ADVANCED KTN-BASED OPTICAL BEAM DEFLECTORS

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Wenbin Zhu

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The dissertation of Wenbin Zhu was reviewed and approved* by the following:

Shizhuo Yin  
Professor of Electrical Engineering  
Dissertation Advisor  
Chair of Committee

James K. Breakall  
Professor of Electrical Engineering

Victor P. Pasko  
Professor of Electrical Engineering  
Coordinator of Graduate Program

Jian Hsu  
Associate Professor of Engineering Science & Mechanics

Kultegin Aydin  
Professor of Electrical Engineering  
Head of the Department of Electrical Engineering

*Signatures are on file in the Graduate School
ABSTRACT

Beam steering systems are widely applied in the areas of 3D printing, 3D imaging, and high-speed bio-imaging systems. All these applications require high-speed high-resolution multi-dimensional beam scanners. Potassium tantalate niobate [KTa$_{1-x}$Nb$_x$O$_3$ (KTN)] crystal-based optical beam deflectors have been widely used in the commercial markets in recent years. In this dissertation, we present a comprehensive study of the working mechanism of KTN beam deflectors and propose new beam deflection mechanisms. To achieve a high-speed KTN beam deflector, we investigate the reason for the responding delay of most KTN-based electro-optical devices. When the operation temperature is above but close to the Curie temperature, the KTN crystal will undergo a phase transition from paraelectric phase to ferroelectric phase with a high external electric field. We find that such field-induced phase transition will limit the responding speed of the KTN-based electro-optical devices. By avoiding the field-induced phase transition, the KTN-based beam deflector can respond in as fast as 10 ns, which is three times faster than the commercial KTN beam scanner. In addition, we combine the composition-gradient-controlled beam deflection and the space-charge-controlled beam deflection in only one piece of KTN crystal to build a two-dimensional beam deflector. In order to realize a 2-D beam deflector, we investigate the coexistence of the space charge and composition gradient in one piece of KTN crystal. If the electric field is parallel to the direction of the composition gradient, the zero-deflection position will shift in the KTN crystal. If the external electric field is perpendicular to the direction of the composition gradient, we can achieve a 2-D beam deflection in the KTN crystal. By adjusting the operating temperature and the driving voltage, we can realize the 2-D beam deflection in one piece of KTN crystal. Moreover, to increase the scanning resolution of the KTN beam deflector, we propose the photon-excitation-enabled KTN beam deflection to enlarge the scanning aperture, further enhancing the scanning resolution. With the photon excitation charging process, we can get a larger
charge injection depth and charge density in the KTN crystal. With the help such charging process, we can obtain a larger deflection aperture in the space-charge-controlled beam deflector, and future increase the scanning resolution. Finally, we provide a method to build a low-voltage high-speed KTN beam deflector and propose a method to realize a high-speed wavelength-tunable laser with the KTN beam deflector.
# TABLE OF CONTENTS

LIST OF FIGURES ........................................................................................................ vii

LIST OF TABLES .......................................................................................................... xi

ACKNOWLEDGEMENTS ............................................................................................... xii

Chapter 1 Introduction ................................................................................................. 1

Chapter 2 Fundamentals of KTN Crystals ................................................................. 11

  2.1 Preparation of KTN and its structures ............................................................... 12
  2.2 KTN properties ................................................................................................. 15
      2.2.1 Physical properties of KTN crystals ......................................................... 14
      2.2.2 Electro-optical properties of KTN crystals ............................................ 20
      2.2.3 Kovacs effect in nanodisordered KTN ....................................................... 24

Chapter 3 Electric-Field-Induced Phase Transition and Ultra-Fast KTN Beam Deflector .... 26

  3.1 Field-induced phase transition ......................................................................... 27
  3.2 SCC KTN beam deflector operating in the electric-field-induced ferroelectric phase ................................................................. 29
  3.3 Experiments and results .................................................................................... 34
  3.4 Discussions and conclusions ............................................................................ 41

Chapter 4 Composition Gradient Controlled KTN Deflector and 2-D Beam Deflection .... 50

  4.1 Composition gradient controlled KTN beam deflector .................................... 52
  4.2 KTN deflectors enabled by the coexistence of space charge and composition gradient ........................................................................................................ 57
      4.2.1 Pre-injected space-charge-induced gradient electric field is parallel to the direction of the composition gradient ................................................................. 58
      4.2.2 External electric field is perpendicular to the direction of the composition gradient ........................................................................................................ 63
  4.3 Experimental results and discussions ............................................................... 75
  4.4 Conclusions .................................................................................................... 83

Chapter 5 Photon Excitation Enabled Space-Charge-Controlled KTN Beam Deflector .... 84

  5.1 Non-uniform charge distribution in KTN and photon excitation enabled beam deflector ........................................................................................................ 86
  5.2 Experimental results ....................................................................................... 90
  5.3 Conclusions ................................................................................................... 95

Chapter 6 Conclusions and Future Directions ........................................................... 96

Reference ....................................................................................................................... 100
LIST OF FIGURES

Figure 1-1: Illustration of optical beam deflectors: (a) polygonal mirror scanner, (b) MEMS mirror scanner, (c) AO beam deflector, and (d) EO beam deflector ............................................. 2

Figure 1-2: Illustration of SCC KTN beam deflector ................................................................. 6

Figure 2-1: Conceptual illustration of the KTN crystal structure ........................................... 12

Figure 2-2: Crystal phase diagram of KTa_{0.63}Nb_{0.37}O_{3} crystals. The data points are extracted from Fig. 5 in Ref. [43] .......................................................... 13

Figure 2-3: Transmittance of a KTa_{0.7}Nb_{0.3}O_{3} crystal. The data points are extracted from Fig. 1-2 in Ref. [59]. .......................................................... 17

Figure 2-4: Photo of a piece of KTN crystal ........................................................................... 18

Figure 2-5: The dispersion relationship of the KTa_{0.63}Nb_{0.37}O_{3} crystal plotted from the data points shown in Fig. 3 of Ref. [16]. ........................................... 19

Figure 2-6: Linear EO coefficients, r_{51} and r_{c}, of KTN crystal as a function of temperature, plotted in solid and dashed lines, respectively. The data points are extracted from Ref. [60] .......................................................... 22

Figure 2-7: Quadratic EO coefficient, s_{11}, of KTa_{0.59}Nb_{0.41}O_{3} crystal as a function of temperature. The data points are extracted from Fig. 3 in Ref. [32]. ......................... 23

Figure 2-8: A conceptual illustration of the permittivity as a function of temperature for a KTN crystal with different temperature cycling histories. Solid curve: reducing temperature, dashed curve: increasing temperature. ................................................. 24

Figure 2-9: Transient EO coefficients of a KTa_{0.5}Nb_{0.5}O_{3} crystal with temperature, acquired at three different cooling rates of 0.45 °C/s (square), 0.20 °C/s (diamond), and 0.03 °C/s (triangle). The data points are extracted from Fig. 5 in Ref. [64]. ......................... 25

Figure 3-1: Illustration of the KTN polarization under different conditions: (a) at a temperature well above the Curie temperature and with no electric field; (b) at a temperature slightly above the Curie temperature and with no electric field; (c) at a temperature slightly above the Curie temperature and with a high electric field .......... 28

Figure 3-2: An illustration of a KTN crystal in the ferroelectric phase ...................................... 29

Figure 3-3: An illustration of a voltage-controlled variable prism working in the paraelectric phase (upper) and the field-induced ferroelectric phase (lower). Beam I represents the light beam passing through the prism without applying an electric field, and Beam II represents the light beam with an applied electric field. In the paraelectric phase, both the thickness and slope of the prism are altered by the applied electric field so that Beam II has a different propagation direction from Beam I. However, in the field-induced ferroelectric phase, only the thickness of the prism is altered by the
applied electric field. Beam II has the same propagation direction as Beam I, and thus there is no change in the beam deflection angle.

Figure 3-4: An illustration of an KTN-crystal-based electric-field-controlled tunable half-wave plate.

Figure 3-5: The experimentally measured responding time of the refractive index change of the KTN crystal with the modulation from the applied external electric field at 26 °C (red) and 31 °C (black).

Figure 3-6: An illustration of the experimental setup used to measure the responding time of the SCC KTN beam deflector.

Figure 3-7: The experimentally measured responding time of the SCC KTN beam deflector at 26 °C (near the Curie temperature, at which the electric-field-induced phase transition occurs) and 31 °C (well above the Curie temperature, with no electric-field-induced phase transition in this case).

Figure 3-8: A conceptual illustration of relative permittivity, $\varepsilon_r$, as a function of temperature with and without applied external electric fields. The electric field shifts the cubic-tetragonal transition temperature to a higher temperature.

Figure 4-1: Illumination of a composition gradient controlled KTN beam deflector.

Figure 4-2: (a) Setup for measuring deflection angle of CGC beam deflection. (b) Photo of a KTN crystal. (c) The experimental system used to measure the deflection angle as a function of applied voltage in the CGC KTN beam deflector.

Figure 4-3: At 36 °C, 37 °C, 38 °C, 39 °C, and 40°C, the deflection angle in the y direction as a function of the external voltage.

Figure 4-4: An illustration of beam deflection when the direction of the external electric field is parallel to the direction of the composition gradient.

Figure 4-5: Illustration of zero-deflection position for (a) the homogeneous case and (b) the inhomogeneous gradient composition case.

Figure 4-6: An illustration of beam deflection when the direction of the external electric field is perpendicular to the direction of the composition gradient.

Figure 4-7: The EDS measured variation of Nb atomic ratio as a function of location.

Figure 4-8: The calculated relative permittivity $\varepsilon_r(y)$ as a function of location, y.

Figure 4-9: The calculated electric field within (a) a homogeneous KTN crystal and (b) an inhomogeneous gradient composition KTN crystal, in which the direction of the external electric field is perpendicular to the direction of the composition gradient.

Figure 4-10: (a) The computed refractive index modulation of an inhomogeneous KTN crystal with a gradient relative permittivity (from 40,000 to 43,250) and a pre-injected
space charge density $\rho = -13 \, C/m^3$, but without an external electric field. (b) The computed refractive index modulation of a homogeneous KTN crystal with a relative permittivity $\varepsilon_r = 40,000$, a pre-injected space charge density $\rho = -13 \, C/m^3$, and an external voltage $V = 1250 \, V$ applied in the x direction. The distance between two electrodes was 4.5 mm. (c) The computed refractive index modulation of an inhomogeneous KTN crystal with a gradient relative permittivity (from 40,000 to 43,250), a pre-injected space charge density $\rho = -13 \, C/m^3$, and an external voltage $V = 1250 \, V$ applied in the x direction. The distance between two electrodes was 4.5 mm.

Figure 4-11: The computed deflection angle (a) in the x direction, $\theta_x$, and (b) in the y direction, $\theta_y$, as a function of the external voltage, in which the pre-injected space charges and composition gradient co-exist and the direction of external voltage is perpendicular to the direction of the composition gradient.

Figure 4-12: The experimental system used to measure the deflection angle as a function of applied voltage. The electric field is parallel to the direction of the composition gradient.

Figure 4-13: The deflection angle as a function of the external voltage in which the pre-injected space charges and composition gradient co-exist and the direction of external voltage is parallel to the direction of the composition gradient. The blue dots are the experimental results and the solid line is the theoretical fitting. The dotted line is the fitting from the SCC beam deflection model with the relative permittivity $\varepsilon_r = 65,000$ and the charge density $\rho = -13 \, C/m^3$.

Figure 4-14: The experimental system used to measure the deflection angle as a function of applied voltage. The electric field is perpendicular to the direction of the composition gradient.

Figure 4-15: (a) The measured deflection angle and the computed deflection angle in the x direction. (b) The measured deflection angle and the computed deflection angle in the y direction.

Figure 4-16: (a) At 25°C, 26°C, 27°C, and 28°C, the deflection angle in the x direction as a function of the external voltage, in which the pre-injected space charges and composition gradient co-exist and the direction of external voltage is perpendicular to the direction of the composition gradient. (b) At 25°C, 26°C, 27°C, and 28°C, the deflection angle in the y direction as a function of the external voltage, in which the pre-injected space charges and composition gradient co-exist and the direction of external voltage is perpendicular to the direction of the composition gradient. (c) The deflection angle in both x and y directions at 25°C, 26°C, 27°C, and 28°C.

Figure 5-1: The measured injection current as a function of applied voltage at 27 °C with the blue photon excitation.

Figure 5-2: The non-uniform charge injection distributions used to calculate the deflection angle as a function of location $x$. The solid line, with the blue photon excitation; and the dashed line, without the blue photon excitation.
Figure 5-3: The deflection angles as a function of location $x$ with a 2000 $V$ applied voltage. Solid line – the calculated deflection angles with the blue photon excitation, dashed line – the calculated deflection angles without the blue photon excitation, circular dots – the experimentally measured deflection angles with the blue photon excitation, and square dots – the experimentally measured deflection angles without the blue photon excitation.

Figure 6-1: Schematic drawing of an ultra-thin CGC KTN beam deflector.

Figure 6-2: Schematic drawing of a wavelength-tunable laser with KTN beam deflector.
LIST OF TABLES

Table 1-1: Comparison of linear EO coefficient of Pockels cells[18] ........................................4
Table 1-2: Comparison of Quadratic EO coefficient of Kerr cells[18] .................................5
Table 2-1: Physical properties of KTa$_{1-x}$Nb$_x$O$_3$. .................................................................16
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Chapter 1

Introduction

Optical beam deflectors, as the simple but essential components of modern optical systems, are widely adopted in many fields including imaging, printing, sensing, displays, and telecommunications. Currently, several methods are used to steer the optical beams, including polygonal mirror scanner[1–3], microelectromechanical system (MEMS) mirror scanner[4–6], piezoelectric beam deflector[7,8], acousto-optic (AO) deflector[9–11], and electro-optic (EO) deflector[12–14]. Due to the differences of the deflection mechanisms and material properties, the scanning characteristics of the deflectors are different. Figure 1-1 illustrates four types of mainstream beam deflectors: (a) The polygonal mirror scanner changes the deflection angle of the input light beam by rotating the polygonal mirror. (b) Micro mirrors implemented in the MEMS scanner were driven by the electrostatic force. By adjusting the angle of the micro mirrors, the MEMS scanner changes the transmission path of the input beams. (c) The periodically modulated refractive index in the AO crystal causes the diffraction on the input beam and changes the output light path. (d) With the driving voltage, a refractive index gradient forms in the EO crystal and deflects the input beam by this field-induced prism effect.

We can make a brief comparison with the aforementioned beam deflectors. The polygonal mirror scanner, MEMS mirror scanner, and piezoelectric beam deflector are based on mechanical movement of the refractive mirror. Their scanning speed is much slower than that of AO and EO beam scanners. With the development of high-speed scanning systems, these beam deflection methods cannot meet the rapid response requirements. Although AO beam deflectors provide fast response time, their transmittance is heavily attenuated in the open state, which severely limits their applications in many imaging, sensing and display systems.
EO beam deflectors can introduce a phase delay across the beam cross section with the EO effect, and thus deflect the optical beams. EO effect refers to a redistribution of the bonding charge and possibly a slight deformation of the lattice structure in the crystal when an electric field is applied across the material. Such change results in a refractive index modulation in the EO crystals. EO deflectors have the advantages of high-speed operation, high-transmittance, and no moving parts, which makes it possible to apply them in high-speed scanning systems.

