared laser diodes (LDs) offers the potential of robust and reliable blue laser sources. $KNbO_3$ crystals are very attractive due to their high nonlinear optical coefficients and the favourable noncritical phase-matching possibilities for wavelengths between 853 and 980 nm.

We demonstrated a compact continuous-wave blue-green laser by direct frequency doubling a monolithically integrated master oscillator power amplifier (MOPA) laser diode in a 17 mm long $KNbO_3$ crystal. More than 40 mW of diffraction limited second-harmonic light at 491 nm was generated with a fundamental power of 950 mW. The 491 nm laser radiation has a frequency linewidth of 30 GHz. The root-mean-square fluctuations of the second-harmonic output power is as low as 0.1% and the power drift is less than 1% over ten hours of operation.

We also demonstrated a continuous-wave blue laser by noncritical phase-matched sum-frequency mixing of a 983 nm MOPA InGaAs laser diode and a 780 nm single-mode AlGaAs laser diode in a $KNbO_3$ crystal. A maximum output power of 65 mW of diffraction limited sum-frequency radiation at 435 nm was generated in a 14.5 mm long crystal. In addition, this blue laser was continuously tunable over the wavelength range from 432 to 438 nm by tuning the wavelength of the AlGaAs laser diode from 770 to 790 nm and the crystal temperature from 49 to 79 ˚C.

Further improvements in conversion efficiency can be expected from optimization of the device design and mainly from implementation of $KNbO_3$ waveguides.

Reference: D. Fluck and P. Günter
"Tunable Blue Light Generation by Sum-Frequency Mixing of AlGaAs and InGaAs Laser Diodes in $KNbO_3$"
*Electronics Letters **32** (10), 901-903 (1996)*

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Liquid Phase Epitaxy of $K_{1-y}Na_yTa_xNb_{1-x}O_3$ (KNTN)

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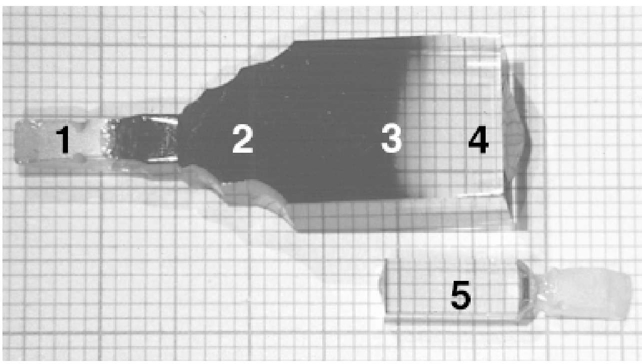
$KTa_xNb_{1-x}O_3$ (KTN) is a complete solid solution of $KTaO_3$ (KT) and $KNbO_3$ (KN) exhibiting 3 phase transitions from the paraelectric cubic to the ferroelectric tetragonal, orthorhombic and rhombohedral phase. The temperatures of the phase transitions can be varied by the Nb concentration (x) between ~0 K for pure KT and ~700 K for pure KN. Electro-optic and pyroelectric coefficients get very high near the transition from the ferroelectric to paraelectric phase. Therefore, materials with a phase transition which can be tailored to be just above the working temperature are very interesting. Furthermore, the addition of small amounts of Na in form of NaF into the KTN/KF melt allows us to grow lattice-matched KNTN films on KT substrates. This is achieved by liquid phase epitaxy (LPE) at 1180 K. The resulting KNTN thin (5 to 30 μm) films are nearly misfit defect free and thus expected to show high electro-optic and pyroelectric effects.

One major problem has been the high resistivity of the substrate (pure KT) which prevented any poling procedure of the ferroelectric KNTN film perpendicular to its main surface. This problem could now be solved by doping the melt for the KT substrates with about 0.02 mol% Ba (Figure below). Electrical resistivities as low as 25 Ωm could be measured. This is about 9 to 10 orders less than the value for pure KT (10^{11} Ωm).

On these Ba:KT substrates KNTN thin films have been grown which were tailored to show their phase transition from ferroelectric to paraelectric at 333 K (60 °C). The pyroelectric responsivity has been measured using the conducting substrate as bottom electrode and thus the use of Ba:KT substrates for LPE of lattice-matched KNTN has been successfully demonstrated.



