LiTaO$_3$ as Holographic Storage Material

E. Krätzig and *R. Orlowski*

Philips GmbH, Forschungslaboratorium Hamburg, D-2000 Hamburg 54, Fed. Rep. Germany

Abstract. The optical storage properties of LiTaO$_3$:Fe are investigated and compared with those of the isomorphous compound LiNbO$_3$:Fe. Absorption, photocurrent, photoconductivity and holographic measurements are reported. In the case of photovoltaic writing similar results for LiTaO$_3$- and LiNbO$_3$-crystals are obtained. However, in the case of photoconductive writing using external electric fields LiTaO$_3$:Fe-crystals yield much better results due to large photoconductivity values. Considering the recording sensitivity and the extremely large storage time LiTaO$_3$:Fe turns out to be one of the most promising materials for photorefractive storage of volume phase holograms.

Pyroelectric crystals have been successfully utilized for the storage of volume phase holograms. The storage is achieved by light induced refractive index changes (photorefractive effects). Upon exposure of the crystals to light interference-patterns electrons are excited and transferred to different sites. The resulting space charge fields modulate the refractive index via electro-optic effect. Uniform illumination erases the space charge fields and brings the crystal back to its original state.

In most cases the studies have been concentrated on LiNbO$_3$, minor attention has been paid to the isomorphous compound LiTaO$_3$.

According to measurements of Glass et al. [1] the photorefractive sensitivity of LiTaO$_3$ for recording without externally applied electric fields is much smaller than that of LiNbO$_3$ both for undoped and Fe-doped crystals. Spinhirne and Estle [2], however, deduce comparable sensitivities for doped LiNbO$_3$- and LiTaO$_3$-crystals from their experiments. Tsuya [3] has investigated the influence of various transition metal dopants. As in the case of LiNbO$_3$ the Fe-ions turn out to be the most effective dopants for the enhancement of storage sensitivity of LiTaO$_3$-crystals. Fe^{2+}-ions have been proposed as donors and Fe^{3+}-ions as traps [1, 3].

In the present contribution we report on optical absorption, photovoltaic and holographic measure-ments of Fe-doped LiTaO$_3$-crystals. The relevant parameters for holographic storage utilizing the bulk photovoltaic effect or the photoconductivity under external electric fields are determined. The comparison of the experimental results with those of LiNbO$_3$ indicates that LiTaO$_3$ is a very attractive material for holographic storage.

1. Experimental Methods

The measurements were performed with single domain LiTaO$_3$-crystals (Union Carbide Corporation) containing between 0.002 and 0.05 wt-% Fe as determined by mass spectroscopic and by x-ray fluorescence analysis. The crystals were partially reduced or oxidized by annealing in vacuum, in argon or in oxygen atmosphere at temperatures slightly below the Curie point at about 660° C. In order to obtain stronger reductions or oxidations annealing treatments were also carried out at temperatures above the Curie point up to about 1100° C. In this case the crystals had to be poled again by electrical currents.

The optical absorption coefficient α was measured with a Cary 17 spectrometer versus an undoped reference crystal or versus air substracting the contri-bution of reflection.

Short-circuited photocurrents in thermal equilibrium were induced in the spectral range between 1.5 and
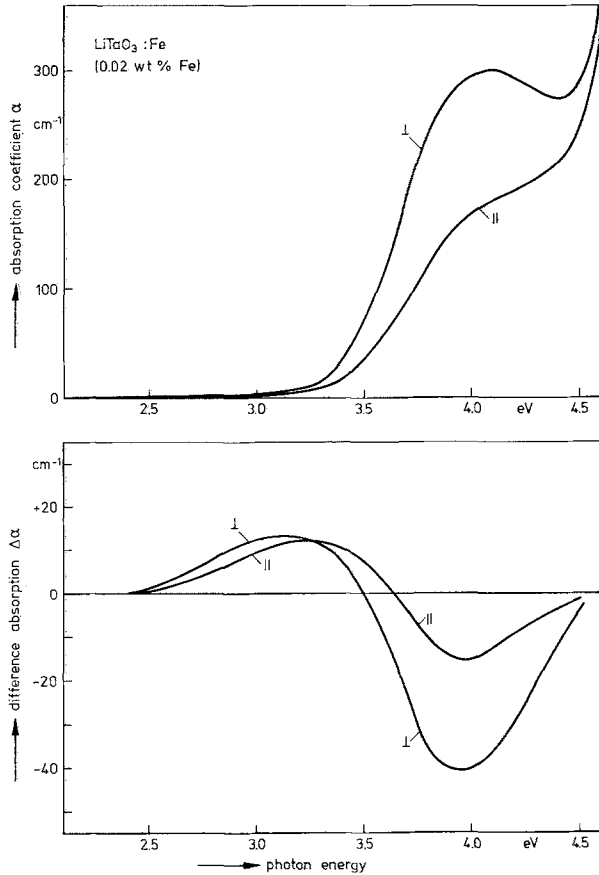
Fig. 1a and b. Optical absorption spectra of a $LiTaO_3$:Fe(0.02wt-% Fe)$^-$ crystal for light polarized parallely ($\parallel$) and perpendicularly ($\perp$) to the c-axis: a) absorption coefficient of an oxidized sample (concentration ratio $c_{Fe^{2+}}/c_{Fe^{3+}} < 0.01$); b) difference absorption $\Delta\alpha$ between a partially reduced ($c_{Fe^{2+}}/c_{Fe^{3+}} = 0.2$) and an oxidized sample ($c_{Fe^{2+}}/c_{Fe^{3+}} < 0.01$)