Among all kinds of EO deflectors, prism-shaped beam deflection[15,16] is one of the earliest deflection models. However, due to the severe non-uniform electric field distribution in the
crystal, the deflector is easily damaged by the piezoelectric or electrostrictive effect, which limits its application in the area of high-power and large-angle-deflection scanning.

Without prism structures, other EO deflection models have also been proposed. They introduce a linear phase delay with an electric field gradient in the EO crystal. In this case, a graded refractive index distribution is caused by the EO effect. Thus, the optical beam is cumulatively deflected when it propagates in the crystal. This type of beam deflection model is a widely used scanning mechanism in the commercial market. Many EO materials, such as KH$_2$PO$_4$[12], PZT[13], and LiTaO$_3$[14], have been fabricated into beam scanners with this deflection mechanism.

The refractive index modulation in the EO material can be expressed by the following equation:

$$\Delta n_{ij} = r_{ijk}E_k + s_{ijkl}E_kE_l,$$  \hspace{1cm} (1.1)

where $\Delta n_{ij}$ is the refractive index change, $r_{ijk}$ is the linear EO coefficient tensor, $s_{ijkl}$ is the quadratic EO coefficient tensor, and $E_k$ and $E_l$ are the electric fields. The first term at the right of Eq. (1.1) represents the linear Pockels effect, wherein the change of the refractive indices is proportional to the applied electric field. Typical Pockels cells, such as ZnS, LiNbO$_3$, and BaTiO$_3$, have linear EO coefficients ranging from $10^{-13}$ to $10^{-12}$ m/V. The second term at the right of Eq. (1.1) represents the quadratic Kerr effect, wherein the change of the refractive indices is proportional to the square of the applied electric field. Typical Kerr cells, such as PLZT, SrTiO$_3$, and KTN, have quadratic EO coefficients ranging from $10^{-15}$ to $10^{-14}$ m$^2$/V$^2$.

Compared to other types of EO materials, potassium tantalate niobate (KTN) has the advantage of an exceptionally large quadratic EO coefficient[16,17]. Table 1-1 lists a brief comparison of several common Pockels cells and Table 1-2 lists a brief comparison of several
common Kerr cells. From the table, we can see that KTN has a larger EO coefficient than other frequently used EO materials.

Table 1-1: Comparison of linear EO coefficient of Pockels cells[18].

<table>
<thead>
<tr>
<th>Pockels Cell</th>
<th>$r_{ij}$ ($10^{-12}$ m/V)</th>
</tr>
</thead>
<tbody>
<tr>
<td>ZnSe</td>
<td>$r_{41}=2.2$</td>
</tr>
<tr>
<td>ZnTe</td>
<td>$r_{41}=4.51$</td>
</tr>
<tr>
<td>KDP</td>
<td>$r_{63}=10.3$</td>
</tr>
<tr>
<td>LiNbO$_3$</td>
<td>$r_{31}=32.6$</td>
</tr>
<tr>
<td>BaTiO$_3$</td>
<td>$r_{31}=1640$</td>
</tr>
<tr>
<td>KTN</td>
<td>$r_{31}=8000$</td>
</tr>
</tbody>
</table>
With the emergence of high-quality sizable KTN crystals that are suitable for device fabrication[19], interest in KTN crystals for different applications such as EO modulators, dynamic optical waveguides, and high-speed beam scanners[20–26] has been growing. The unique features of high scanning speed and non-mechanical movement make the KTN-based beam scanner useful in many different optical systems, such as high-speed spectrometers[27], high-speed optical coherent tomography[28], wavelength-tunable lasers[29], dynamic optical beam splitters[30], and alignment-free holographic memory systems[31].

One of the most popular KTN-based beam deflectors in the commercial market is the space-charge-controlled (SCC) KTN beam deflector. In 2008 and 2011, the NTT Photonics Laboratories from Japan proposed two different models to explain the physical mechanisms of SCC KTN beam deflection. In the earlier 2008 model[32], the electrons are instantaneously injected into the crystal by an applied external electric field, which results in a non-uniform electric field that in

<table>
<thead>
<tr>
<th>Kerr Cell</th>
<th>$s_{ij} \times 10^{-18} m^2/V^2$</th>
</tr>
</thead>
<tbody>
<tr>
<td>ADP</td>
<td>$s_{11}-s_{12}=-1.63$</td>
</tr>
<tr>
<td>KDP</td>
<td>$s_{11}-s_{12}=-2.58$</td>
</tr>
<tr>
<td>SrTiO$_3$</td>
<td>$s_{11}-s_{12}=31$</td>
</tr>
<tr>
<td>PLZT</td>
<td>$s_{33}-s_{13}=1768$</td>
</tr>
<tr>
<td>BaTiO$_3$</td>
<td>$s_{11}-s_{12}=2290$</td>
</tr>
<tr>
<td>KTN</td>
<td>$s_{11}-s_{12}=2890$</td>
</tr>
</tbody>
</table>

Table 1-2: Comparison of Quadratic EO coefficient of Kerr cells[18].
turn generates a graded refractive index distribution via the Kerr effect. Such a graded refractive index distribution could deflect the incoming light beams. However, the scanning speed of such deflection is limited by the electron mobility within the KTN crystal. In the later 2011 model[21], the electrons are pre-injected and trapped in the KTN crystal. Again, a graded refractive index distribution is formed via the Kerr effect. Figure 1-2 is a schematic drawing of an SCC KTN beam deflector.

![Illustration of SCC KTN beam deflector.](image)

In this model, the electric field distribution can be expressed as[21]

\[
E(x) = -\frac{eN}{\varepsilon} \left(x - \frac{d}{2} + \frac{eV}{eNd}\right),
\tag{1.2}
\]

where \(V\) is the applied voltage, \(d\) is the electrode gap, \(x\) is the distance from the cathode, \(e\) is the elementary electric charge, \(\varepsilon\) is the permittivity, and \(N\) is the pre-injected and trapped electron
charge density. Assuming that the polarization of the input light is along the direction of the electric field, the refractive index change induced by the Kerr effect is given by[21]:

\[
\Delta n(x) = -\frac{1}{2} n^3 g_{11} e^2 N^2 \left( x - \frac{d}{2} + \frac{eV}{eNd} \right)^2,
\]

(1.3)

where \( n \) is the refractive index and \( g_{11} \) is the quadratic EO coefficient in polar form. The corresponding scanning angle is expressed as[21]

\[
\theta(x) \approx L \frac{d}{dx} \Delta n(x) = -n^3 g_{11} e^2 N^2 L \left( x - \frac{d}{2} + \frac{eV}{eNd} \right),
\]

(1.4)

where \( L \) is the interaction length of the light within the crystal. From Eq. (1.4), it is easy to see that the scanning angle is proportional to the product of the applied electric field and the stored electron charge density. If the applied voltage is adjusted, the scanning angle will be altered accordingly. Thus, the scanning speed is only limited by the response time of the voltage source but not by the electron migration velocity. However, the highest experimentally reported speed was only 700 kHz[33,34]. There may be another reason for this responding delay.

To determine the cause of the slower experimental results than theoretical prediction[21,35] and to significantly increase the scanning speed of the SCC KTN beam scanner, in this study, a thorough investigation of the physical mechanism of the electric-field-induced phase transition and its influence on the scanning speed of the KTN beam scanners is conducted. We find that due to the existence of the electric-field-induced phase transition at a temperature slightly above the Curie temperature, the KTN crystals operate in the linear EO regime instead of the quadratic EO regime. In this case, the beam deflection angle is only proportional to the injected charge density. To change the beam deflection angle, one has to change the injected charge density,
which is limited by the electron mobility in KTN crystals. Thus, the maximum reported scanning speed was only approximately 700 kHz. To overcome this phase-transition-induced speed limitation, this study proposes and implements a SCC KTN beam deflector not only at a temperature above the Curie point but also at a temperature above the critical end point, which ensures that the KTN scanner operates in the paraelectric phase. Without the field-induced phase transition, there is a three orders-of-magnitude increase in the scanning speed from the microsecond regime to the nanosecond regime by increasing the operational temperature from below the critical end point to above the critical end point. This represents a major technological advance in the speed of optical beam scanners.

Although the SCC KTN deflectors can achieve the responding speed in the nanosecond regime, this deflects the optical beam in one dimension only. In most beam steering applications such as 3D printing and in vivo imaging, one of the essential challenges has been the high-resolution high-speed multi-dimensional optical beam scanner. To develop a high-resolution multi-dimensional KTN deflector, we comprehensively study another beam deflection mechanism—composition-gradient-controlled beam deflection—and analyze the deflection behavior of KTN deflectors in the case of coexisting pre-injected space charge and composition gradient. Such a coexistence can enable new functionalities of KTN crystal-based EO deflectors. When the direction of the composition gradient is parallel to the direction of the external electric field, the zero-deflection position can be shifted, which can reduce the internal electric-field-induced beam distortion, and thus enhance the resolution. When the direction of the composition gradient is perpendicular to the direction of the external electric field, two-dimensional beam scanning can be achieved by harnessing only one piece of KTN crystal, which can result in a compact, two-dimensional beam deflector. Both theoretical analyses and experiments are conducted, and the results of the them are consistent with each other. These new functionalities can expedite the usage
of KTN deflection in many applications such as 3D printing, high-resolution imaging, and free-space broadband optical communications.

Another issue of the SCC KTN beam deflector is that the aperture is limited by the space charge injection depth. Due to the existence of the trapping effect[36], the injection depth is typically only on the order of a millimeter. This results in a millimeter-range aperture, which is not large enough for applications that require both large deflection angle and large aperture. To overcome this fundamental limitation, this study reports a method of increasing the aperture of SCC KTN deflectors by harnessing the physical mechanism of blue light photon excitation. The trapped electrons increase their kinetic energy by absorbing the energy of the excitation photon, which in turn increases the possibility of escape from the trapping quantum well. The reduced trapping effect increases the injection depth under the same external injection voltage and time. Thus, a larger aperture for the KTN deflector can be obtained. This represents a substantial increase in the deflection angle at a much deeper penetration depth, which can be useful for applications such as high-speed 3D printings and displays.

**Major accomplishments and discoveries:**

In summary, the major accomplishments and discoveries of this work are listed below and are covered in the following chapters of the dissertation:

- Three-order increase in scanning speed of SCC KTN deflector by eliminating electric-field-induced phase transition in KTN crystal – (Chapter 3)
  (W. Zhu et. al., *Scientific Reports*, 6 (2016): 33143[37])

- New functionalities of KTN deflectors enabled by the coexistence of pre-injected space charge and composition gradient – (Chapter 4)

- Photon-excitation-enabled large-aperture SCC KTN beam deflector – (Chapter 5)

Chapter 2

Fundamentals of KTN Crystals

As the fundamental material for fabricating beam deflectors, KTN has been of interest for more than half a century [16] due to its large EO effect. This chapter comprehensively introduces KTN crystal structures, crystal growth, physical properties, and electro-optical properties—particularly the extraordinary quadratic Kerr effect under the super-cooling process.
2.1 Preparation of KTN and its structures

Potassium tantalate niobate (KTN) is a solid solution of potassium tantalate (KTaO$_3$) and potassium niobate (KNbO$_3$). KTaO$_3$ and KNbO$_3$ have similar unit cell size but quite different phase transition temperature[41,42]. KTN has a Perovskite-type structure, which is shown in Fig. 2-1.

![Figure 2-1: Conceptual illustration of the KTN crystal structure.](image)

As a typical Perovskite compound, the potassium (K) atoms are located at the cube-corner positions, the tantalum (Ta) or niobium (Nb) atom is positioned at the body-center position, and the oxygen (O) atoms are situated at the face-center positions.

To maintain a stable cubic structure, the requirements of the ion size are rigorous. Any slight buckling or distortion may cause several lower symmetry distorted versions. Due to the thermally-induced ion/dipole shifts, the crystal symmetry can be changed by the thermodynamics. Thus, at different temperatures, KTN crystals can show different phases. The temperature at which KTN undergoes a phase transition from cubic phase to tetragonal phase is called the Curie temperature[16]. Above the Curie temperature, KTN is a cubic symmetric crystal. As the temperature continues to decrease, the phase of KTN crystals changes from cubic to tetragonal,
then to orthorhombic, and last to rhombohedral phase. The phase transition temperature is based on the ratio from Ta to Nb, as shown in the phase diagram in Fig. 2-2.

![Figure 2-2: Crystal phase diagram of KTa$_x$Nb$_{1-x}$O$_3$ crystals. The data points are extracted from Fig. 5 in Ref. [43].](image)

In 1959, Triebwasser[43] first grew and reported the KTN single crystal. Soon after that, Geusic et al.[17] reported a large EO effect in KTN crystals. Due to the large EO coefficients, KTN crystals attracted much interest in the following decades. Many techniques were used to prepare the KTN single crystals or thin films, such as Kyropoulos process[44], TSSG technique[45–48], liquid phase epitaxy (LPE)[48,49], RF sputtering[49,50], chemical solution deposition (CSD)[51,52], sol-gel method[53,54], metal-organic chemical vapor deposition (MOCVD)[55,56], and pulse laser deposition (PLD)[57,58].

However, no KTN device was commercially available for a long time following its discovery. This is because it is difficult to obtain a high-quality sizeable KTN single crystal. In 2008, NTT lab from Japan successfully grew such a high-quality sizeable KTN crystal[19]. They
reported that the KTN crystal had a size of $40 \text{mm} \times 40 \text{mm} \times 20 \text{mm}$ and a high optical transparence, and it could be fabricated into many optical devices, such as high-speed optical beam scanners and high-speed vari-focal lenses.
2.2 KTN properties

2.2.1 Physical properties of KTN crystals

Because KTN is a solid solution of KTaO$_3$ and KNbO$_3$, most of the physical properties of KTN crystal are between the properties of KTaO$_3$ and KNbO$_3$ and are based on the mole concentration ratio of KTaO$_3$ and KNbO$_3$. In Table 2-1 are listed the physical properties of KTN, including thermal properties and mechanical properties.
Table 2-1: Physical properties of KTa$_{1-x}$Nb$_x$O$_3$.

