Abstract

A few years ago, electro-optic high-speed scanning (> 10,000 rad/s) at high deflection angles (>±100 mrad) has been demonstrated successfully using KTa$_{1-x}$Nb$_x$O$_3$ (KTN) as crystal material. KTN scanners were commercially available shortly after. Presented experiments with KTN scanners show that beam profile deformation occurs, at which the degree of deformation is dependent mainly on the deflection angle mid-point position, the deflection angle amplitude and the laser pulse fluence, the latter being crucial for ultrashort laser pulses. Analysis of physical models of KTN scanners and comparison to experimental results point out that trapped space charges are the main reason for deflection and the observed dependencies.

1. Motivation

It is well known that the average power of ultrashort pulsed lasers increased significantly over the past years. Commercial laser systems reach 400 W of average output power (at 15 MHz repetition rate) [1], scientific laser systems more than 1 kW (at 10 MHz repetition rate) [2]. Although this allows an increase of processing speed in principal, one major challenge has to be faced when transferring such laser systems into applications such as micro-structuring. Due to the high repetition rate, pulse-plasma interaction and
heat accumulation take place if lateral pulse-to-pulse separation is not sufficiently high. Produced structures are then nearly comparable to ns-laser machining [3].

Therefore, the beam deflection velocity has to be at least on an order of ablation diameter multiplied by laser repetition rate, which results in a necessary deflection angle velocity of appr. 1000 rad/s for typical setups used in microstructuring. Galvanometer-based scanners only allow deflection angle velocities of approximately up to 100 rad/s, cp. tab. 1. In terms of advanced microstructuring with ultrashort pulsed lasers, other beam guiding technologies such as acousto-optical deflectors, polygon wheel scanners etc. have to be taken into account to a larger extent in future [4].

In the following, we will address such a novel scanning technology, the KTN scanner (for abbreviation ‘KTN’ and further details on functionality refer to ch. 2) [5,6]. KTN scanners, being a type of electro-optic scanner, are commercially available since 2010 and offer very high deflection angle velocities compared to other scanning technologies. For a comparison of KTN scanners with other scanning technologies, refer to tab. 1. Basic knowledge of guiding laser beams with cw or quasi-cw (i.e. pulse duration of μs and longer) is present [7], e.g. beam profile deformation in form of astigmatism occurs under certain conditions (to be discussed below). We characterized the KTN scanner in regards to the latter effect in more detail to enable possible further enhancement of physical models for KTN scanners. Also, experience with high-energy ultrashort laser pulses is not available up to date. Effects due to high photon density are expected and addressed within the paper.

Table 1. Comparison of KTN scanners to typical values of other 1D scanning technologies for near-infrared wavelength range; (*1): Perspective development of KTN within next few years according to direct conversation with NTT AT Corp.

| Scanning technology | KTN | Galvanometer | Polygon mirror | AOD |
|---------------------|-----|--------------|----------------|-----|
| Max. deflection angle velocity in 10^3 rad/s | 30 (100 *) | 0.1 … 0.2 | 10 | 10 … 20 |
| Typ. response time in μs | 1 | 200 … 1000 | > 2,000 | 1 |
| Max. deflection angle in rad | 0.15 | ~ 1 | ~ 1 | 0.05 |
| Max. Aperture in mm | 0.5 … 1 (2 *) | ~ 30 | ~ 30 | 5 |
| Transmittance | ~ 90% | > 95% | > 95% | ~ 85% |

Nomenclature

d thickness of KTN crystal (separation between cathode and anode)
D KTN-induced cylinder lens refraction power
Δn index of refraction change
e permittivity
e elementary electric charge
f voltage frequency / deflection angle frequency
F focal length
g_{ij} g coefficient
L length of KTN crystal
N trapped space charge density
2. Analytical modeling of KTN scanners: State of the art

Potassium tantalate niobate (KTa$_{1-x}$Nb$_x$O$_3$, abbreviated as KTN) is a crystal material known since 1950s and applied in optics since 1960s [8,9]. With a correct ratio of Ta:Nb [8] the quadratic electro-optic coefficient (Kerr effect) can reach approximately $s_{11} = 10^{-14}$ m²/V² [5] for a certain crystal temperature (typically chosen to be a few degrees above room temperature). The Kerr effect in KTN is therefore much stronger compared to most other eligible materials [10]. Due to this fact, KTN crystals were used for electro-optic scanners early [9] using typical prism-shaped geometries.