Upper crystal: as-grown Ba doped KT. (1) seed (pure KT), (2) strongly Ba doped region (dark blue), (3) continuous transition to lighter doped KT, (4) pure KT (all Ba ions have been built in). Lower crystal (5): pure KT for comparison.

Sponsor: Swiss Priority Program LESIT

MBE Growth and Characterization of Ferroelectric Thin Films

Y. Tao, F. Gitmans, I. Gamboni and A. Kündig

Ferroelectric thin films are becoming very attractive due to the trend towards miniaturization of electronic and optic devices. One of our research aims is to grow ferroelectric thin films on silicon substrates using proper buffer layers so that monolithic devices containing ferroelectric components can be realized using the mature silicon technology. The second aim is to grow superlattices composed of different ferroelectric materials, to investigate the novel physical properties introduced by the long range structural and compositional modulation, and the interfacial strain in the system.

$LiTaO_3$ is a well-known ferroelectric crystal. Due to its large pyroelectric coefficient, high Curie temperature, and low dielectric constant, $LiTaO_3$ thin films are very attractive for pyroelectric detector applications. We have prepared polycrystalline $LiTaO_3$ thin films on Si(111) substrates using an epitaxial PtSi layer as oxygen barrier and growth template. X-ray diffraction (XRD) and transmission electron microscopy (TEM) revealed a strong preferential orientation of $LiTaO_3$(012)/PtSi(010)/Si(111), i. e., the spontaneous polarization vector of the films is ~ 57° off the surface normal. XRD and TEM were also used to investigate the effects of growth temperature and annealing conditions on the crystallinity and microstructure of the films. Films grown at 900 ˚C showed the best crystallinity. The pyroelectric current response showed a value of 100 - 200 μA/W in the range between 10 Hz and 10 kHz, indicating the $LiTaO_3$ thin films are promising candidate for pyroelectric applications.

$LiNbO_3$/$LiTaO_3$ superlattices with periods of 100 and 150 Å have been prepared on *c*-axis $LiNbO_3$ substrates. XRD and cross-section TEM showed that the superlattices grow epitaxially with sharp interfaces. Lower growth rates (0.7 Å/s) results in single crystalline films. While for growth rates over 1 Å/s, twinned domain structures occur. This is explained by an initial Volmer-Weber growth on the pseudo-hexagonal substrate surface. Stoichiometric $BaTiO_3$ and $SrTiO_3$ thin films have also been prepared on Si and glass substrates by co-evaporation of BaO/ SrO and TiO_2 at the substrate temperature of 650 °C with growth rates between 0.5 and 1 Å/s. $BaTiO_3$ and $SrTiO_3$ bulk crystals were used as standards in measuring the chemical composition of the deposited films. Since BaO and SrO sublime before they melt, the control over the surface morphology of the source materials is difficult, therefore the long-term stability of the BaO and SrO sources is limited. This problem should be solved by evaporating pure Ba (or Sr) metal from Knudsen sources.