<table>
<thead>
<tr>
<th>Properties</th>
<th>Tetragonal</th>
<th>Cubic</th>
<th>Nb/(Ta+Nb)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Lattice constant (Å)</td>
<td>3.9970</td>
<td>3.9941</td>
<td>0.37</td>
</tr>
<tr>
<td>Melting point (K)</td>
<td>1536.90</td>
<td>1520.31</td>
<td>0.33</td>
</tr>
<tr>
<td>Density (g/cm$^3$)</td>
<td>6.235</td>
<td>6.180</td>
<td>0.33</td>
</tr>
<tr>
<td>Elastic stiffness coefficient (GPa)</td>
<td>c$<em>{11}$ = 424.8295, c$</em>{33}$ = 121.3778, c$<em>{44}$ = 82.8600, c$</em>{12}$ = 68.0517, c$<em>{13}$ = 80.7003, c$</em>{66}$ = 93.6141, c$<em>{11}$ = 489.0866, c$</em>{33}$ = 472.4396, c$<em>{44}$ = 87.9732, c$</em>{12}$ = 65.1750, c$<em>{13}$ = 64.7585, c$</em>{66}$ = 84.1298, 0.5</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Bulk modulus (GPa)</td>
<td>135.62</td>
<td>204.58</td>
<td>0.5</td>
</tr>
<tr>
<td>Shear modulus (GPa)</td>
<td>91.79</td>
<td>124.12</td>
<td>0.5</td>
</tr>
<tr>
<td>Young’s modulus (GPa)</td>
<td>224.689</td>
<td>309.79</td>
<td>0.5</td>
</tr>
<tr>
<td>Thermal expansion (K$^{-1}$)</td>
<td>6.4×10$^{-6}$, 6.6×10$^{-6}$</td>
<td></td>
<td>0.33, 0.37</td>
</tr>
<tr>
<td>Specific heat (J/g-K)</td>
<td>0.421</td>
<td>0.430</td>
<td>0.33, 0.37</td>
</tr>
<tr>
<td>Thermal conductivity (W/m-K)</td>
<td>8.551</td>
<td>5.592</td>
<td>0.33, 0.37</td>
</tr>
<tr>
<td>Thermal diffusion coefficient (mm$^2$/s)</td>
<td>2.132</td>
<td>1.689</td>
<td>0.33, 0.37</td>
</tr>
<tr>
<td>Resistivity (Ω-cm)</td>
<td>5×10$^{11}$, 2×10$^{8}$</td>
<td></td>
<td>0.37, 0.40</td>
</tr>
</tbody>
</table>
Because the photonic bandgap of KTN crystals is 3.1 eV, the absorption occurs at a wavelength of 4 μm. The KTN has a wide transmission window from 400 nm to 4 μm, as shown in Fig. 2-3.

![Figure 2-3: Transmittance of a KTa0.7Nb0.3O3 crystal. The data points are extracted from Fig. 1-2 in Ref. [59].](image)

Figure 2-4 is a photo of a double-sided polished KTN single crystal with dimensions of 10 mm x 10 mm x 1 mm. As mentioned previously, the high-quality KTN is colorless and optically transparent. Figure 2-5 shows the refractive index of a KTa0.63Nb0.37O3 crystal in the anomalous dispersive curve. The dispersion relationship fits well with a single-term Sellmeiser formula,
\[ n_0^2 - 1 = \frac{3.7994}{1 - \left(\frac{A_s}{\lambda}\right)^2}, \]  

(2.1)

where \( \lambda_s = 0.2012 \, \mu m \).

Figure 2-4: Photo of a piece of KTN crystal.
Figure 2-5: The dispersion relationship of the KTa$_{0.63}$Nb$_{0.37}$O$_3$ crystal plotted from the data points shown in Fig. 3 of Ref. [16].
2.2.2 Electro-optical properties of KTN crystals

When an external electric field, $E$, is applied to the KTN crystal, the bond charges in the crystals are redistributed, which changes the dielectric impermeability tensor (or refractive indices). Such change can be expressed as the following equation:

$$\eta_{ij}(E) - \eta_{ij}(0) \equiv \Delta \eta_{ij} = f_{ijk}P_k + g_{ijkl}P_kP_l,$$

where $P$ is the electric polarization, and $f_{ijk}$ and $g_{ijkl}$ are used for defining the linear and quadratic EO coefficients, respectively. Since the electric polarization, $P$, and the electric field, $E$, are related as

$$P = (\varepsilon_{ij} - \varepsilon_0)E,$$

where $\varepsilon_{ij}$ is the permittivity tensor, Eq. (2.2) can be modified as

$$\Delta \eta_{ij} = r_{ijk}E_k + s_{ijkl}E_kE_l,$$

where

$$r_{ijk} = f_{ijk}(\varepsilon_k - \varepsilon_0),$$

$$s_{ijkl} = g_{ijkl}(\varepsilon_k - \varepsilon_0)(\varepsilon_l - \varepsilon_0).$$
As mentioned in Section 2.1, when the temperature is below the Curie temperature, KTN is in the ferroelectric phase. The quadratic EO effect is much smaller than the linear EO effect and can be ignored under the electric field. In this case, the linear EO coefficient tensor of the ferroelectric KTN can be written as

\[
\mathbf{r}_{ij} = \begin{pmatrix}
0 & 0 & r_{13} \\
0 & 0 & r_{13} \\
0 & 0 & r_{33} \\
0 & r_{51} & 0 \\
0 & r_{51} & 0 \\
0 & 0 & 0
\end{pmatrix},
\]

(2.6)

Figure 2-6 shows the linear EO coefficients, \( r_{51} \) and \( r_{c} \), as a function of temperature, which was reported by Van Raalte[60] in 1967. Here,

\[
r_{c} = r_{33} - \left( \frac{n_{a}}{n_{c}} \right)^{3} r_{13},
\]

(2.7)

where \( n_{a} \) is the refractive index on its orthogonal plane and \( n_{c} \) is the refractive index along the c-axis.
When the temperature is above the Curie temperature, KTN is in the paraelectric phase. If a voltage is applied across the KTN crystal, the quadratic EO effect is dominant in KTN. The quadratic EO coefficient tensor can be written as

\[
[s_{ij}] = \begin{pmatrix}
s_{11} & s_{12} & s_{12} & 0 & 0 & 0 \\
s_{12} & s_{11} & s_{12} & 0 & 0 & 0 \\
s_{12} & s_{12} & s_{11} & 0 & 0 & 0 \\
0 & 0 & 0 & s_{44} & 0 & 0 \\
0 & 0 & 0 & 0 & s_{44} & 0 \\
0 & 0 & 0 & 0 & 0 & s_{44}
\end{pmatrix}
\]  

(2.8)

Figure 2-6: Linear EO coefficients, \( r_{51} \) and \( r_c \), of KTN crystal as a function of temperature, plotted in solid and dashed lines, respectively. The data points are extracted from Ref. [60].
Figure 2-7 shows the quadratic EO coefficient, $s_{11}$, of a KTa$_{0.59}$Nb$_{0.41}$O$_3$ crystal as a function of temperature. This was reported by Nakamura[32] in 2008.

Figure 2-7: Quadratic EO coefficient, $s_{11}$, of KTa$_{0.59}$Nb$_{0.41}$O$_3$ crystal as a function of temperature. The data points are extracted from Fig. 3 in Ref. [32].
2.2.3 Kovacs effect in nanodisordered KTN

Kovacs effect refers to the properties of materials at any given temperature being different from the effect of heating and cooling processes[61–63]. In the glassy system, the system behaviors are different at the nonequilibrium state, depending on its thermal cycling history. In KTN crystal, the evolution of the relative permittivity with the temperature in the heating process is different from that in the cooling process, as shown in Fig. 2-8.

![Figure 2-8: A conceptual illustration of the permittivity as a function of temperature for a KTN crystal with different temperature cycling histories. Solid curve: reducing temperature, dashed curve: increasing temperature.](image)

In 2013, Chang et al. discovered an enhancement of EO coefficients by the super-cooling process[23,64]. The EO properties of a KTN glassy system exhibit the Kovacs effect. EO modulation can vary for different thermal histories; by a super cooling process, EO coefficients are
enhanced by 3.5 times those of a thermal equilibrium state. Figure 2-9 shows the transient EO coefficients of a KTa$_{0.6}$Nb$_{0.4}$O$_3$ crystal as a function of temperature at different cooling rates. This result was reported by Chang[64] in 2013.

![Figure 2-9](image)

Figure 2-9: Transient EO coefficients of a KTa$_{0.6}$Nb$_{0.4}$O$_3$ crystal with temperature, acquired at three different cooling rates of 0.45 °C/s (square), 0.20 °C/s (diamond), and 0.03 °C/s (triangle). The data points are extracted from Fig. 5 in Ref. [64].

With a cooling rate 0.45 °C/s, the EO coefficient can be as large as 6.94x10$^{-14}$ m$^2$/V$^2$, which is the largest EO coefficient among all the EO materials reported so far. The benefits from the enhancement of EO coefficients in such nanodisordered KTN crystal can greatly reduce the required voltage for most EO devices.
Chapter 3

Electric-Field-Induced Phase Transition and Ultra-Fast KTN Beam Deflector

Electric-field-induced phase transition refers to the fact that, even if it is above the Curie temperature, the material will undergo a phase transition from the paraelectric phase to the ferroelectric phase with an applied external high electric field. In such field-induced ferroelectric phase, the responding speed of KTN-based EO devices is limited by the emergence of the polar micro-domains in the microscopic scale.

To overcome this speed limitation caused by the electric-field-induced phase transition, this study suggests that KTN-based EO devices should be operated at a temperature above the critical end point. This results in a significant increase in the scanning speed of the KTN-based beam scanners from the microsecond to nanosecond regime, which is a three-order-of-magnitude increase in the speed.
3.1 Field-induced phase transition

In 2014, T. Imai et al[65] from NTT lab in Japan observed the phenomenon of field-induced phase transition in KLTN \((K_{0.95}Li_{0.05}Ta_{0.73}Nb_{0.27}O_3)\) crystals. They noticed that the KLTN crystal could undergo a phase transition from the paraelectric phase to the ferroelectric phase under an applied external electric field, even at a temperature above the Curie temperature. The higher the electric field and the closer the sample is to the Curie temperature, the more the phase transition is facilitated. Such discovery immediately attracted our attention to this phenomenon, since KTN has similar crystalline structures to KLTN. We speculate that such field-induced phase transition can also occur in KTN crystals.

As mentioned in Chapter 2, KTN is a solid solution of potassium tantalate \((K_TaO_3)\) and potassium niobate \((K_NB_O_3)\) with a Perovskite-type structure[16]. In the Perovskite cells, potassium (K) atoms are located at the corners of each cube, and six oxygen (O) atoms are positioned at the face centers. The niobium (Nb) atoms or tantalum (Ta) atoms are in the center of each cube. When the temperature is well above the Curie temperature, the niobium ions randomly shift from the center of each cube, and hence generate dipoles. Due to the randomness of the dipole directions in each cell, they would cancel each other out, therefore exhibiting a zero polarization at both nanoscopic and macroscopic scales. This state of KTN crystal is shown in Fig. 3-1(a). If we lower the temperature and maintain it slightly above the Curie temperature, the thermally induced random dipole movement becomes weaker, and the localized polar nanoregions (PNRs) appear due to the interaction among adjacent dipoles[64]. Although each PNR has a nonzero polarization at the nanoscopic scale, the macroscopic polarization is still zero due to the random polarization orientations of PNRs. Thus, the crystal still appears in the paraelectric phase, as shown in Fig. 3-1(b). However, if a high electric field is applied on the KTN crystal at this temperature, the polarization orientations of most PNRs will be aligned along the direction of the external electric
field. Consequently, the material has a single polarization direction and appears as if it were in the ferroelectric phase, as shown in Fig. 3-1(c). If we increase the temperature and maintain it above a certain point, such field-induced phase transition can be prevented. This temperature point is called the critical end point[65].

Figure 3-1: Illustration of the KTN polarization under different conditions: (a) at a temperature well above the Curie temperature and with no electric field; (b) at a temperature slightly above the Curie temperature and with no electric field; (c) at a temperature slightly above the Curie temperature and with a high electric field.
3.2 SCC KTN beam deflector operating in the electric-field-induced ferroelectric phase

As mentioned in Chapter 1, the deflection angle of the SCC KTN beam deflector operating in the paraelectric phase can be expressed as Eq. (1.4). If the temperature is below the critical end point (still above the Curie temperature) and the applied electric field is large enough, the SCC KTN beam deflector will undergo a phase transition and operate in the electric-field-induced ferroelectric phase. At this moment, Eq. (1.4) must be modified accordingly.

Figure 3-2: An illustration of a KTN crystal in the ferroelectric phase.
Figure 3-2 illustrates a KTN-based deflector in the ferroelectric phase. For illustrative purposes, we can assume the direction of the applied external electric field is along the z-axis, which means $E_x = E_y = 0$, $E_z \neq 0$, and the field-induced optical axis is also along the z-axis. Under this simplification, $n_x = n_y = n_o$ and $n_z = n_e$, where $n_x$, $n_y$, and $n_z$ represent the refractive indices of the crystal for the x-, y-, and z- polarized light, respectively; $n_o$ and $n_e$ are the refractive indices of the ordinary ray and extraordinary ray, respectively.

The general equation of the index ellipsoid of the linear EO effect with an applied external electric field $\vec{E} = E_x \hat{x} + E_y \hat{y} + E_z \hat{z}$ can be written as

$$
\begin{align*}
&x^2 \left( \frac{1}{n_x^2} + r_{11} E_x + r_{12} E_y + r_{13} E_z \right) \\
&+ y^2 \left( \frac{1}{n_y^2} + r_{21} E_x + r_{22} E_y + r_{23} E_z \right) \\
&+ z^2 \left( \frac{1}{n_z^2} + r_{31} E_x + r_{32} E_y + r_{33} E_z \right) \\
&+ 2xy (r_{41} E_x + r_{42} E_y + r_{43} E_z) \\
&+ 2xz (r_{51} E_x + r_{52} E_y + r_{53} E_z) \\
&+ 2yz (r_{61} E_x + r_{62} E_y + r_{63} E_z) = 1.
\end{align*}
$$

(3.1)

Since KTN has a 4mm symmetry in its ferroelectric phase, its linear EO coefficients, $r_{ij}$, are in the form of

$$
\begin{bmatrix}
0 & 0 & r_{31} \\
0 & 0 & r_{31} \\
0 & 0 & r_{33} \\
r_{51} & 0 & 0 \\
r_{51} & 0 & 0 \\
0 & 0 & 0
\end{bmatrix}
$$

(3.2)

Substituting Eq. (3.2) and $n_x = n_y = n_o$, $n_z = n_e$ into Eq. (3.1), it can be simplified as
\[
\left( \frac{1}{n_o^2} + r_{13}E_z \right)x^2 + \left( \frac{1}{n_o^2} + r_{13}E_z \right)y^2 + \left( \frac{1}{n_e^2} + r_{33}E_z \right)z^2 + 2r_{51}E_yy + 2r_{51}E_xxz = 1. \tag{3.3}
\]

Since the applied external electric field is only along the z-axis \((E_x = E_y = 0, E_z \neq 0)\), Eq. (3.3) can be further simplified as

\[
\left( \frac{1}{n_o^2} + r_{13}E_z \right)x^2 + \left( \frac{1}{n_o^2} + r_{13}E_z \right)y^2 + \left( \frac{1}{n_e^2} + r_{33}E_z \right)z^2 = 1. \tag{3.4}
\]

Thus, the principal refractive indices under the electric field are given by

\[
\frac{1}{n'_x} = \frac{1}{n_o^2} + r_{13}E_z, \tag{3.5a}
\]

\[
\frac{1}{n'_y} = \frac{1}{n_o^2} + r_{13}E_z, \tag{3.5b}
\]

\[
\frac{1}{n'_z} = \frac{1}{n_e^2} + r_{33}E_z. \tag{3.5c}
\]

Due to \(r_{ij}E \ll n\), we can solve Eqs. (3.5) and obtain:

\[
n'_x = n'_y \approx n_o - \frac{1}{2} r_{13} n_o^3 E_z, \tag{3.6}
\]

\[
n'_z \approx n_e - \frac{1}{2} r_{33} n_e^3 E_z. \tag{3.7}
\]
Therefore, if a z-polarized laser beam propagates in this crystal, the refractive index modulation can be given by

\[ \Delta n = -\frac{1}{2} r_{33} n_e^3 E_z = \frac{1}{2} r_{33} n_e^3 \frac{eN}{\varepsilon} \left( x - \frac{d}{2} + \frac{eV}{eNd} \right). \] (3.8)

The scanning angle is

\[ \theta(x) \approx L \frac{d}{dx} \Delta n(x) = \frac{1}{2} L r_{33} n_e^3 \frac{eN}{\varepsilon}. \] (3.9)

From Eq. (3.9), we can see that the beam deflection angle of such ferroelectric KTN beam deflector only depends on the pre-injected charge density. It does not depend on the magnitude of the applied external electric field. Thus, to adjust the deflection angle, one has to change the charge density. In this case, even with the pre-injected and trapped charges, the scanning speed is still limited by the electron mobility.