In 2006 it was discovered that by depositing titanium electrodes, an ohmic contact between electrode and KTN crystal forms. As a result, space charges (electrons) can be injected into the crystal and electrical conduction in (mobile) space-charge-controlled mode (SCM) takes place [5]. Accordingly the electric field follows a square-root law [5] when a voltage of low frequency (near DC) is applied between the electrodes. As index of refraction and electrical field are linked via the Kerr effect, the resulting index of refraction change as a function of applied voltage $V$ is obtained as [5]:

$$\Delta n_{\text{SCM}}(x) = \frac{9}{8} n_0^3 s_{ij} \frac{V^2 x}{d^3} \approx \frac{9}{8} n_0^3 g_{ij} \epsilon \frac{V^2 x}{d^3} \quad (I)$$

Fig. 1 depicts position and orientation of x-axis, KTN scanning device etc. As a remark, $V$ is always positive. When polarity changes, cathode and anode switch places, i.e. the beam is always deflected
towards the cathode.

Eq. 1 is true for low frequencies $f$ of voltage $V$. When frequencies reach approximately 50 kHz and more, the migration length of mobile space charges becomes significantly smaller than typical crystal thicknesses [11]. Hence, mobile space-charge-controlled mode of operation is becoming increasingly insignificant with higher voltage frequencies.

At the same time, space charges are trapped in the KTN-crystal as true charges. This effect may be induced e.g. by a short pulse of constant DC-voltage. Trapped space charges change electric field distribution, too, and lead to an index of refraction change as follows [11]:

$$
\Delta n_{\text{TCM}}(x) = -\frac{1}{2} n_0 g_0 e^2 N^2 \left( x - \frac{d}{2} + \frac{eV}{eNd} \right)^2
$$

The latter effect, referred to as trapped space charge mode (TCM), is independent on the voltage frequency. In summary, SCM applies for low voltage frequencies only and is coupled with TCM, which applies when trapped space charges are present (which, from a practical point of view, is nearly always the case). Also, the density of trapped space charges $N$ is dependent on the voltage for low frequencies in a non-linear manner (because of the non-linear correlation of voltage and current, cp. [5]) and with hysteresis, thus making exact description of TCM difficult.

As a beam travels through the crystal, the wave front is tilted according to the index of refraction gradient along $x$. After passing a crystal thickness $L$, the beam will be tilted by:

$$
\theta(x) = L \frac{d}{dx} \Delta n(x)
$$

The resulting lens power $D$ can be calculated by the well-known equation:

$$
D = \frac{d}{dx} \theta(x)
$$

When eq. 1 (SCM) is used in eqs. 3 and 4, the tilting angle $\theta$ is constant along $x$ and the lens power $D = 0$. However, when eq. 2 (TCM) is used, the tilting angle is dependent on $x$ and the lens power $D$ becomes:

$$
D = \frac{1}{F} = -Ln_0 g_0 e^2 N^2
$$

Therefore an extended beam will become astigmatic. For comparison to the experimental results it is important to point out that $D$ is not dependent on $V$ according to eq. 5, but on $N^2$. The position of the optical axis of the induced cylinder lens on $x$ is obtained by solving eq. 2 for $\Delta n_{\text{TCM}} = 0$:

$$
x = \frac{d}{2} - \frac{eV}{eNd}
$$

Thus, the optical axis is directly dependent on $V$. The KTN scanner can therefore be interpreted as a
cylindrical lens which is moved along the x-axis by applying a voltage V. Fig. 1 schematically shows tilting of the beam and $\Delta n(x)$ distributions for eqs. 1 and 2.