Sponsor: Swiss Priority Program LESIT

Photorefractive effects at 1.3 µm and 1.5 µm in proton irradiated $KNbO_3$

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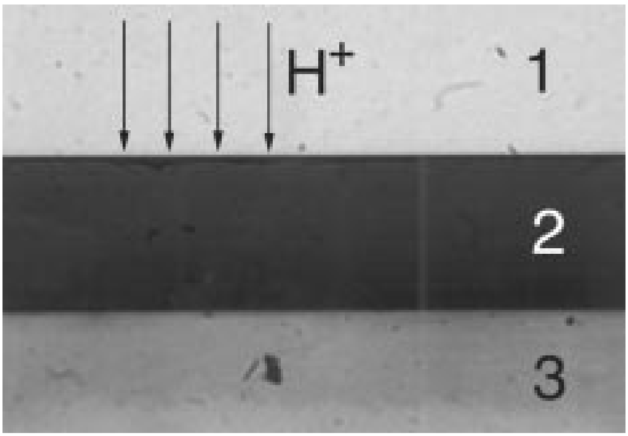
Photorefractive (PR) crystals such as $KNbO_3$, $BaTiO_3$, $LiNbO_3$ and $Sr_{1-x}Ba_xNb_2O_6$ are very promising for all-optical signal processing. Due to the need of nonlinear optical devices in optical communication systems operating at near infrared wavelengths, attention has been drawn to the extension of the photorefractive response up to communication wavelengths of 1313 and 1550 nm. By using high energy (3 MeV) proton irradiation, we achieved for the first time a photorefractive two-beam coupling net gain at the telecommunication wavelengths of 1313 and 1550 nm in a ferroelectric oxide[1]. A net gain is of crucial importance for possible applications. By varying the proton energy, it is possible to adjust the thickness of the modified layer from 2 - 100 µm. The major advantage of ion-irradiated ferroelectric oxide waveguides is that charge diffusion is sufficient to build-up quite high gains, and therefore, no external fields have to be applied to these structures (in contrast to photorefractive semiconductor devices) which makes them potentially interesting for telecommunication applications. Further on, we have also shown, that ion irradiation is a very useful tool to modify the photorefractive properties of ferroelectric oxides in a controlled and reproducible way.



$KNbO_3$ crystal irradiated from the top with 3 MeV protons, leading to a waveguide layer with a thickness of 55 µm. The irradiated region is electron conducting, whereas the virgin bulk crystal is hole conducting. 1) Air, 2) Irradiated region (55 µm), 3) Virgin bulk crystal.

Reference: S. Brülisauer, D. Fluck, and P. Günter, "Photorefractive effect in proton-implanted Fe-doped $KNbO_3$ waveguides at telecommunication wavelengths", *J. Opt. Soc. America B*, ***13*** *(11), 2544 - 2548 (1996)*

Sponsor: ETH Zürich

Tunable nanosecond and picosecond infrared laser source based on optical parametric generation in $KNbO_3$

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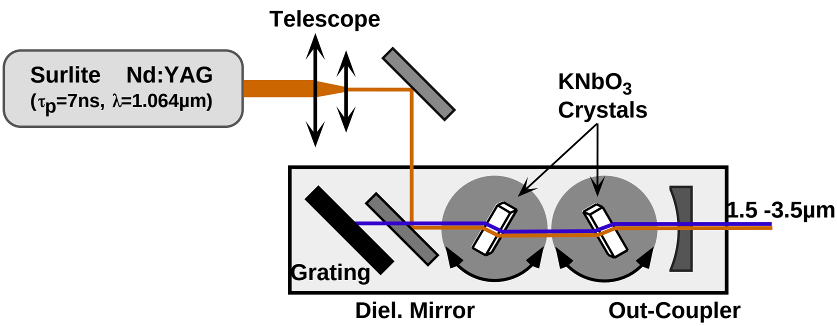
For spectroscopic investigations of the linear and nonlinear optical properties of materials it is necessary to have laser sources at various wavelengths. Optical parametric generation and amplification of light in a nonlinear crystal is most attractive and provides the possibility of building widely tunable laser sources.

In this project we are building tunable light sources based on two different concepts: an optical parametric oscillator (OPO) system for ns pulses and a optical parametric generator / amplifier (OPG/OPA) system in the ps regime. Due to its large effective nonlinear optical coefficients, its high damage threshold as well as its wide phase-matching possibilities we chose $KNbO_3$ as nonlinear optical material.

The ns OPO is directly pumped by a Nd:YAG laser (λ = 1064 nm, 7 ns) and uses two $KNbO_3$ crystals in the cavity in walk off compensated geometry. To get tunable wavelengths in the infrared region with ps-pulses, a OPG/OPA system was constructed. The initial idea to pump the $KNbO_3$-crystals with a frequency doubled Nd:YLF-laser (λ = 523.5 nm) had to been abandoned due to a large two photon absorption coefficient in $KNbO_3$. The newly designed setup will now be pumped directly by the Nd:YLF-laser (λ = 1047 nm).

Wavelength selection for both systems will be done through angle tuning of the crystals and line narrowing by gratings.



Setup of the $KNbO_3$ walk-off compensated ns OPO system pumped at 1064 nm.

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