As an intuitive illustration, the KTN-based EO beam deflector can be considered as a voltage-controlled variable prism. As shown in Figure 3-3, in such a variable prism, the slope of the output surface and the thickness of the prism can be adjusted by the driving voltage. If the KTN beam deflector operates in the paraelectric phase, both the thickness and slope of the prism changes with the electric field modulation. Thus, it can adjust the deflection angle of the incoming light beam according to the electric field. However, if the beam deflector works in the field-induced ferroelectric phase, only the thickness of the prism changes with the electric field modulation. The slope remains the same. Thus, it cannot adjust the deflection angle of the light beam according to the electric field. In this case, one has to change the charge density to change the slope and deflect the incoming light beam.
Figure 3-3: An illustration of a voltage-controlled variable prism working in the paraelectric phase (upper) and the field-induced ferroelectric phase (lower). Beam I represents the light beam passing through the prism without applying an electric field, and Beam II represents the light beam with an applied electric field. In the paraelectric phase, both the thickness and slope of the prism are altered by the applied electric field so that Beam II has a different propagation direction from Beam I. However, in the field-induced ferroelectric phase, only the thickness of the prism is altered by the applied electric field. Beam II has the same propagation direction as Beam I, and thus there is no change in the beam deflection angle.
3.3 Experiments and results

To validate the proposed ideas, a KTN beam deflector is fabricated with the following specifications. First, a KTN crystal \((T_c \approx 24^\circ C)\) is diced into \(7 \, mm \times 4 \, mm \times 2 \, mm\) piece and all six surfaces are well polished. Then, to pre-inject the electrons and apply the driving electric field, we coat Ti/Au electrodes on the two \(4 \, mm \times 2 \, mm\) opposite surfaces. After electrode coating, the KTN crystal is mounted on a temperature controller and connected to an ultra-fast high-voltage switchable power supply. The voltage signal can be quickly switched on or off within 1-2 ns. In addition, a high-speed photodetector (FEMTO Messtechnik GmbH HCA-S-200M-Si) is used to measure the responding time of the system.

Before we measure the responding speed of the beam deflector, an experiment to determine the responding time of the refractive index modulation with the high-speed applied electric signal is conducted. In the experiment, the KTN crystal, which serves as an electric-field-controlled tunable half-wave plate, is placed between two polarizers with 45-degree polarization (see Fig. 3-4). Typically, the second polarizer is called the analyzer. A diode-pumped solid-state (DPSS) laser (Coherent, Inc. Compass 532-200) with a 532-nm wavelength is used as the light beam source.
When the temperature is well above the Curie temperature, the KTN crystal is in the paraelectric phase, and the electric-field-induced refractive index modulation can be expressed as

\[
\Delta n = -\frac{1}{2} n^3 (g_{11} - g_{12}) \varepsilon^2 \left( \frac{V}{d} \right)^2,
\]

(3.10)

where \( n \) is the refractive index, \( g_{11} \) and \( g_{12} \) are the polar form quadratic EO coefficients for vertical and horizontal polarized light, \( \varepsilon \) is the permittivity, \( V \) is the applied external voltage, and \( d \) is the gap spacing between electrodes. Although the vertical and horizontal polarized light travel the same distance, \( t \), in the crystal, due to the different refractive indices they meet, the output phases are different, and hence the polarization of the output laser beam is also modulated. The phase difference between the vertical and horizontal polarized light is

Figure 3-4: An illustration of an KTN-crystal-based electric-field-controlled tunable half-wave plate.
\[ \Delta \phi = 2\pi \cdot \frac{\Delta n \cdot t}{\lambda} = \frac{2\pi \cdot t}{\lambda} \left[ -\frac{1}{2} n^3 (g_{11} - g_{12}) \varepsilon^2 \left( \frac{V}{d} \right)^2 \right], \]  

where \( \lambda \) is the wavelength of the input light. Based on this phase difference, the quadratic half-wave voltage, at which voltage the output polarization direction of the laser beam is altered by 90 degrees, can be derived as

\[ V_{\pi q} = \frac{d}{\varepsilon_0 \varepsilon_r} \sqrt{\frac{\lambda}{n^3 (g_{11} - g_{12}) t^t}}, \]  

where \( \varepsilon_0 \) is the vacuum permittivity, and \( \varepsilon_r \) is the relative permittivity. Without applying the external driving voltage, due to the cubic phase of the KTN crystal, the polarization direction of the incoming laser beam is not changed, so that the light can pass through the analyzer. At this moment, we can obtain the output laser intensity from the photodetector. If we apply the half-wave voltage on the KTN crystal, the polarization direction of the incoming light beam is altered by 90 degrees, which will in turn be blocked by the analyzer. In this case, we should not obtain an output signal from the photodetector. Thus, when a half-wave voltage is applied to the KTN crystal and then quickly turned off, we can observe a quick increase in the output light intensity with the photodetector.

Similarly, when the KTN crystal is in the ferroelectric phase, based on Eqs. (3.6) and (3.7), the electric-field-induced refractive index difference between the vertical and horizontal polarized light is expressed as

\[ \Delta n' = n'_x - n'_y = (n_e - n_o) - \frac{1}{2} (r_{33} n_e^3 - r_{13} n_o^3) \cdot \frac{V}{d}, \]  

where \( n'_x \) and \( n'_y \) are the refractive indices for vertically and horizontally polarized light, respectively.
and the corresponding phase difference between the vertical and horizontal polarized light is

$$\Delta \phi' = 2\pi \cdot \frac{\Delta n' \cdot t}{\lambda} = \frac{2\pi \cdot t}{\lambda} \cdot \left[ (n_e - n_o) - \frac{1}{2} (r_{33}n_e^3 - r_{13}n_o^3) \cdot \frac{V}{d} \right].$$  \hspace{1cm} (3.14)

Thus, the linear half-wave voltage, $V_{\pi t}$, is derived as,

$$V_{\pi t} = \frac{\lambda d}{(n_e^2 r_{33} - n_o^2 r_{13}) t}.$$  \hspace{1cm} (3.15)

Again, when a half-wave voltage is applied on the KTN crystal and then quickly switched off, we can observe a quick increase in the output light intensity.

In the experiment, when a 900 $V$ voltage is first applied on the KTN crystal at 26°C (above but close to the Curie temperature), we find that the output light intensity reaches a minimum value. This means that the polarization direction of the incoming light is rotated by 90 degrees. When the applied 900 $V$ voltage is quickly turned off, a quick increase in the output light intensity is observed, which is shown as the red line in Fig. 3-5. The responding time is approximately 3 ns. Next, when a 1400 $V$ voltage is applied on the KTN crystal at 31°C (well above the Curie temperature), the output light intensity reaches the minimum. When the applied 1400 $V$ voltage is quickly turned off, a quick increase in the output light intensity is observed again (shown as the black line in Fig. 3-5). The responding time is slightly faster approximately 2 ns. At any rate, the responding time of the refractive index change of the KTN crystal with the modulation from the applied external electric field is on the order of a nanosecond in both cases. We believe that the responding time is mainly limited by the RC time constant of the circuit as well as the responding speed of the switchable high-voltage source itself.
Figure 3-6: The experimentally measured responding time of the refractive index change of the KTN crystal with the modulation from the applied external electric field at 26 °C (red) and 31 °C (black).

Figure 3-6 illustrates the experimental system used to measure the responding time of the SCC KTN beam deflector. In the system, a polarizer is placed in front of the KTN beam deflector to make sure the polarization direction of the input light beam is in the same direction as the electric field to maximize the EO effect. Without the applied external voltage, the propagation direction of the input light is not affected by the KTN crystal. Thus, the light beam can reach the photodetector and generate the maximum output signal. When an external voltage is applied on the KTN crystal, the light beam is deflected from the photodetector and we can observe a dramatic drop in the output.
signal from the photodetector. In other words, when we switch off the high-voltage signal from the KTN beam deflector, within 1-2 ns we can obtain an output light intensity increase from low level to high level at the nanosecond scale if the responding time of the beam deflector is fast enough. Otherwise, the beam deflector cannot follow the high-speed voltage modulation.

Figure 3-6: An illustration of the experimental setup used to measure the responding time of the SCC KTN beam deflector.

In the experiment, a 2000 V voltage is first applied on the KTN beam deflector and then quickly switched off at a temperature of 26°C (above but close to the Curie temperature). Figure 3-7 shows the measured light intensity as a function of delay time. It can be seen that the responding time is approximately 1500 ns, which is three orders-of-magnitude longer than the responding time of the refractive index change in the experiments described above. From this experimental result, we can confirm that the responding time of the beam deflector is much longer than that of the refractive index change due to the electric-field-induced phase transition. In other words, although the refractive index is modulated with the removal of the voltage, the gradient of the refractive index remains the same at the nanosecond scale, as illustrated in Fig. 3-3. The gradient change of the refractive index only occurs when the stored charge density is changed, which happens at the microsecond scale due to the limited electron mobility in the KTN crystal. In Fig. 3-7, the output
light beam intensity starts to increase quickly after 1500 ns. We speculate that the KTN crystal undergoes a phase transition from the field-induced ferroelectric phase back to the paraelectric phase as the applied external electric field is removed. After such phase transition, the responding speed can increase in the paraelectric phase according to the above analysis. The measured responding time (~1500 ns) in our experiment also matches the previously reported scanning speed[21,33], which is on the order of hundreds of kilohertz.

After measuring the responding speed at 26°C, we increase the temperature to 31°C, which is well above the Curie temperature and also above the critical end point. A 2000 V voltage is applied on the KTN beam deflector and then quickly turned off at this temperature. Figure 3-7 also shows the measured output light beam intensity as a function of delay time. It can be seen that the responding time is on the order of a nanosecond, which is compatible with the responding time of the refractive index change. From this experimental result, we can confirm that the responding time of the SCC KTN beam deflector can be on the order of a nanosecond as long as it operates in the paraelectric phase by avoiding the field-induced phase transition.

Figure 3-7: The experimentally measured responding time of the SCC KTN beam deflector at 26 °C (near the Curie temperature, at which the electric-field-induced phase transition occurs) and 31 °C (well above the Curie temperature, with no electric-field-induced phase transition in this case).
3.4 Discussions and conclusions

To obtain a better understanding of the theoretical study and experimental results, the following analysis is conducted. We first analyze the quadratic EO effect of the KTN crystal in the ferroelectric phase. Because the relative permittivity is small in the ferroelectric phase and the refractive index change induced by the quadratic EO effect is proportional to the square of permittivity, the quadratic EO effect of KTN in the ferroelectric phase is substantially smaller than the linear EO effect in the ferroelectric phase and can be neglected. This situation is discussed in detail in the following paragraph.

Figure 3-8 shows a conceptual illustration of the relative permittivity, $\varepsilon_r$, of KTN crystal as a function of temperature with and without external electric fields. We can see that the relative permittivity is approximately 2000 in the ferroelectric phase if the temperature is well below the Curie temperature; the relative permittivity can be as large as 17500 in the ferroelectric phase if the temperature is below but close to the Curie temperature[66]. Moreover, the electric field can shift the paraelectric (cubic) to ferroelectric (tetragonal) transition temperature to a higher temperature[67]. The stronger the electric field that is applied, the larger the shift that can be observed. For example, with a 100 $V/mm$ electric field, there can be a 3 °C forward shift in the phase transition temperature[67]. Since the transition temperature of the KTN sample in our experiments is 24 °C without the applied external electric field, the transition temperature may become higher than 26 °C when a 100+ $V/mm$ electric field is applied. Thus, with a 100+ $V/mm$ external electric field, the KTN crystal will be in the field-induced ferroelectric phase if the operational temperature is only 26 °C; this situation has a relative permittivity of approximately 2000. To ensure that the 900 $V$ half-wave voltage, which is measured at 26 °C, is primarily caused by the linear EO effect, we can make the following calculation. By substituting $n = 2.314$, $g_{11} - g_{12} = 0.16 m^4/C^2$, $t = 2 mm$, $\lambda = 532 nm$, $\varepsilon_0 = 8.85 \times 10^{-12} F/m$, $\varepsilon_r = 2000$, and $d = 7 mm$
into Eq. (3.12), we obtain the theoretically calculated quadratic half-wave voltage, \( V_{q\pi-T} = 5479 \, V \), which is much higher than the experimentally measured 900 \( V \) half-wave voltage. On the other hand, since \( n_0 \approx n_e \approx 2.314 \) and \( r_{33} \gg r_{13} \), by substituting \( V_{nl} = 900 \, V \), \( t = 2 \, mm \), \( \lambda = 532 \, nm \), \( n_e = 2.314 \), and \( d = 7 \, mm \) into Eq. (3.15), we obtain the effective linear EO coefficient \( r_{33}^{\text{eff}} = 167 \, pm/V \) in this field-induced ferroelectric phase. This result makes sense because it is less than the peak value of \( r_{33} \) measured in the pure ferroelectric phase[68], which is measured at the temperature lower than the original transition temperature, but is still within the same range. In other words, unlike the pure ferroelectric phase, not all PNRs are perfectly aligned in the direction of external electric field at this field-induced ferroelectric phase. Thus, the effective \( r_{33}^{\text{eff}} \) is less than the peak value of \( r_{33} \). Since 900 \( V \) is not high enough for the quadratic EO modulation and the linear EO effect is dominant in this case, we only need to consider the linear EO effect in the regime of EO modulation in such a field-induced ferroelectric phase.
Furthermore, since the beam deflection induced by the quadratic EO effect is also quite small in the field-induced ferroelectric phase, it can also be neglected, as discussed below. Based on Eqs. (1.4) and (3.9), when a light beam travels through the center of the electrode gap, where $x = d/2$, the amount of beam deflection angle in the ferroelectric phase, $\theta_f$, can be expressed as

$$\theta_f = \theta_1 + \theta_2 = \frac{1}{2} L r_{33} n^3 \frac{\rho}{\varepsilon_0 \varepsilon_r} - n^3 g_{11} \rho L \varepsilon_0 \varepsilon_r \frac{V}{d},$$

(3.16)
where $\rho = e \cdot N$ is the injected charge density. The first term of Eq. (3.16), $\theta_1$, represents the contribution from the linear EO effect and the second term of Eq. (3.16), $\theta_2$, represents the contribution from the quadratic EO effect. As an example, we can make the following numerical estimation. In the steady state, the injected charge density, $\rho$, depends on the magnitude of injecting electric field\[36]. When the 900 $V$ half-wave voltage is applied, the magnitude of the electric field is $900 V/7 mm = 129 V/mm$. According to Ref.\[36], the injected charge density is approximately $10 C/m^3$ when the penetration depth is larger than 0.5 $mm$, which is similar to the case in our experiment. By substituting $L = 2 mm$, $r_{33-off} = 167 m/V$, $n_e = 2.314$, $\rho = 10 C/m^3$, $\varepsilon_0 = 8.85 \times 10^{-12} F/m$, and $\varepsilon_r = 2000$ into Eq. (3.16), we obtain $\theta_1 = 1.16 mrad = 0.067^\circ$. Similarly, by substituting $n = 2.314$, $g_{11} = 0.136 m^4/C^2$, $\rho = 10 C/m^3$, $L = 2 mm$, $\varepsilon_0 = 8.85 \times 10^{-12} F/m$, $\varepsilon_r = 2000$, $V_\pi = 900 V$, and $d = 7 mm$ into Eq. (3.16), we obtain $|\theta_2| = 0.077 mrad = 0.004^0$, which is about 17 times smaller than $\theta_1$. Thus, the contribution to beam deflection from the quadratic EO effect can be neglected in the ferroelectric phase when the 900 $V$ half-wave voltage is applied.

