Electrical switching of holographic lenses and holographic mirrors in Lithium Niobate

P. Arora\textsuperscript{a,b}, V. Petrov\textsuperscript{a}, J. Petter\textsuperscript{a}, K. Singh\textsuperscript{b}, T. Tschudi\textsuperscript{a}.

\textsuperscript{a}Institute of Applied Physics, TU- Darmstadt, Hochschulstr. 6, Darmstadt, GERMANY 64289;
\textsuperscript{b}Department of Physics, Indian Institute of Technology, Hauz Khas, Delhi, INDIA 110016.

ABSTRACT

We present here the realization of fast electro-optic switches and switchable holographic lenses based on electric field multiplexing of volume holograms in lithium niobate crystals. We demonstrate the electrical control of holographic lenses and holographic mirrors for switching of the focal length and the direction of the light propagation, respectively. Since the recording mechanism of the hologram and the electrical control through the electro-optic effect need different geometric conditions, we use the optimal orientation of the lithium niobate crystals to have the most efficient electrical control over the diffraction efficiency. The advantages of this technique to employ fast electro-optic switches are the simple realization, the low expenses involved and the low switching time, limited only by the resources and potentiality to apply the external electric field to the material. The switching time in the range of few hundred microseconds has been estimated with this technique.

Keywords: Volume holography, Electric field multiplexing, Electro-optic switches.

1. INTRODUCTION

The Bragg condition for volume holograms, recorded in reflection geometry\textsuperscript{1,2}, in electro-optic crystals can be controlled by applying an external electric field to the recording material. Via the electro-optic effect, the average refractive index of the material can be varied. This results in strong electric field selectivity\textsuperscript{3} of the reconstructed hologram and provides the possibility to record and retrieve several holograms in the same volume of the material. The technique of electric field multiplexing\textsuperscript{4,5} can be used e.g. for optical memory systems\textsuperscript{3} and the electrical control of the transfer function of optical filters\textsuperscript{6}. To “switch on” a particular hologram or to switch between different holograms, one has to merely apply the specific electric field. We demonstrate here the electrical switching of volume holograms in lithium niobate crystals, in the form of holographic lenses and holographic mirrors for switching of the focal length and the direction, respectively. The recording mechanism of the hologram and the electrical control through the electro-optic effect need different geometric conditions. Therefore, an optimal orientation of the lithium niobate crystals is used to have the most efficient electrical control over the diffraction efficiency. The advantages offered by this technique to multiplex and to switch between volume holograms are: the simple realization, the low expenses involved and the low switching time, limited only by the resources and potentiality to apply the external electric field to the material.

2. THEORETICAL BACKGROUND

In the perfect reflection geometry (Bragg angle $\Theta_B = 90^\circ$) of holographic recording, the Bragg condition has the form:

$$\Lambda = \frac{\lambda}{2n(E_{\text{ext}})}$$ (1)

where $\Lambda$ is the grating spacing, $\lambda$ is the wavelength of light in vacuum and $n$ is the average refractive index of the material, which depends on the external electric field $E_{\text{ext}}$, for the case of electro-optic material. On application of external electric field, refractive index of the material changes and hence the grating period changes as can be seen in eq. 1. The variation of refractive index leads to a change in the diffraction efficiency. So, the case of diffraction efficiency changing under the influence of the external electric field leads to the same behaviour in EFS (Electric Field Selectivity)

\* poonam.arora@physik.tu-darmstadt.de; phone +49-6151-163482, fax +49-6151-164123, www.physik.tu-darmstadt.de/lto
as with spectral or angular selectivity. For a hologram recorded in reflection geometry with a thickness of the hologram $T$, it can be shown that this EFS can be estimated as:

$$\frac{\Delta n}{n} \approx \frac{\Lambda}{T}$$  \hspace{1cm} (2)

where $\Delta n$ is the variation of the average refractive index due to the external electric field. From the electro-optic effect, the change of refractive index, caused by the application of an external electric field to the material is given by:

$$\Delta n = \frac{n^3 r_{eff} E_{ext}}{2}$$  \hspace{1cm} (3)

where $r_{eff}$ is the effective electro-optic coefficient of the material. Using eqns. (2) and (3), the expression for electric field selectivity $E_{sw}$, of volume reflection holograms is obtained as:

$$E_{sw} = \frac{2\Lambda}{n^2 T r_{eff}}$$  \hspace{1cm} (4)

where, $T$ is the thickness of the hologram in the direction of light propagation. To obtain a theoretical expression for the dependence of the diffraction efficiency on $E_{ext}$, which causes $\Delta n$, we have to use a specific geometry having following requirements: the orientation of the crystal, the direction of the applied electric field, the direction of light propagation and the orientation of light polarization. The condition, which is close to the optimal one for lithium niobate and for an extraordinary beam is found when the grating vector $\mathbf{k}'$ is oriented in the range of $30^\circ$-$50^\circ$ relative to the $\mathbf{E}'$-axis of the crystal. For this, we considered the transverse electro-optic effect and the electric field to be applied perpendicular to the grating vector. In this case, the diffraction efficiency is described by Kogelnik’s theory and has the form:

$$\eta = \frac{1}{\left(\frac{\xi}{\nu}\right)^2 + 1 - \left(\frac{\xi}{\nu}\right)^2} \coth^2\left(\sqrt{\frac{\eta}{\nu^2 - \xi^2}}\right)$$  \hspace{1cm} (5)

where, $n_1$ is the grating amplitude, for the perfect reflection geometry $\nu = \frac{\pi n T}{\lambda}$ is the modulation parameter that determines the diffraction efficiency in the case when Bragg condition is matched and $\xi = \frac{2\pi n T}{\lambda} \left(\frac{\Delta n}{n}\right)$ is the detuning parameter. We define $\alpha$ as the angle between the $\mathbf{E}'$-axis of the crystal and the direction of the applied electric field. To find the optimal orientation of the crystal, we encounter a compromising situation between two parameters: the grating amplitude and the effective electro-optic coefficient, as both are dependent on angle $\alpha$ as it can be seen in the following equations:

$$n_1 = \frac{1}{2} n^3 r_{eff} (\alpha) E_{sw} (\alpha)$$  \hspace{1cm} (6)

$$r_{eff} = r_{13} \cos \alpha \sin^2 \alpha + r_{13} \cos^3 \alpha + 2 r_{33} \cos \alpha \sin^2 \alpha - r_{22} \sin^3 \alpha$$

So, we choose an optimal value of angle $\alpha$ such that an acceptable grating amplitude as well as a commensurable electro-optic coefficient is achieved. With numerical simulations and theoretical calculations, we found that the optimal value of $\alpha$ lies in the range of $40^\circ$-$50^\circ$ (Fig. 1b). In our experiments, we used crystals with $\alpha = 45^\circ$.

### 3. EXPERIMENTAL SET-UP

The basic experimental set-up for the investigation of electrical control of holographic lenses is shown in Fig.1a. An Nd:YAG cw laser with 150 mW output power and extraordinary polarization is used. The plane wave obtained after the beam expander assembly is split into two beams: $\sigma$ and $\rho$. The LiNbO$_3$ crystal is illuminated from opposite sides by
the recording beams $\sigma$ and $\rho$. In this case the Bragg angle $\Theta_B$ is approximately $89.5^\circ$. The lens is introduced in the path of one of the recording beams for recording the hologram. After recording a hologram, the signal beam $\sigma$ is blocked and the reconstructed beam $\sigma_o$ is detected by a photodiode or a CCD camera placed at the focal plane of the lens. By applying different electric fields to the crystal, the dependence of the diffraction efficiency on the external field is measured. The dimension of the iron doped LiNbO$_3$ crystals used are $10 \times 8 \times d$ mm$^3$, where $d = 1$ mm and 2.5 mm. The concentration of Fe$^{2+}$ in both the crystals is 0.05 mol%. The pair of electrodes are attached to the top and bottom surfaces and the distance between the electrodes was $d$ mm, as shown in Fig. 1b.

Fig. 1. (a) Experimental set-up for recording and read-out of the holograms of lenses. (b) Orientation of the LiNbO$_3$ crystal in the experiment: $\vec{\sigma}$ and $\vec{\rho}$ are the propagation vectors of the recording beams, $\alpha$ is the angle between the $\vec{c}$-axis and the applied electric field, $\vec{P}$ is the orientation of the wave polarization, $\vec{E}_{ext}$ is the external electric field, $T$ is the thickness of the crystal.

The experimental set-up for investigating the electrical control of holographic mirrors is shown in Fig.2a. The term holographic mirrors is used for holograms of plane waves coming from different directions. For multiplexing of holograms of two mirrors, we used an interferometer geometry (as shown in Fig. 2a.) to have large separation between the two recording beams and hence directional switching with large angular separation between the two reconstructed beams.

Fig. 2. (a) Experimental set-up for the recording and read-out of holographic mirrors, 1- Nd:YAG cw laser, 2-beam expander assembly, 3-polarizer, 4-diaphragm, 5-beam splitter, 6-mirror, 7-crystal with electrodes, 8-shutter, 9-screen. (b) Read-out of the hologram of mirror 1 and mirror 2.