It also has to be noted that the dependence of tilt angle $\theta$ on voltage $V$ is quadratic for eq. 1 (low frequency of voltage, SCM) and linear for eq. 2 (high frequency, TCM). Consequently, it would be expected that there is a significant dependence of the tilt angle on the voltage frequency, but experimental studies [11] showed no such behavior up to now. This makes clear that the current physical models are not completely representing the actual behavior. This especially refers to the trapped space charge density $N$, which is interpreted to be constant in eqs. 2, 5 and 6. For low voltage frequencies, this is not necessarily true. An adaption is proposed in ch. 5 according to the experimental results.

3. Experimental procedure

3.1. Experimental setup

For experimental studies a setup as shown in Fig. 2 is used. The KTN scanner used in the experiments is of the type ‘KSMS1D1064-00’ produced by NTT AT Corp. for 1064 nm wavelength. It includes a cylindrical lens to compensate for the cylinder lensing effect according to eq. 5. The focal length of the compensation lens is typically around -4 mm. The lens is optimized for a specific parameter set of sinusoidal voltage at a frequency of 100 kHz and -150 V DC bias voltage (for explanation on DC bias voltage refer to ch. 3.2) and is arranged in direct vicinity to the beam exit side of the KTN crystal. As much lower voltage frequencies are used in later experiments, astigmatism is expected, cp. [12].

![Fig. 2. Schematical layout of experimental setup. Red, solid line: Laser beam. Blue, dashed line: Signal flow](image)

The laser used in the experiments emits laser pulses of 400 fs pulse duration, 1064 nm wavelength, 1 mm $1/e^2$ beam diameter, $M^2 \approx 1.2$ and max. pulse energy $2 \mu$J at 1 MHz max. repetition rate. The laser beam is focused with a plano-convex lens of 175 mm focal length to a beam diameter of approximately 160 $\mu$m to transmit the aperture of the KTN crystal (0.5 mm) without clipping.. The KTN crystal is arranged to be in the focus of the focussing lens (the rayleigh length equals 16 mm and is much larger than the crystal length). The laser power is modulated by a polarizing attenuator (and additional neutral density filters if needed). The emission of laser pulses is triggered by the laser-internal acousto-optic modulator.

The laser power is measured in front of the KTN-crystal using either Coherent LM3 or Coherent PS19Q thermopile sensors. Beam profiles are acquired by placing the camera chip of a Coherent LaserCamHR to the indicated positions I and II in Fig. 2, equating separations of KTN crystal to camera chip of 38 mm and 110 mm respectively. It has to be noted that some supplemental optics ($\lambda/2$ waveplate, telescope and mirrors) are not shown in Fig. 2 for ease of representation.
3.2. Signal path and sequence

The signal path is depicted in Fig. 2, too. A frequency generator outputs a defined signal waveform which is used to both supply the KTN scanner driver input and trigger a delay generator. The KTN driver attenuates the input voltage by a factor of 100 and supplies the KTN scanner with the final control voltage of frequency $f$, peak-to-peak voltage $V_{pp}$, and DC bias voltage $V_{DC}$. The delay generator is used to both trigger the camera exposition and a burst of laser pulses at a specified pulse-to-pulse time delay. The camera exposition time is chosen to acquire one pulse burst. The moment of single pulse emission jitters in relation to the trigger signal by approximately $1 \mu s$. As KTN scanning frequency is on an order of a kHz and below in the experiments, this jitter is insignificant and can be neglected (which was confirmed experimentally). All experiments are carried out on the rising slope of the control voltage.

Fig. 3 shows how $V_{pp}$ and $V_{DC}$ will influence the beam deflection. $V_{DC}$ shifts the middle point of deflection. $V_{pp}$ controls the peak-to-peak deflection angle.

4. Experimental results

Prior to the main experiments, preliminary characterization has been carried out. As a result, the transmission of the KTN crystal at a wavelength of 1064 nm was determined to be 88%. Impact on pulse duration was checked using a Newport Spectra Physics ‘PulseScout’ autocorrelator. The pulse duration was stable at 400 fs prior to and after the KTN crystal and no influence on pulse duration was identified.

As beam scanning in practical applications mostly uses meandering patterns, triangular voltage waveform was compared to sinusoidal. Regarding experimental results presented in ch. 4.1, a sinusoidal control voltage waveform delivered results of less standard deviation. Therefore, it was decided to use a sinusoidal control voltage waveform for the following experiments despite the fact that a triangular waveform would be more application-oriented.