Moreover, in the optical modulation experiment, due to the small beam deflection angle, the effect of beam deflection can be neglected. As described above, at 26 $^\circ C$, the 900 $V$ half-wave voltage-induced transversal shift at the focal plane of the photodetector is $x_{1-26} = f \cdot \theta_f \approx f \cdot \theta_1 = 50 mm \cdot 1.17 mrad = 0.058 mm$, where $f = 50 mm$ is the focal length of the lens in front of the photodetector. This transversal shift is much smaller than the radius of the photodetector, $r_p = 0.4 mm$. Thus, even if there is beam deflection when applying the 900 $V$ voltage, the deflected beam can still be detected as long as the light beam is focused on the center of the photodetector when no voltage is applied. In other words, the output light beam intensity change is caused by the EO modulation but not by the EO beam deflection. The fast response at 26 $^\circ C$ can represent the responding time of refractive index change at a nanosecond scale.
Similar to the case in 26 °C, at 31 °C, the operational temperature is well above the Curie temperature and also above the critical end point. Thus, the crystal is in the pure paraelectric phase. At this moment, the quadratic EO effect is dominant. Thus, we can ignore the first term in Eq. (3.16), as given by

$$\theta_p = -n^3 g_{11} \rho L \varepsilon_0 \varepsilon_r \frac{V}{d},$$  \hspace{1cm} (3.17)

When the 1400 V half-wave voltage is applied, the magnitude of the electric field is $1400 \, V/7\, mm = 200 \, V/mm$, which increases the injected charge density to the level of approximately $50 \, C/m^3$. By substituting the experimentally measured half-wave voltage at 31 °C, $V_{\pi - \text{exp}} = 1400 \, V$, $n = 2.314$, $g_{11} - g_{12} = 0.16 \, m^4/C^2$, $t = 2 \, mm$, $\lambda = 532 \, nm$, $\varepsilon_0 = 8.85 \times 10^{-12} \, F/m$, and $d = 7 \, mm$ into Eq. (3.12), the relative permittivity of our KTN sample at 31 °C is calculated as $\varepsilon_r = 7800$. By substituting $n = 2.314$, $g_{11} = 0.136 \, m^4/C^2$, $\rho = 50 \, C/m^3$, $L = 2 \, mm$, $\varepsilon_0 = 8.85 \times 10^{-12} \, F/m$, $\varepsilon_r = 7800$, $V_{\pi} = 1400 \, V$, and $d = 7 \, mm$ into Eq. (3.17), we obtain $|\theta_p| = 2.32 \, mrad = 0.133^0$. The corresponding amount of transversal shift at the focal plane of the photodetector is $x_{1-31} = f \cdot \theta_p = 0.116 \, mm$, which is again smaller than the radius of the photodetector, $r_p = 0.4 \, mm$. Thus, if we focus the output light beam on the center of the photodetector when no voltage is applied, the deflected light beam induced by the half-wave voltage can still be detected by the photodetector. Therefore, the influence of beam deflection can be neglected in the EO modulation experiment.

However, to observe the beam deflection effect in the EO deflector, in addition to removing the analyzer, we need to make the following modifications even if the same KTN sample and geometry are used. At the beginning, a 2000 V voltage is applied at both 26 °C and 31 °C, which results in a larger beam deflection as well as injected charge density due to the increased bias field.
When a 2000 V voltage is applied, the magnitude of the electric field is $2000 V/7 \text{mm} = 286 V/\text{mm}$, which results in an even higher injected charge density, approximately $90 \, \text{C/m}^3$.

At 26 °C, the KTN crystal is in the field-induced ferroelectric phase with the 2000 V voltage. By substituting $L = 2 \, \text{mm}$, $r_{33-\text{eff}} = 163 \, \text{m/V}$, $n_e = 2.314$, $\rho = 90 \, \text{C/m}^3$, $\varepsilon_0 = 8.85 \times 10^{-12} \, \text{F/m}$, and $\varepsilon_r = 2000$ into Eq. (3.16), we obtain $\theta_1 = 10.5 \, \text{mrad} = 0.603^\circ$. Similarly, substituting $n = 2.314$, $g_{11} = 0.136 \, \text{m}^4/\text{C}^2$, $\rho = 90 \, \text{C/m}^3$, $L = 2 \, \text{mm}$, $\varepsilon_0 = 8.85 \times 10^{-12} \, \text{F/m}$, $\varepsilon_r = 2000$, $V = 2000 \, \text{V}$, and $d = 7 \, \text{mm}$ into Eq. (3.16), we obtained $|\theta_2| = 1.53 \, \text{mrad} = 0.088^\circ$, which is still much smaller than $\theta_1 = 0.603^\circ$. Thus, the contribution to beam deflection from the quadratic EO effect can again be neglected in the field-induced ferroelectric phase, even when 2000 V is applied. The corresponding transversal shift becomes $x_{1-26-2000} = f \cdot \theta_f \approx f \cdot \theta_1 = 50 \, \text{mm} \times 10.5 \, \text{mrad} = 0.526 \, \text{mm}$, which is larger than the radius of the photodetector, $r_p = 0.4 \, \text{mm}$. Thus, if we focus the light beam on the center of the photodetector when no voltage is applied, the light beam can be easily deflected away from the photodetector by applying a 2000 V voltage so that we can observe the beam deflection effect.

At 31 °C, the KTN crystal is in the paraelectric phase. Substituting $n = 2.314$, $g_{11} = 0.136 \, \text{m}^4/\text{C}^2$, $\rho = 90 \, \text{C/m}^3$, $L = 2 \, \text{mm}$, $\varepsilon_0 = 8.85 \times 10^{-12} \, \text{F/m}$, $\varepsilon_r = 7800$, $V = 2000 \, \text{V}$, and $d = 7 \, \text{mm}$ into Eq. (3.17), we obtain $|\theta_p| = 5.98 \, \text{mrad} = 0.343^\circ$. The corresponding transversal shift becomes $x_{1-31-2000} = f \cdot \theta_p = 0.299 \, \text{mm}$ at 31 °C. Although this value is significantly larger than the one obtained by applying 1400 V, which is 0.116 mm, it is still slightly smaller than the radius of the photodetector, which is 0.4 mm. To observe the beam deflection effect, we make another modification in this experiment. Instead of focusing the light beam on the center of the photodetector when no voltage is applied, we focus the light beam a little bit away from the center of the photodetector in the EO deflector experiment, which ensures that most of the light beam can be deflected away from the photodetector with the 2000 V voltage. Unfortunately, since the focused
light beam has a Gaussian profile, a small percent of the light beam (i.e., the tail portion of the light beam) is still not deflected away from the photodetector even with a 2000 V applied voltage in the paraelectric phase. This is the reason why the initial light intensity is higher (~0.2 a.u.) before the voltage is switched off for the KTN in the paraelectric phase. Moreover, although the initial light intensity is much lower at 26 °C than the one at 31 °C in the EO deflection experiment due to the larger deflection angle, it is still not zero. Similar to the case of Fig. 3-5, this non-zero initial light intensity at 26 °C is caused by the noticeable light scattering of the KTN crystal at 26 °C because it is near the phase transition temperature. Since scattered light propagates in all directions, a small portion of scattered light is detected by the photodetector.

In addition, we analyze the variations in the peak-to-peak output light intensity between the ON and OFF states for the cases of 26 °C and 31 °C, respectively, which are caused by different factors. In the case of Fig. 3-5, the variation in the peak-to-peak output light intensity is caused by the difference in light scattering at different temperatures. The closer the sample is to the Curie temperature, the larger the scattering will be because of the increased size of the polar nanoregions (PNR) at the temperature near the Curie temperature. In our experiment, we observe a larger scattering at 26 °C because it is closer to the Curie temperature. Due to the existence of scattering at 26 °C, the linearly polarized light is partially (a small percentage) depolarized after passing through the KTN crystal. Since the depolarized light cannot be totally blocked by the analyzer, a portion of depolarized light is detected by the photodetector even with half-wave voltage ON. On the other hand, the scattering is much smaller at 31 °C because it is farther away from the Curie temperature. In this case, although more light is transmitted after travelling through the KTN crystal due to the increased on-line transmittance of KTN crystal, the transmitted light still is a linearly polarized light and can be totally blocked by the analyzer before reaching the photodetector. Therefore, regarding the initial light intensity at 26 °C, the red curve of Fig. 3-5 is higher than the curve at 31 °C, the black curve of Fig. 3-5.
In the case of Fig. 3-7, the variation in the peak-to-peak output light intensity is caused by the difference in deflection angle at different temperatures. As described above, the beam deflection-induced transversal shift is 0.526 mm at 26 °C with a 2000 V voltage, which is larger than the radius of the photodetector, \( r_p = 0.4 \) mm. Thus, by focusing the light beam on the center of the photodetector when no voltage is applied, the light beam can be easily deflected away from the photodetector when a 2000 V voltage is applied. This results in a lower initial light intensity before 2000 V is switched off for KTN in the field-induced ferroelectric phase. However, the beam deflection-induced transversal shift is 0.299 mm at 31 °C with a 2000 V voltage, which is somewhat smaller than the radius of photodetector (0.4 mm). Although the beam deflection effect can be observed by focusing the light beam a little bit away from the center of the photodetector in the EO deflector experiment, a small percentage of the light beam is still not totally deflected away from the photodetector even with a 2000 V applied voltage in the paraelectric phase. This is the reason why the initial light intensity was higher (~0.2 a.u.) before 2000 V is switched off for KTN at the paraelectric phase.

In conclusion, the electric-field-induced phase transition plays a significant role in determining the scanning speed of a SCC KTN beam deflector. In the electric-field-induced ferroelectric phase, although there can be a high-speed field-induced refractive index modulation, the refractive index gradient remains the same as long as there is no change in the pre-injected charge density at nanosecond scale. In this case, the responding speed of a SCC KTN beam deflector is limited by the electron mobility in the KTN crystal even in the presence of the pre-injected and trapped electrons. Thus, for very high-speed nanosecond scale applications, the electric-field-induced ferroelectric phase must be avoided by operating the SCC KTN beam deflector at a temperature not only above the Curie point but also above the critical end point. This results in a three-order-of-magnitude increase in the scanning speed from the microsecond to the nanosecond regime. This represents a major technological advance in the field of high-speed beam
scanning devices. This improvement can be useful for many applications, such as high-speed optical coherence tomography, ultrafast reconfiguration free-space optical communications, and ultrafast laser display and printing.
Chapter 4

Composition Gradient Controlled KTN Deflector and 2-D Beam Deflection

With the rapid advances in three-dimensional (3D) printing and high-resolution in vivo imaging, there is increasing demand for a high-resolution high-speed multi-dimensional optical beam scanner. It is difficult for conventional mechanical deflectors[69–71] to meet the required sub-microsecond-scale deflection speed. To overcome the speed limitation of mechanical deflectors, there has been significant interest in developing high-speed, non-mechanical beam scanners[12–14]. Among the many different types of non-mechanical beam scanners, the KTN-crystal-based EO beam deflector has the highest deflection speed[37,72]. Although the conventional prism-shaped KTN beam deflector was reported more than half a century ago[16,17], recent efforts have been focused on developing KTN beam deflectors based on two types of unconventional physical deflection mechanisms. One type is based on pre-injected space-charge-controlled (SCC) KTN beam deflection[21,36,73], and the other type is based on composition-gradient-controlled (CGC) beam deflection[30,74–76]. Both SCC- and CGC-based deflectors have the advantages of simple configuration and large deflection angle. Extremely fast nanosecond deflection speed has also been achieved in SCC KTN beam deflectors[35,37]. However, only one-dimensional (1D) beam deflection has been achieved when a single piece of KTN crystal is used in either SCC or CGC beam deflectors, which severely limits the application of KTN deflectors. Furthermore, the internal electric field caused by the space charge will lead to a non-uniform refractive index distribution, which will cause a beam distortion[77] and reduce the resolution in many large-aperture applications.

To overcome the above fundamental deficiency, in this chapter we present a systematic study on the KTN beam deflector when both SCC and CGC deflection mechanisms exist. Although KTN deflectors based on the SCC or CGC mechanism have been reported individually, theoretical
and experimental investigations on the case that harnesses both SCC and CGC beam deflection mechanisms are lacking. We find that the coexistence of pre-injected space charge and composition gradient can enable new functionalities. When the direction of the composition gradient is parallel to the direction of external electric field, the zero-deflection position can be shifted, which can reduce the internal electric-field-induced beam distortion, and thus enhance the resolution. In contrast, when the direction of the composition gradient is perpendicular to the direction of external electric field, a two-dimensional (2D) beam deflection can be achieved by harnessing only one single piece of KTN crystal, which can result in a compact 2D beam scanner.
4.1 Composition gradient controlled KTN beam deflector

KTN is a solid solution of potassium tantalate (KT) and potassium niobate (KN). Its Curie temperature, at which KTN undergoes a phase transition from ferroelectric to paraelectric phase, is a function of its material composition[78,43]. Assuming that there is a composition gradient existing in the KTN crystal, as shown in Fig. 4-1, the Curie temperature of the crystal, $T_c$, will be a function of location, $x$.

When the temperature is above the Curie temperature, the permittivity of the KTN crystal, $\varepsilon$, follows the Curie-Weiss law[16]:

$$\varepsilon(x) \propto \frac{1}{T - T_c(x)} \quad (4.1)$$

where $T$ is the operating temperature. Based on Eq. (4.1), at a fixed operating temperature, the permittivity of the KTN crystal is also a function of location, $x$. 

Figure 4-1: Illumination of a composition gradient controlled KTN beam deflector.
When the electric field, $E$, is applied to the KTN crystal, as shown in Fig. 4-1, the refractive index modulation can be expressed as:

$$
\Delta n(x) = -\frac{1}{2} n^3 g_{11} \varepsilon(x)^2 E^2,
$$

where $\Delta n$ is the refractive index change in the KTN crystal, $n$ is the refractive index without the electric field, and $g_{11}$ is the quadratic EO coefficient in polar form. From the above analysis, it can be seen that if the material composition is not uniformly distributed, there will be a non-uniform permittivity distribution in the KTN crystal, and hence a non-uniform refractive index distribution under a fixed electric field. With the graded refractive index distribution, the KTN crystal can function as a beam deflector.

Furthermore, the deflection angle of such beam deflector can be obtained by the following equation:

$$
\theta(x) \approx \frac{\partial \Delta n(x)}{\partial x} \cdot L = -Ln^3 g_{11} \varepsilon(x) \frac{\partial \varepsilon(x)}{\partial x} E^2,
$$

where $L$ is the length of the crystal, as shown in Fig. 4-1. Based on Eq. (4.3), if there is a composition gradient in the KTN crystal, the permittivity, $\varepsilon$, is a function of location, $x$, and

$$
\frac{\partial \varepsilon(x)}{\partial x} \neq 0.
$$
Thus, the deflection angle, $\theta$, is a function of the electric field, and proportional to the square of the electric field.