As shown in the experimental set-up, the two signal beams $\sigma_1$ and $\sigma_2$ enter the crystal on either side of the reference beam $\rho$. One of the beams is blocked and the hologram of one mirror is recorded without application of the field to the crystal. Then an appropriate value of the electric field is applied to the crystal and a hologram of the second mirror is recorded while blocking the first recording beam now. During the read-out we see directional switching with application of the appropriate electric field, as shown in Fig. 2b.
4. RESULTS AND DISCUSSION

We first measured the diffraction efficiency of the hologram of a lens as a function of the applied electric field, to have an estimate of the electric field selectivity (EFS), to multiplex another hologram using the Rayleigh’s criterion. The EFS was found to be 2 kV/cm for the hologram of lens as well as for a mirror. We multiplexed holograms of two lenses with focal lengths of 40 cm and 60 cm (Fig. 3a.) and with the electrical control of these holographic lenses, as expected we exhibited switching of focal length from 40 cm to 60 cm and vice versa. Fig. 3b. shows the actual and reconstructed focal distributions for the lenses at their focal planes. Ideally, an infinitely extended plane wave incident on a lens must be focused almost to a point at the focal plane of the corrected lens. The actual focal distribution here resembles an Airy pattern which is supposed to approach a delta function distribution in the limit of the aperture radius going to infinity. The reconstructed focal distributions are also distorted. According to our study, there are some defects or scattering centers in the crystal which scatter the beam and cause distortions in the reconstructed beam and the focal distribution.

![Fig. 3](image)

Fig. 3 (a) Diffraction efficiency as a function of the applied field for multiplexing of holograms of lenses with focal length 1: 40cm recorded at $E_{ext} = 0$ and 2: 60cm recorded at $E_{ext} = +2kV/cm$. (b) & (c) Actual and reconstructed focal distribution for the lens with focal length (b) 40cm, (c) 60cm.

The multiplexing of holograms of mirrors is done using the same process as used for holograms of lenses. Two tilted gratings (holograms) were multiplexed corresponding to the two mirrors placed at an angular separation of about $50^\circ$, at different values of the applied field. While read-out, by applying 2 kV/cm to the crystal, the beam is reconstructed in a different direction as shown in Fig. 4. With the electrical control of holographic mirrors, we exhibited directional switching with an angular separation of $50^\circ - 32'$ between the two beams reconstructed on switching (Fig. 2b). This angular separation can be further increased and is limited by the dimensions of the crystal and the diameter of the beam.

![Fig. 4](image)

Fig. 4. Pictures showing electrical switching of holograms of mirrors on a screen, for crystal with thickness, (a) $d = 1mm$ and (b) $d = 2.5mm$; at three values of applied field, 1: $E_{ext} = 0$, 2: $E_{ext} = +1kV/cm$ and 3: $E_{ext} = +2kV/cm$.

To estimate the switching time in our systems, we used a square pulsed voltage supply with 1 kHz frequency instead of continuously tunable dc voltage supply. Corresponding to this input voltage pulse, we captured the output signal obtained with a photodiode detecting the reconstructed beam. The plots obtained for the input square voltage pulse as a function of time and the output signal showing the behaviour of diffraction efficiency with time are shown in Fig. 5a.
The plot for diffraction efficiency (output signal) with time resembles with the charging and discharging curves for a capacitor. The crystal between two electrodes is equivalent to an RC circuit (Fig. 5b) and so the switching time is limited by the RC-time constant. We calculated the capacitance of the crystal and also the resistance and got the theoretical plot for the exponential decay of the capacitor equivalent RC-time constant (Fig. 5c). By fitting the experimental curve (Fig. 5d) to the exponential decay plot of an equivalent capacitor, the RC-time constant is calculated and is about 100 microseconds.

Fig.5. (a) Measured dependence of diffraction efficiency (upper left curve) and input signal (lower left curve) on time for crystal with a thickness of \( d = 2.5 \text{mm} \). (b) Simplified equivalent RC circuit of the crystal with electrodes with a voltage applied to it. (c) Theoretical curve for discharging of a capacitor with RC-time constant of \( 80 \mu \text{s} \). (d) Experimental curve of the diffraction efficiency as a function of time for a crystal with \( d = 2.5 \text{mm} \).

5. CONCLUSIONS

We have successfully demonstrated the electrical switching of holographic lenses, which provides switching of focal length from \( 40 \text{cm} \) to \( 60 \text{cm} \) and vice versa at a switching speed of about \( 100 \mu \text{s} \). Such a system is competitive with liquid crystal lenses. The advantages of electrically switchable lenses are much faster switching and simple realization as no complex control system is required as in the case of liquid crystal lenses. The electrically switchable holographic mirrors deflect the beam at relatively large angles (directional switching) with switching speed of few hundred microseconds. Such systems are competitive with electro-optic and acousto-optic deflectors and MEM (Micro Electro Mechanical) devices. MEM devices are complicated structures and these devices do not provide fast switching due to high inertia. Electro-optic and acousto-optic deflectors have relatively fast switching, but these are complex and expensive systems. Due to fast switching and simple realization, the use of the presented technique for tunable and switchable integrable components is being studied.

REFERENCES