For experiments in ch. 4.1, the pulse energy was kept below 50 nJ to avoid beam profile deformation, cp. ch. 4.2. The beam profile camera is at position I for all experiments in ch. 4.1 and at position II for ch. 4.2 (see Fig. 2).

4.1. Dependence of beam profile circularity on DC-Bias voltage, signal frequency and signal amplitude

As the trapped space charge density $N$ and thus the KTN-induced cylinder lens power $D$ are known to be dependent on DC-bias voltage $V_{DC}$, studies are carried out to determine optimal values of $V_{DC}$ in terms of maximizing beam profile circularity (minimizing residual astigmatism). The voltage frequency $f$ is varied and the peak-to-peak voltage $V_{pp}$ is fixed at 300 V. Within one rising slope of the control
voltage, 5 single pulses are triggered with a pulse-to-pulse delay equaling 1/5 of the rising slope duration. The circularity values shown in Fig. 4 left, represent the mean value of the 5 acquired single pulse circularities. The average standard deviation is only 7% of the measured value and is therefore not shown in the graph for more clear representation. No clear dependence of pulse profile circularity on actual scan position can be identified in the experiments. The beam profile was stable over the whole scan range within reasonable certainty.

With optimal values of \( V_{DC} \) for different frequencies, the influence of peak-to-peak voltage \( V_{pp} \) on the beam profile circularity is studied. Results are shown in Fig. 4 right. As before, the values for circularity are the mean of values acquired for several single pulses, which are equally spread along the full range of one rising slope of the control voltage. As the average standard deviation is only 3% of the measured value, it is not represented. Distinct dependencies of circularity on both \( V_{DC} \) and \( V_{pp} \) are identified.

Fig. 4. Dependence of pulse beam profile circularity. Values of circularity represent mean value of several single pulses (stated in diagram) equally spread out along one rising slope of voltage. Left: Dependence on DC-bias voltage \( V_{DC} \) and voltage frequency \( f \) at \( V_{pp} = 300 \) V. Right: Dependence on peak-to-peak voltage \( V_{pp} \) and voltage frequency \( f \)

Fig. 5 shows exemplary beam profiles after passing the KTN scanner for one set of parameters shown in Fig. 4. The scanning frequency equals 100 Hz. As can be seen, the circularity gradually becomes lower for a lower scanning angle amplitude.

Fig. 5. Beam profiles after KTN crystal at varying scan angle amplitude and \( f = 100 \) Hz, \( V_{DC} = -170 \) V. As shown 5, 3 and 1 single pulses are detected respectively
4.2. Beam profile deformation at high pulse energies

Experiments on pulse profile deformation at high pulse energies were carried out. The voltage frequency is set to 5 Hz or 500 Hz respectively and the repetition rate to 1 MHz (pulse-to-pulse time delay 1 μs). Pulse bursts are emitted when the signal voltage equals \( V_{DC} \), i.e. at the center point of deflection. Different numbers of pulses are used. The resulting beam profiles at camera position II (separation 110 mm between camera chip and KTN crystal) are shown in Fig. 6 ranging from slightly before onset of deformation (left pictures) to fully evolved deformation (right pictures). The values in the lower right corners of each beam profile picture indicate the fluence of one single pulse in mJ/cm². The pulse energies vary accordingly between 240 nJ (equaling 3.1 mJ/cm² fluence) and 1.72 μJ (equaling 22.4 mJ/cm² fluence).

Fig. 6. Beam profiles at camera position I and varying number of pulses in burst, frequency and single pulse fluence (values shown in lower right corner of each single picture). \( V_{pp} \) is fixed at 300 V, equaling a deflection angle range of approximately +/- 50 mrad

5. Discussion

Results in ch. 4.1 point to a significant dependence of the KTN-induced cylinder lens power \( D \) on the voltage \( V_{DC} \). This is interpreted as a dependence of trapped space charge density \( N \) on voltage \( V \), cp. eq. 5, and was anticipated. At the same time dependence of \( D \) on \( V_{pp} \) cannot be explained easily at first.