To confirm the above analysis, the following experiments are conducted.

Figure 4-2(a) shows the experimental setup for measuring the deflection angle as a function of applied voltage at different temperatures. A piece of KTN crystal, whose Curie temperature is approximately 35°C, is cut into a $3\ cm \times 1\ cm \times 1\ cm$ piece, as shown in Fig. 4-2(b). All six surfaces are well polished. Metal electrodes are coated on two opposite $3\ cm \times 1\ cm$ surfaces. A temperature controlled is used to adjust the operating temperature, and a voltage source is used to control the driving voltage. As shown in Fig. 4-2, the direction of the composition gradient is along the $y$-axis, and the electric field is applied along the $x$-axis. The experimental system is shown in Fig. 4-2(c).
In the experiment, an x-polarized laser beam with a 633-nm wavelength propagates along z-axis and is deflected by the KTN beam deflector. The KTN crystal is placed 9.8 m away from the graphic screen, which is used to measure the beam shift along the y-axis. A set of voltages, 0 V, 1200 V, 1600 V, 2000 V, 2400 V, 2800 V, 3200 V, 3600 V, and 4000 V, is applied on the KTN deflector. For each applied voltage, the amount of transversal deflections is measured by reading out the location of the output beam on the graphic screen. Figure 4-3 depicts the beam deflections in the y direction as a function of the applied voltage at 36 °C, 37 °C, 38°C, 39 °C, and 40°C, respectively. The circular-shaped dots in Fig. 4-3 show the experimentally measured deflection
angle in the y direction, and the solid lines are the theoretical fitting based on Eq. (4.3). By comparing the experimental dots with the theoretical curves, one can clearly see that the experimental and simulation results are consistent.

Figure 4-3: At 36 °C, 37 °C, 38 °C, 39 °C, and 40 °C, the deflection angle in the y direction as a function of the external voltage.
4.2 KTN deflectors enabled by the coexistence of space charge and composition gradient

In 2011, Miyazu et al. proposed a pre-injected SCC KTN beam deflection model[21]. With this model, Miyazu et al. explained the high-speed potential of SCC KTN deflectors. However, this SCC beam deflection model is only suitable for the case of KTN crystal with a homogeneous composition. It cannot be applied to the situation enabled by the coexistence of pre-injected space charge and composition gradient. Thus, a new theoretical model must be developed.
4.2.1 Pre-injected space-charge-induced gradient electric field is parallel to the direction of the composition gradient

First, we investigate the case in which the direction of the external electric field is parallel to the direction of the composition gradient, as illustrated in Fig. 4-4. In Fig. 4-4, the direction of the electric field is in the y-direction, as marked by the yellow arrow in the figure that is in parallel with the direction of the composition gradient as marked by the pink arrow. The blue dots represent the pre-injected space charge. We can assume that a y-polarized incoming light beam propagates along the z-direction, as marked by the solid green line. For the purpose of simplicity, we further assume that the pre-injected space charge has a uniform distribution. The pre-injected space charge density is $\rho$. In this case, Maxwell’s equation can be written as
\[
\n\nabla \cdot (\varepsilon(y)\vec{E}) = \rho,
\]

(4.5)

where \(\vec{E} = (E_x, E_y, E_z)\) denotes the applied external electric field vector; and \(\varepsilon(y)\) is the permittivity of the KTN crystal that is a function of location, \(y\), due to the existence of composition gradient in the \(y\) direction. In the Cartesian coordinates, Eq. (4.5) can be expressed as

\[
\frac{\partial (\varepsilon(y)E_x)}{\partial x} + \frac{\partial (\varepsilon(y)E_y)}{\partial y} + \frac{\partial (\varepsilon(y)E_z)}{\partial z} = \rho.
\]

(4.6)

Since the permittivity is homogeneous in the \(x\) and \(z\) directions and the external electric field is only applied in the \(y\) direction, based on the symmetry, \(E_x\) and \(E_z\) must be zero. Thus, Eq. (4.6) can be simplified as

\[
\frac{\partial (\varepsilon(y)E_y)}{\partial y} = \rho.
\]

(4.7)

Equation (4.7) has an analytic solution:

\[
\varepsilon(y)E_y = \rho y + M,
\]

(4.8)

where \(M\) is a constant that can be determined by the following boundary condition
\[ \int_{0}^{H} E_y dy = V, \quad (4.9) \]

where \( H \) and \( V \) are the distance and voltage difference between two electrodes, respectively. From Eqs. (4.8) and (4.9), we can solve \( M \) as

\[
M = \frac{V - \rho \int_{0}^{H} \frac{y}{\varepsilon(y)} dy}{\int_{0}^{H} \frac{1}{\varepsilon(y)} dy}. \quad (4.10)
\]

Thus, the electric field distribution in the crystal can be expressed as

\[
E_y = \rho y + \frac{V - \rho \int_{0}^{H} \frac{y}{\varepsilon(y)} dy}{\int_{0}^{H} \frac{1}{\varepsilon(y)} dy} \frac{1}{\varepsilon(y)}. \quad (4.11)
\]

If we let

\[
J = \int_{0}^{H} \frac{y}{\varepsilon(y)} dy, \quad (4.12a)
\]

\[
K = \int_{0}^{H} \frac{1}{\varepsilon(y)} dy, \quad (4.12b)
\]
Eq. (4.11) can be simplified as

\[
E_y = \frac{\rho y + \frac{V - \rho I}{K}}{\varepsilon(y)} = \frac{\rho(y - \frac{I}{K}) + \frac{V}{K}}{\varepsilon(y)}. \tag{4.13}
\]

Thus, the refractive index change of the y-polarized light caused by the Kerr EO effect can be obtained as[22,24,26]

\[
\Delta n(y) \approx -\frac{1}{2} n^3 g_{11} (\varepsilon(y) E_y)^2 = -\frac{1}{2} n^3 g_{11} \left( \rho \left( y - \frac{I}{K} \right) + \frac{V}{K} \right)^2, \tag{4.14}
\]

where \( n \) is the refractive index of the KTN crystal without the electric field, and \( g_{ij} \) is the second-order EO coefficient in the polar form[17,79,80]. Under the approximations of paraxial case and small refractive index variation, the deflection angle \( \theta \) after an interaction length \( L \) can be further derived as[21]

\[
\theta \approx L \frac{d\Delta n(y)}{dy} = -n^3 g_{11} L \rho^2 \left( y - \frac{I}{K} + \frac{V}{\rho K} \right), \tag{4.15}
\]

If we compare the above result, Eq. (4.15), with the homogeneous KTN crystal case[21], Eq. (1.4), it is easy to see that the deflection angle, \( \theta \), is still linearly dependent on the voltage, \( V \). However, when there is no external electric field, the locations of zero-deflection, where \( \theta = 0 \), are different. In the previous homogeneous composition case, if we make \( \theta = 0 \) in Eq. (1.4) with \( V = 0 \), the
zero-deflection location is at the center, where \( y = H/2 \) in our case, as shown in Fig. 4-5(a). On the other hand, in the inhomogeneous composition gradient case, if we make \( \theta = 0 \) in Eq. (4.15) with \( V = 0 \), we can get \( y = J/K \), which means the zero-deflection location may not be at the center, as shown in Fig. 4-5(b). Thus, by controlling the composition distribution of the KTN crystal during the growth process, we can adjust the zero-deflection position and reduce the internal electric-field-induced beam distortion[77], which can be useful for many applications with large aperture beam deflection.

![Diagram](image)

Figure 4-5: Illustration of zero-deflection position for (a) the homogeneous case and (b) the inhomogeneous gradient composition case.
4.2.2 External electric field is perpendicular to the direction of the composition gradient

Figure 4-6 illustrates the configuration of the KTN deflector when the external electric field is perpendicular to the direction of the composition gradient. In this case, the external electric field is applied in the \( x \) direction, the composition gradient is along the \( y \) direction, and the \( x \)-polarized light beam propagates in the \( z \) direction. Similar to the case of Fig. 4-4, the blue dots represent the pre-injected space charges. Since \( E_z \) is zero based on the symmetry, Eq. (4.6) can be accordingly simplified as

\[
\varepsilon(y) \frac{\partial E_x}{\partial x} + E_y \frac{d\varepsilon(y)}{dy} + \varepsilon(y) \frac{\partial E_y}{\partial y} = \rho. \tag{4.16}
\]

Furthermore, under the steady state, there is no time-dependent magnetic field. The curl of the electric field in the Cartesian coordinates can then be expressed as
From Eq. (4.17), we can obtain the following relationship

$$\frac{\partial E_y}{\partial x} = \frac{\partial E_x}{\partial y}. \quad (4.18)$$

By taking $\partial/\partial x$ operation on both sides of Eq. (4.16) and substituting Eq. (4.18) into Eq. (4.16), one can obtain the following partial differential equation that contains only $E_x$,

$$\varepsilon(y) \left( \frac{\partial^2 E_x}{\partial x^2} + \frac{\partial^2 E_x}{\partial y^2} \right) + \frac{d\varepsilon(y)}{dy} \frac{\partial E_x}{\partial y} = 0. \quad (4.19a)$$

Similarly, by taking $\partial/\partial y$ operation on both sides of Eq. (4.16) and substituting Eq. (4.18) into Eq. (4.16), one can obtain the following partial differential equation that contains only $E_y$,

$$\varepsilon(y) \left( \frac{\partial^2 E_y}{\partial x^2} + \frac{\partial^2 E_y}{\partial y^2} \right) + \frac{d\varepsilon(y)}{dy} \frac{\partial E_y}{\partial y} + \left( \frac{d^2 \varepsilon(y)}{dy^2} - \frac{1}{\varepsilon(y)} \left( \frac{d\varepsilon(y)}{dy} \right)^2 \right) E_y + \frac{\rho}{\varepsilon(y)} \frac{d\varepsilon(y)}{dy} = 0. \quad (4.19b)$$

Moreover, we assume the following boundary conditions:
\[ \int_{0}^{W} E_x dx = V, \quad (4.20a) \]
\[ E_y(0, y) = 0, \quad (4.20b) \]
\[ E_y(W, y) = 0, \quad (4.20c) \]

where \( W \) and \( V \) are the distance and the voltage difference between two electrodes, respectively. Theoretically speaking, by solving Eqs. (4.19) and (4.20) simultaneously, one can obtain \( E_x \) and \( E_y \). In this case, the refractive index modulation of the x-polarized light beam due to the quadratic EO effect can be expressed as[16]

\[ \Delta n(x, y) \approx -\frac{1}{2} n^3 g_{11} (\varepsilon(y) E_x)^2 - \frac{1}{2} n^3 g_{12} (\varepsilon(y) E_y)^2. \quad (4.21) \]

Then, the deflection angles in the x direction, \( \theta_x \), and y direction, \( \theta_y \), can be derived as,

\[ \theta_x = L \frac{\partial \Delta n(x, y)}{\partial x} = -Ln^3 g_{11} \varepsilon(y)^2 E_x \frac{\partial E_x}{\partial x} - Ln^3 g_{12} \varepsilon(y) E_y \frac{\partial E_y}{\partial x}, \quad (4.22a) \]
\[ \theta_y = L \frac{\partial \Delta n(x, y)}{\partial y} \]

\[ = -Ln^3 g_{11} \varepsilon(y) \frac{d\varepsilon(y)}{dy} E_x^2 - Ln^3 g_{11} \varepsilon(y)^2 E_x \frac{\partial E_x}{\partial y} - Ln^3 g_{12} \varepsilon(y) \frac{d\varepsilon(y)}{dy} E_y^2 \]

\[ - Ln^3 g_{12} \varepsilon(y)^2 E_y \frac{\partial E_y}{\partial y} \quad (4.22b) \]

Unfortunately, no obvious closed-form analytic solutions for Eqs. (4.19) and (4.20) can be obtained when \( \varepsilon(y) \) is not a constant and \( \rho \neq 0 \). Instead of finding the analytic solutions of Eqs. (4.19) and (4.20), we conduct numerical simulations to validate the proposed model. To ensure that the simulation result can reflect the real situation, realistic parameters are determined and used in the simulation.

Figure 4-7: The EDS measured variation of Nb atomic ratio as a function of location.
First, we investigate $\varepsilon(y)$ by looking at a real KTN crystal with a size of $2.5\ mm \times 3.5\ mm \times 4.5\ mm$. All six surfaces of the sample are well polished. Since the permittivity is a function of the atomic ratio between niobium and tantalum atoms at a given temperature of a KTN crystal[78,43], the permittivity distribution is determined by measuring this atomic ratio via Energy Dispersive Spectroscopy (EDS). Figure 4-7 shows the experimentally measured variation of atomic ratio as a function of location, in which the triangle-shape dots denotes the measuring points and the dotted line is the curve fitting result. From Fig. 4-7, one can see that there is a near linear variation in the atomic ratio, which can result in a near linear change in the Curie temperature[78,43], as given by

$$T_c(y) = Ay + B, \tag{4.23}$$

where $y$ is the distance from the top surface, as illustrated in Figs. 4-4 and 4-6, and $A$ and $B$ are two constants.

Based on the Curie-Weiss law[16], the relative permittivity is further obtained as

$$\varepsilon_r(y) = \frac{\varepsilon(y)}{\varepsilon_0} = \frac{C}{T - T_c(y)} = \frac{C}{T - Ay - B}, \tag{4.24}$$

where $T$ is the operating temperature, $\varepsilon_0$ is the vacuum permittivity, and $C$ is a constant. From Eq. (4.24), it can be seen that the permittivity is a function of $y$ at a given temperature. In the simulation, we assume that $T = 26\ ^\circ C$, $A = 0.075^\circ C/mm$, $B = 23.5^\circ C$, and $C = 100,000^\circ C$. Figure 4-8 depicts the calculated relative permittivity, $\varepsilon_r(y)$, as a function of location $y$. It can be seen that the
relative permittivity is within the range of 40,000 to 43,250, which is on the same order as the previously reported results for the KTN crystal with the similar composition[36,65]. To compute the electric field and beam deflection, we further assume that a 1250 V external applied voltage is applied in the x direction, the composition gradient is in the y direction, and the uniformly distributed pre-injected charge density is \( \rho = -13 \text{ C/m}^3 \), which is again on the same order as the previous reported experimental results[36,65]. The negative value represents the major pre-injected space charge is electrons. For the purpose of comparison, first, we compute the electric field without composition gradient, in which case \( \varepsilon_r (y) = 40,000 \) is a constant. Figure 4-9(a) shows the simulation result in the homogenous case. One can see that the overall electric field is still along the x direction, which is in the same direction as the external electric field. Then, we computed the electric field with the permittivity gradient, as depicted in Fig. 4-8. Figure 4-9(b) shows the simulation result in the inhomogeneous gradient composition case. It can be seen that the direction of the total electric field is no longer entirely along the direction of the external field. There is a small component in the y direction. Note that, to visualize this component in the y direction, we enlarge \( E_y \) by 100 times when producing Figure 4-9(b).
Figure 4-8: The calculated relative permittivity $\varepsilon_r(y)$ as a function of location, $y$. 
Figure 4-9: The calculated electric field within (a) a homogeneous KTN crystal and (b) an inhomogeneous gradient composition KTN crystal, in which the direction of the external electric field is perpendicular to the direction of the composition gradient.
Furthermore, we can obtain the refractive index modulation inside the KTN crystal by inserting the above calculated electric field into Eq. (4.21). To illustrate the change in refractive index modulation induced by the external electric field, we first compute the refractive index modulation of an inhomogeneous KTN crystal with a gradient relative permittivity (from 40,000 to 43,250) and a pre-injected space charge density $\rho = -13 \, C/m^3$ without an external electric field. Figure 4-10(a) depicts the calculated result. It can be seen that the refractive index modulation is almost uniform, although the sample has a gradient permittivity and pre-injected space charges. The slight variation in refractive index is caused by the pre-injected charge-induced internal electric field, which has a negligible effect on the beam transmission. Next, we compute the refractive index modulation in a homogeneous KTN crystal with a relative permittivity $\varepsilon_r = 40,000$, a pre-injected space charge density $\rho = -13 \, C/m^3$, and under an external voltage $V = 1,250 \, V$ applied in the $x$ direction. The distance between two electrodes is 4.5 mm. Figure 4-10(b) depicts the calculated result. In Fig. 4-10(b), a refractive index gradient can be clearly seen, but it is only along the $x$ direction. Last, we compute the refractive index modulation in an inhomogeneous KTN crystal with a gradient relative permittivity distribution (from 40,000 to 43,250) in the $y$ direction, a pre-injected space charge density $\rho = -13 \, C/m^3$, and under an external voltage $V = 1250 \, V$ applied in the $x$ direction. Figure 4-10(c) depicts the calculated result. A refractive index gradient, can be seen in both $x$ and $y$ directions, which enables a 2D beam deflection.
Figure 4-10: (a) The computed refractive index modulation of an inhomogeneous KTN crystal with a gradient relative permittivity (from 40,000 to 43,250) and a pre-injected space charge density $\rho = -13 \, \text{C/m}^3$, but without an external electric field. (b) The computed refractive index modulation of a homogeneous KTN crystal with a relative permittivity $\varepsilon_r = 40,000$, a pre-injected space charge density $\rho = -13 \, \text{C/m}^3$, and an external voltage $V = 1250 \, \text{V}$ applied in the x direction. The distance between two electrodes was 4.5 mm. (c) The computed refractive index modulation of an inhomogeneous KTN crystal with a gradient relative permittivity (from 40,000 to 43,250), a pre-injected space charge density $\rho = -13 \, \text{C/m}^3$, and an external voltage $V = 1250 \, \text{V}$ applied in the x direction. The distance between two electrodes was 4.5 mm.
Finally, we compute the beam deflection angle as a function of the external applied voltage by substituting the calculated electric fields into Eqs. 4.22(a) and 4.22(b). In the computation, similar to the case of Fig. 4-10(c), we assume that the composition gradient is along the y direction with a length of $H = 2.5 \, \text{mm}$, the external voltage is applied in the x direction with a length of $W = 4.5 \, \text{mm}$ (perpendicular to the direction of the composition gradient), and the x-polarized incoming light beam propagates a length of $L = 3.5 \, \text{mm}$ in the crystal in the z direction. The relative permittivity varies from 40,000 to 43,250 in the y direction according to Fig. 4-8, and the pre-injected space charge density is $\rho = -13 \, \text{C/m}^3$. First, we compute $\theta_x$ as a function of the external voltage by substituting the calculated electric field into Eq. 4.22(a). The solid line in Fig. 4-11(a) depicts the computed $\theta_x$ as a function of the external voltage. In Fig. 4-11(a), the deflection angle in the x direction, $\theta_x$, increases nearly linearly as the voltage increases. This is consistent with the result predicted by Eq. 4.22(a), in which $\theta_x \propto E_x$ and $E_y$. Then, we compute $\theta_y$ as a function of the external voltage by substituting the calculated electric field into Eq. 4.22(b). The solid line in Fig. 4-11(b) depicts the computed $\theta_y$ as a function of the external voltage. In Fig. 4-11(b), the deflection angle in the y direction, $\theta_y$, increases nearly parabolically as the voltage increases. This is again consistent with the result predicted by Eq. 4.22(b), which contains the quadratic $E_x^2$ and $E_y^2$ terms in the expression of $\theta_y$. In Fig. 4-11, compared with the x direction, the deflection angle in the y direction is smaller, which is caused by the small composition gradient in the y direction within our sample. This smaller y deflection can be increased by harnessing a KTN crystal with a larger composition gradient, which will be investigated in the future follow-on works.
Figure 4-11: The computed deflection angle (a) in the x direction, $\theta_x$, and (b) in the y direction, $\theta_y$, as a function of the external voltage, in which the pre-injected space charges and composition gradient co-exist and the direction of external voltage is perpendicular to the direction of the composition gradient.
4.3 Experimental results and discussions

To validate the proposed theory described in the above section, we conduct the following experiments. First, we prepare a KTN crystal with a composition gradient and dice it into the dimensions used in the previous analysis. The corresponding dimensions in the x, y, and z directions are $W = 4.5\ mm$, $H = 2.5\ mm$, and $L = 3.5\ mm$, respectively. The composition gradient is along the y direction. All six surfaces are well polished. To validate Eq. (4.15) when the electric field is parallel to the direction of the composition gradient, we coat the Au/Ti electrodes on the $4.5\ mm \times 3.5\ mm$ surfaces. The Au/Ti electrode is selected because space charge can be pre-injected.

Then, we build an system with the KTN beam deflector, which is as illustrated in Fig. 4-12, to measure the amount of beam deflection. The system is composed of a vertically polarized diode-pumped solid-state laser with an output wavelength of 532 nm, a KTN crystal mounted on the top of a Peltier thermo-electric module that is connected to a temperature controller, a tunable voltage source, and a graphic screen to measure the amount of deflection in the x and/or y directions. The distance between the KTN deflection and graphic screen is set at 3.8 $m$, which allows measurement of deflections as small as 0.01 $mrad$. 
Next, we measure the laser beam deflection as a function of applied voltage. In the experiment, the operating temperature is set at 25°C. The y-polarized laser beam is aligned along the z direction and hits on the central area of the 2.5 mm x 4.5 mm surface of the KTN crystal. A set of different voltages 0 V, 75 V, 100 V, 125 V, 150 V, 175 V, 200 V, 225 V, and 250 V, is applied on the electrodes. For each applied voltage, the amount of transversal deflections is measured by reading out the location of the output beam on the graphic screen. Then, we can obtain the deflection angles from the ratio between the transversal deflection and the propagation distance, which is the distance between the KTN deflector and the graphic screen. In Fig. 4-13, the blue circular dots show the experimentally measured deflection angles in the y direction as a function of applied voltage. The solid line is the theoretical fit of the proposed model. From the Fig. 4-13, it is clear that they agree well, which confirms the correctness of our proposed theory. To compare our deflection model with the original SCC model without composition gradient[21], we produce the
red dotted line in Fig. 4-13 with a fixed relative permittivity $\varepsilon_r = 65,000$ and a charge density $\rho = -13 \, C/m^3$. The dotted line passes the origin of the coordinate system; however, the solid line does not pass, which also agrees with our analysis: the zero-deflection position may be shifted due to the inhomogeneity of the crystal.

To validate the model with the electric field perpendicular to the direction of the composition gradient, we remove electrodes on the KTN crystal and conduct the following experiments. The Ti/Au electrodes were coated on the 2.5 mm x 3.5 mm surfaces. Similar to Fig.
4-12, we build the system shown in Fig. 4-14 to measure the amount of deflection in both $x$ and $y$ directions.

Figure 4-14: The experimental system used to measure the deflection angle as a function of applied voltage. The electric field is perpendicular to the direction of the composition gradient.

The laser in Fig. 4-14 is a horizontally polarized diode-pumped solid-state laser with an output wavelength of 532 nm. The electric field is applied along the $x$ direction, which is perpendicular to the direction of the composition gradient. The $x$-polarized laser beam is aligned along the $z$ direction and hits on the central area of the 2.5 mm x 4.5 mm surface of the KTN crystal. A set of different voltages 0 V, 200 V, 400 V, 600 V, 800 V, 1,000 V, and 1,250 V, is applied on the KTN crystal. For each applied voltage, the amount of transversal deflection is measured in both $x$ and $y$ directions by reading out the location of the output beam on the graphic screen. Then, the deflection angles are obtained from the ratio between the transversal deflection and the propagation distance, which is the distance between the KTN deflector and the graphic screen. The triangular-shaped dots in Fig. 4-15(a) show the experimentally measured deflection
angles in the \( x \) direction as a function of applied voltage and the circular-shaped dots in Fig. 4-15(b) show the experimentally measured deflection angle in the \( y \) direction as a function of applied voltage. The solid lines are the simulated results, and match those shown in Fig. 4-11. By comparing the experimental dots with the theoretical curves, it is clearly to see that the experimental and simulation results are consistent. Note that there are small deviations between the simulation results, marked by the solid line, and experimental results, marked by the triangular and circular dots, as depicted in Figs. 4-15(a) and 4-15(b), respectively. We believe that these differences are mainly caused by our simplified theoretical model: in the simulation, we assume that the injected charge is uniformly distributed\[21\]; however, in reality, the charge distribution may not be uniform\[36\]. In the future follow-on works, we may study the case with a nonuniform space charge distribution in the KTN beam deflector.
To achieve a two-dimensional beam deflection, we need to adjust the applied voltage and the composition gradient, which is also the permittivity gradient, to control the deflection in both x and y directions. Because the relative permittivity of KTN crystals, $\varepsilon_r(y)$, is a function of operating temperature, as given by Eq. (4.24), the effort on changing the permittivity gradient can be realized by adjusting the operating temperature. In other words, although we cannot change the composition

![Figure 4-15](image)

Figure 4-15: (a) The measured deflection angle and the computed deflection angle in the x direction. (b) The measured deflection angle and the computed deflection angle in the y direction.
gradient after the crystal is grown, we can change the permittivity gradient by adjusting the operating temperature.

To further illustrate the 2D deflection capability, Figures 4-16(a) and 4-16(b) depicts the beam deflections in both x and y directions as a function of the applied voltage at 25°C, 26°C, 27°C, and 28°C, respectively. From Figs. 4-16(a) and 4-16(b), one can see that under a fixed applied voltage, different temperatures can result in different deflection angles in both x and y directions. Figure 4-16(c) shows the deflection angle in both x and y directions under different temperatures. At a selected operating temperature, we can achieve a 2D beam deflection trace by controlling the applied voltage. Thus, by adjusting the applied voltage and operating temperature, we can achieve a 2D beam scanning with only one piece of KTN crystal. Notice that, in the proposed 2D beam scanning, for each trace, the beam scanning speed could be very fast. However, to change to different traces in 2D beam scanning, we have to change the temperature, which limits overall 2D beam scanning speed. Thus, the presented 2D beam scanning is particularly suitable for the application, which only needs high-speed scanning in each trace: for example, an adjustable-orientation laser line/curve scanner. We further note that, in the conventional 2D scanning, one variable related to x-deflection and another variable related to y-deflection are usually independently controlled. However, in the presented 2D scanning of this paper, electric field and operating temperature are independently controlled. Although the change of electric field or operating temperature may affect both x- and y-deflection, the electric field and operating temperature are indeed two independent variables. By changing the electric field and operating temperature, we can realize 2D scanning. This is like the case, instead of scanning in the rectangular coordinates, we perform the scanning in the polar coordinates.
Figure 4-16: (a) At 25°C, 26°C, 27°C, and 28°C, the deflection angle in the x direction as a function of the external voltage, in which the pre-injected space charges and composition gradient co-exist and the direction of external voltage is perpendicular to the direction of the composition gradient. (b) At 25°C, 26°C, 27°C, and 28°C, the deflection angle in the y direction as a function of the external voltage, in which the pre-injected space charges and composition gradient co-exist and the direction of external voltage is perpendicular to the direction of the composition gradient. (c) The deflection angle in both x and y directions at 25°C, 26°C, 27°C, and 28°C.
4.4 Conclusions

In conclusion, we conduct theoretical and experimental investigations on KTN beam deflectors that contain both pre-injected space charges and composition gradient. We find that new functionalities can be enabled by the co-existence of pre-injected space charges and composition gradient. In particular, when the direction of the external applied voltage is perpendicular to the direction of the composition gradient, a 2D beam deflection can be realized with only one piece of KTN crystal, which could substantially reduce the cost and footprint of the 2D beam deflector. This kind of compact and cost-effective 2D deflector can be useful for a variety of applications, such as compact 2D/3D laser printing systems, broadband free-space optical communications, and high-resolution optical imaging and display.
Chapter 5

Photon Excitation Enabled Space-Charge-Controlled KTN Beam Deflector

High-speed high-resolution beam deflectors are needed for many applications, including high-speed printing, imaging, and displays. Among different types of optical deflectors, the SCC KTN beam deflectors have the advantages of high responding speed, all solid-state operation, large deflection angle, and simple architecture[21]. By operating the deflector above the critical end point, a nanosecond deflection speed can be achieved[37]; this is the fastest deflector among different types of deflectors. Such nanosecond deflection speed can enable new applications, such as next-generation ultrafast 3D printing and broadband reconfigurable free-space optical communications. However, the aperture of an SCC KTN deflector is limited by the depth of charge injection, which is typically on the order of a millimeter[36,81]. Such a limited aperture also affects the scanning resolution (also known as “the number of distinguishable scanning spots”, $N_r$), as given by[16]

$$N_r \propto \frac{\theta_d}{\lambda} D, \quad (5.1)$$

where $\theta_d$ is the range of angle deflection, $\lambda$ is the operational wavelength, and $D$ is the aperture. Thus, to achieve high-resolution high-speed scanning, it is significant to increase the deflection aperture. Since the deflection aperture is limited by the depth of charge injection, to increase the aperture, one has to increase the depth of charge injection. Furthermore, since the depth of charge injection is determined by the strength of the trapping effect, to increase the depth of charge injection, one must reduce the trapping effect. In this chapter, to enable a large-aperture wide-angle deflection, we harness the physical mechanism of blue light photon excitation to alleviate the trapping effect, which in turn increases the depth of charge injection as well as the deflection.
aperture and scanning resolution. A step-by-step description approach is adopted in this chapter, as described in detail below.
5.1 Non-uniform charge distribution in KTN and photon excitation enabled beam deflector

We start with the simple case without the trapping effect. In this case, we can assume that the charge is uniformly injected into a KTN crystal. We further assume that the incoming light beam propagates along the z direction and the external voltage is applied along the x direction, as depicted in Fig. 1-2. Based on the pre-injected space charge model, the deflection angle can be expressed as Eq. (1.4).