When interpreting the results in ch. 4.2, two main conclusions can be drawn. First, there is an onset for multiphoton absorption and thus photon-kinetic acceleration of space charges at approximately 10 mJ/cm². The space charges diffuse away from the interaction zone and the beam profile is deformed heavily, cp. Fig 6. The threshold fluence for the deformation is dependent on the number of pulses, i.e. it is an accumulative effect. Second, as the threshold fluence is significantly lower for 12 pulses at \( f = 500 \) Hz compared to 100 pulses at \( f = 5 \) Hz, accumulation of photon-kinetic acceleration has to take place on a
time scale longer than 1/500 Hz = 2 ms. This implies a migration speed of space charges below d/2 ms = 0.25 m/s. This is surprising, as according to [13] the migration speed due to electron mobility for \( V = -150 \) V and \( d = 0.5 \) mm is on a range of 990 m/s (for mobile space charges).

The results are explainable, when trapped space charges are taken into account as the main reason for deflection instead of mobile space charges. Trapped space charges have a much a lower migration speed, which complies with results in ch. 4.2. At the same time they accumulate in the KTN crystal over a long period of time. This explains the change of \( D \) when increasing \( V_{pp} \) (Fig. 4, right diagram): When \( V_{pp} \) increases, max. negative voltage is increased to \( V_{pp} + V_{DC} \). Accordingly, more trapped space charges reside in the crystal, increasing \( D \) according to eq. 5.

Early publications show very good accordance of the (mobile) space charge model (eq. 1, SCM) with experimental results when applying only \( V_{DC} \) [5]. With an adaption to the trapped space charge model (eq. 2, TCM) nearly the same good accordance is achieved. For this, it is assumed that \( N \sim V \) (which is only true for low voltages, cp. [5]) and that there are no trapped space charges in the crystal yet \( N(V=0) = 0 \). Then, eqs. 1 and 2 for \( x = d/2 \) become:

\[
\Delta n_{TCM}(d/2) = -\frac{1}{2} n_e g_e \varepsilon^2 \left( \frac{V}{d} \right)^2 \approx \Delta n_{SCM}(d/2) = \frac{9}{16} n_e g_e \varepsilon^2 \left( \frac{V^2}{d^2} \right)
\]  

(7)

I.e. the trapped space charge model deviates from the mobile space charge model only by appr. 12.5%. It is therefore highly likely that trapped space charges generate deflection to a large part, whereas mobile space charges have a minor impact. This also explains why no significant dependence of the beam deflection angle amplitude on the frequency has been observed up to now [11]. the trapped space charge density is independent on the frequency to a large part. For further enhancement of the TCM model, dependence of the trapped space charge density \( N \) on voltage \( V \) and frequency \( f \) has to be determined in more detail.

6. Conclusion and Outlook

Experimental results showed significant dependencies of beam profile circularity, i.e. KTN-induced astigmatism, on both the middle point of deflection (controlled via \( V_{DC} \)) and the deflection angle amplitude (controlled via \( V_{pp} \)), but not on the deflection angle frequency \( f \). For application of KTN scanners in microstructuring, it is therefore highly preferable to use fixed values for \( V_{DC} \) and \( V_{pp} \), otherwise fluctuations in the produced structures will result.

Laser-induced beam deformation due to multiphoton absorption within the crystal occurred at fluences of approximately 3 mJ/cm² and above, limiting the applicable pulse energy to appr. 3 µJ (beam diameter 0.5 mm). A direct way of increasing this value is to use larger aperture and beam diameters. To our knowledge, NTT AT Corp. plans to increase the aperture to at least 2 mm in near-future, thus increasing the applicable pulse energy to an estimated value of appr. 50 µJ. Furthermore, NTT AT Corp. will make a version of the KTN scanner available, which offers a higher fluence threshold of beam profile deformation (at slightly smaller max. deflection angle). The latter device will be available soon.

An analysis of obtained results pointed to the trapped space charge mode being the major reason for deflection. The mobile space charge mode seems to have a significantly lower impact, if any. In the near future, we will conduct further analysis and adaption of the trapped space charge mode models. It is expected that, along with other effects, there will be influences of \( V_{DC} \) on the beam deflection angle amplitude.
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