However, since there is a trapping effect in a real charge injection process, the injected charge will no longer have a uniform distribution with a finite charge time. It may take a number of hours to several days to realize a uniform charge distribution; but the typical charging time is only on the order of minutes. In this case, there are more injected charges at the area near the cathode. The charge density decreases as the position x increases[36]. To quantitatively analyze the relationship between the distribution of charge injection and the deflection angle, we assume that the charge has a uniform distribution near the cathode and then the charge density exponentially decays after a certain point. We notice that such an assumption closely corresponds to the experimentally measured charge distribution reported in Ref. [36] and is consistent with the theoretical model described in Ref. [82]. Mathematically, the charge distribution is given by

$$\rho(x) = \begin{cases} \rho_0, & 0 \leq x \leq d_1 \\ \rho_0 e^{-\alpha(x-d_1)}, & d_1 < x \leq d \end{cases}$$

(5.2)

where \(\rho_0\) is a constant, \(\alpha\) is a constant, and \(d_1\) is the distance of the initial uniform distribution region. From this charge distribution, the electric field inside the KTN crystal can be obtained by solving the following Maxwell equation:
\[ \nabla \cdot E(x) = \frac{\rho(x)}{\varepsilon}. \] (5.3)

The solution of Eq. (5.3) is

\[ E(x) = \int \frac{\rho(x)}{\varepsilon} \, dx + C_1 = \frac{Q(x)}{\varepsilon} + C_1, \] (5.4)

where \( Q(x) = \int \rho(x) \, dx \), and \( C_1 \) is a constant that can be determined from the following equation

\[ \int_0^d E(x) \, dx = V_0, \] (5.5)

where \( V_0 \) is the external applied voltage.

By solving Eqs. (5.4) and (5.5) simultaneously, we obtain

\[ E(x) = \frac{Q(x)}{\varepsilon} - \frac{1}{\varepsilon d} \int_0^d Q(x) \, dx + \frac{V_0}{d}. \] (5.6)

Then, the corresponding refractive index modulation, \( \Delta n(x) \), and the deflection angle, \( \theta(x) \), can be derived as
\[ \Delta n(x) = -\frac{1}{2} n^3 g_{11} e^2 E(x)^2 = -\frac{1}{2} n^3 g_{11} e^2 \left[ \frac{Q(x)}{\varepsilon} - \frac{1}{\varepsilon d} \int_0^d Q(x) dx + \frac{V_0}{d} \right]^2, \quad (5.7) \]

\[ \theta(x) \approx L \frac{\partial \Delta n(x)}{\partial x} = -Ln^3 g_{11} \rho(x) \left[ Q(x) - \frac{1}{d} \int_0^d Q(x) dx + \frac{V_0 \varepsilon}{d} \right]. \quad (5.8) \]

From Eq. (5.8), it is clearly to see that the deflection angle is proportional to the injected charge distribution, \( \rho(x) \), even in the case of non-uniform charge distribution. Thus, to increase the deflection angle at the location of large \( x \), we must increase the injected space charge density at the location of large \( x \).

To effectively increase the injected charge density, first, we need to study the physical mechanism that limits the maximum injected charge density. Due to the existence of the screening effect[36,81], the electrons injected from the cathode can be trapped by the localized states near the cathode. This can lead to electron accumulation at the area near the cathode, which in turn can reduce the driving force of the electron drift. In other words, electrons are confined or called “frozen” in a limited region near the cathode and can hardly reach the anode. Thus, we have difficulties realizing a uniform charge distribution. Furthermore, this “frozen” state is a slowly varying state and it takes an extremely long time (many days) to reach the final steady state[36]. Thus, with a finite pre-charging time (e.g., on the order of minutes), the depth of charge injection is only on the order of a millimeter.

To increase the depth of charge injection, we employ blue light photon excitation to reduce the screening, or “trapping”, effect. We irradiate the 405-nm light on the KTN crystal while applying the pre-injection voltage until the injection current reaches the stable state. Once the current is stable, the 405-nm light is removed while the pre-charging voltage is still applied on the
KTN crystal. When the trapped electrons absorb 405-nm wavelength blue photons, the kinetic energy of electrons is significantly increased. This in turn substantially increases the electrons escaping rate from the trapping quantum well. The reduced trapping effect makes electrons become more mobile, which results in an increased depth of charge injection.
5.2 Experimental results

To quantitatively analyze the injected charge density affected by the blue light irradiation, we consider the following equation[83]:

\[ J_c = e\mu N_f E - eD_d \frac{\partial N_f}{\partial x}, \]  \hspace{1cm} (5.9)

where \( J_c \) is the injected current density, \( e \) is the elementary charge, \( \mu \) is the carrier charge mobility, \( N_f \) is the free charge density, \( D_d \) is the diffusion constant, and \( x \) is the distance from the cathode. Because the diffusion term has little effect on the process[83], from Eq. (5.9), it can be seen that the free charge density is proportional to the injected current density. Thus, we must determine if the blue photon excitation can enhance the charge injection process to obtain an increased current density. To verify this analysis, we conduct the following experiments.

In the experiment, a KTN crystal with a Curie temperature of approximately 25 °C is cut into a 10 mm x 10 mm x 2.5 mm cube. All six surfaces are well polished. Next, we coat titanium electrodes on two opposing 10 mm x 2.5 mm surfaces to facilitate charge injection. Then, the KTN crystal is mounted on the top of a Peltier thermo-electric module that is connected to a temperature controller to maintain the operating temperature at 27 °C. A high-voltage source is connected to the titanium electrodes for applying the external voltage and a low-noise current amplifier and an oscilloscope is used to measure the injected current.

We start from the measurement of the injected current without the blue photon excitation and with the external applied voltage up to 2000 V. The measured current is near zero. In other words, the free charge density also closes to zero. This experimental result indicates that most
injected electrons are trapped by the localized states near the cathode and can hardly reach the anode. Thus, there is almost zero free charge density in the KTN crystal, which results in a near zero injection current.

After testing the traditional charging process, we measure the injected current with the blue photon excitation while applying an external voltage up to 2000 $V$. A blue light LED with an output wavelength of 405 $nm$ and an output power of 1 $W$ is placed 2 $cm$ away from the KTN crystal. The KTN crystal is also mounted on the top of a Peltier thermo-electric module that is connected to a temperature controller to maintain the operating temperature at 27 $^\circ C$. Figure 5-1 shows the experimentally measured injection current as a function of applied voltage with the blue photon excitation. We can observe a noticeable injected current, and the injected current is proportional to the applied voltage, which is consistent with Eq. (5.9). This experimental result confirms that the injected current can reach the anode via the blue photon excitation. In other words, a deeper injection depth could be achieved by the blue photon excitation.
To ensure that the blue photon excitation can indeed enable a large-aperture beam deflection, we also conduct the following theoretical analyses and experiments. First, we calculate the deflection angle as a function of location $x$ for the non-uniform charge injection cases with and without the blue photon excitation. We assume that $\rho_0 = -5.62 \, \text{C/m}^3$, $\alpha = 0.09$ in Eq. (5.2) for the case with the blue photon excitation and $\rho_0 = -4.87 \, \text{C/m}^3$, $\alpha = 0.12$ for the case without the blue photon excitation, which are within the same order of magnitude as the previously reported results[21,36,84]. Based on Eq. (5.2), the solid and dashed curves in Fig. 5-2 represent the non-uniform charge injection distributions for the cases with and without the blue photon excitation, respectively. In the calculation, we assume that a 2000 V voltage is applied on the KTN crystal. By

Figure 5-1: The measured injection current as a function of applied voltage at 27 °C with the blue photon excitation.
substituting the charge injection data obtained in Fig. 5-2 and $V_0 = 2000V$ into Eq. (5.8), we can get the solid and dashed curves in Fig. 5-3, which depict the computed deflection angles as a function of location $x$ for the cases with and without the blue photon excitation, respectively. To verify the above theoretical analyses, we experimentally measure the deflection angles as a function of location $x$ for the cases with and without the blue photon excitation by applying a 2000 V external voltage. The wavelength of the laser is 532 nm. The circular dots and square dots in Fig. 5-3 show the experimental measured deflection angles for the cases with and without the blue photon excitation. By comparing the experimental results with the calculation results, it is evident that they agree well, which confirms the correctness of our theoretical analyses.

Figure 5-2: The non-uniform charge injection distributions used to calculate the deflection angle as a function of location $x$. The solid line, with the blue photon excitation; and the dashed line, without the blue photon excitation.
Figure 5-3: The deflection angles as a function of location $x$ with a 2000 $V$ applied voltage. Solid line – the calculated deflection angles with the blue photon excitation, dashed line – the calculated deflection angles without the blue photon excitation, circular dots – the experimentally measured deflection angles with the blue photon excitation, and square dots – the experimentally measured deflection angles without the blue photon excitation.
5.3 Conclusions

In conclusion, we report a method to increase the aperture and scanning spatial resolution of an SCC KTN beam deflector by harnessing the physical mechanism of blue photon excitation. We call this mechanism as photon-excitation-enabled beam deflection. The kinetic energy of trapped electrons can be significantly increased by the blue photon excitation, which, in turn, can significantly increase the electrons escaping rate from the trapping quantum well. Thus, electrons can penetrate a longer distance from the cathode. A larger aperture and higher scanning spatial resolution can be achieved by the enhanced penetration depth. The enhanced electron penetration is experimentally verified by the increased injection current and the increased deflection angle. The increased deflection angle at the deeper penetration depth by the blue photon excitation is also experimentally confirmed by measuring the deflection angles as a function of location $x$ with and without blue photon excitation. The increased aperture and scanning resolution can be helpful for expediting the deployment of SCC KTN in demanding applications, such as ultrafast 3D printing and next-generation, broadband, reconfigurable free-space optics communications.
Chapter 6

Conclusions and Future Directions

This research is driven by the demands on the high-speed, high-resolution, multi-dimensional beam scanners in the commercial markets. In this dissertation, we systematically study the KTN crystal based optical beam deflectors. According to the requirements of high-speed operation, we study the field-induced phase transition in the KTN crystal. We find that the KTN crystal appears as if it is in the ferroelectric phase if the temperature is above but close to the Curie temperature. In such a pseudo-ferroelectric phase, a number of polar micro-domains with the same polarization direction will appear and severely delay the responding time of most KTN based EO devices. This is the reason why most commercial KTN based EO devices can only reach a kHz-range responding frequency. To solve this problem, we proposed to operate the KTN based EO devices at the temperature above the critical end point. When the temperature is above the critical end point, the field-induced phase transition will disappear, and hence the KTN based EO devices can achieve a fast responding speed. We demonstrated such enhancement of responding speed in a KTN based optical beam deflector. When the temperature is close to its Curie temperature, the responding speed of the beam deflector is approximately 1500 ns. However, with the temperature increasing further from the Curie temperature, we can achieve a responding speed as fast as 10 ns, which is three times faster than that of commercial KTN beam deflectors. By avoiding the field-induced phase transition in KTN crystals, we can operate the KTN based EO devices with a nanosecond-range responding time.

Due to the commercial demands on the compact multi-dimensional beam steering system, we proposed a 2-D beam deflection model in only one piece of KTN crystal. First, we present a comprehensive study on the composition-gradient-controlled KTN beam deflection. With a nonuniform KTaO$_3$-KNbO$_3$ ratio, we can achieve a graded refractive index distribution in the KTN
crystal when applying the driving voltage. Thus, the KTN crystal can function as a beam scanner with a periodic driving voltage. The deflection angle of the CGC beam deflector is proportional to the square of the driving electric field. By combining the CGC beam deflection with the space-charge-controlled beam deflection, we can realize a two-dimensional beam deflector within only one piece of KTN crystal. Theoretical analysis and experimental results confirms that we can adjust the deflection angle in two dimensions by adjusting the applied voltage and operation temperature.

Finally, we propose a new method to enhance the charge injection depth in the SCC beam deflector to increase the aperture of the KTN beam deflector, and further increase the scanning resolution. This new beam deflection model is called photon excitation enabled KTN beam deflection. During the pre-charging process, the electrons migrate into the KTN crystal from the cathode. Due to the trapping effect of the localized states, most electrons are accumulated at the region near the cathode, which prevents more electrons from injecting into the crystal. This causes the effective deflection aperture to be only the area near the cathode. To avoiding such a screening effect, we use a blue LED light with a 405-nm wavelength to illuminate the KTN crystal during the pre-charging process. With the help of the blue light photon excitation, the trapped electrons become mobile and more electrons migrates into the KTN crystal. Such a photon excitation pre-charging process largely increase the charge injection depth and charge density in the KTN crystal, which can enlarge the effective beam deflection aperture and enhance the beam deflection angle.

In this dissertation, we increase the responding speed of the KTN beam deflector by three orders, realize a 2D beam deflection with one piece of KTN crystal, and increase the aperture and resolution of the KTN deflection by the photon excitation pre-charging process. These achievements provide the possibility to realize a high-speed, high-resolution, multi-dimensional beam scanner in the commercial markets.
Although we have made steady progress studying the features of KTN-based optical beam deflectors, there remain many unanswered questions, as well as exciting avenues of research to explore applications of KTN beam deflectors.

To drive a KTN-based beam deflector, a periodic voltage source of greater than 1000 V is necessary based on the KTN dimension in previous chapters. However, a high-voltage, high-repetition-rate power supply is not commonly available in the commercial market. To make the KTN based beam deflector widely accepted in the potential application areas, we need to develop a low-voltage, high-speed KTN beam deflector. One possible way is to reduce the thickness of the CGC KTN beam deflector. For example, in Chapter 4.1, if we want to achieve a 1.2 mrad deflection angle with a 3 cm x 1 cm x 1 cm CGC KTN deflector, a voltage of 4000 V is required. This means that the required electric field is $4000 \, V / 1 \, cm = 400 \, kV/m$. If we can reduce the thickness of the KTN crystal to 0.1 mm, as shown in Fig. 6-1, the required driving voltage is only $400 \, kV/m \times 0.1 \, mm = 40 \, V$. It is easy to find a high-repetition-rate voltage supply with an output of 40 V in the commercial market.

![Figure 6-1: Schematic drawing of an ultra-thin CGC KTN beam deflector.](image-url)
Moreover, the KTN based optical beam deflector can be applied in the wavelength-tunable laser. Figure 6-2 is a schematic drawing of a high-speed wavelength-tunable laser. The laser cavity is composed of a gain medium, total reflector, output coupler, gratings and KTN beam scanner. By adjusting the applied voltage, we can adjust the laser input angle of the gratings. Thus, only the laser with the wavelength meeting the grating equation can be amplified in the cavity. Due the high-speed nature of the KTN beam deflector, such a wavelength-tunable laser can achieve a high-speed response.

![Schematic drawing of a wavelength-tunable laser with KTN beam deflector.](image)

Figure 6-2: Schematic drawing of a wavelength-tunable laser with KTN beam deflector.
Reference


58. W. Yang, Z. Zhou, B. Yang, Y. Jiang, Y. Pei, H. Sun, and Y. Wang, "Effect of oxygen atmosphere on the structure and refractive index dispersive behavior of \( \text{KTa}_{0.5}\text{Nb}_{0.5}\text{O}_3 \) thin films prepared by PLD on Si (0 0 1) substrates," *Appl. Surf. Sci.* **258**, 3986 (2012).


Appendix

Selected Publications

Journal Papers


**Conference Proceedings**


VITA

Wenbin Zhu

Mr. Wenbin Zhu obtained his Bachelor of Science in Optoelectronic Engineering from Nankai University (China) in 2013. In Nankai University, he built a bend sensing system with twisted long period gratings and also simulated the temperature distribution in skin under laser irradiation with different wavelengths.

In the Pennsylvania State University, Mr. Zhu involves in multiple projects, which includes high-speed multi-channel optical waveguides, ultrafast electro-optical modulators, and high-speed optical beam scanners. In addition to the knowledge on electro-optical devices, he is an expert on optical bench test and simulation, who is familiar in several commercial simulation tools (e.g., COMSOL multiphysic and RSoft Design Suit). He also has extensive experience in the cleanroom fabrication and characterization.