4 eV by incoherent light of a 1 kW xenon lamp in combination with a grating monochromator. The crystals were uniformly illuminated and edge electrodes of silver paste were used. Because of the influence of light absorption the measured currents are related to a mean light intensity $I = I_0[1 - \exp(-\alpha d)](\alpha d)^{-1}$, where I_0 is the incident intensity and d the crystal thickness. To reduce the influence of absorption as much as possible very thin crystals (d between 0.1 and 0.3 mm) were used.

The deviation of the photocurrent density j under the influence of an external field was found to be proportional to the field strength thus defining the photoconductivity σ_l. A linear relation between σ_l and the incident light intensity was verified. The dark conductivity σ_d was in all cases small compared to σ_l for the light intensities used on the order of 1 mW/cm^2.

Photo-induced voltages and fields were measured by applying external fields for compensation. In the case of large compensation fields the corresponding values

were extrapolated due to the linear relation between the deviation of photocurrent density j and the applied field strength.

The holographic measurements were carried out using the 350.7 nm line of a krypton laser and a two beam interference arrangement similar to that described earlier [4]. External electric fields up to 15 kV/cm were applied along the polar c-axis, the internal resistance of the voltage source was negligible compared to the crystal resistance. The entire sample was illuminated by the interference pattern of two plane light waves. The fringes were chosen perpendicularly to the c-axis, fringe spacing was 2.5 μm. The modulation index was reduced by simultaneous illumination with a non-interfering third beam. The fundamental component Δn_f of the induced refractive index distribution was obtained from the first-order diffraction efficiency. The photorefractive sensitivity is then given by the slope of Δn_f in the initial state of illumination. The dynamic behaviour of refractive index changes was investigated for small saturation diffraction efficiencies (light polarization perpendicular to the c-axis, $m \approx 0.4$). In this case interactions between the recording beams via an already written hologram can be neglected.

Because of the extremely small values the dark conductivity σ_d was also measured by holographic means. The dark relaxation of a recorded elementary phase grating was monitored from time to time by a He–Ne laser beam in appropriate Bragg condition. The dark conductivity is obtained from the decay time.

2. Experimental Results

2.1. Optical Absorption

Absorption measurements provide informations on concentrations of Fe^{2+}- and Fe^{3+}-ions, which are of importance for the photorefractive properties. Undoped $LiTaO_3$-crystals are transparent in the near IR, the visible and the near uv spectral region up to photon energies of about 4.6 eV, where the fundamental electronic absorption begins. Fe-impurities cause characteristic bands similar to those of $LiNbO_3$:Fe [5]. At about 1.1 eV localized $d-d$ crystal field transitions on Fe^{2+}-ions are observed, at about 2.6 and 2.9 eV weak spin forbidden $d-d$ transitions on Fe^{3+}-ions. Of special interest for the transport properties is the absorption band around 3 eV, which has been attributed [5] to an intervalence transfer $Fe^{2+} \rightarrow Ta^{5+}$. We have confirmed the correlation of the 1.1 eV and the 3 eV band by measuring a constant ratio of the absorption coefficients: $\alpha_\perp(3\,eV)/\alpha_\perp(1.1\,eV) \approx 25$.

At higher photon energies we have observed an additional band clearly distinct from the fundamental electronic absorption (Fig. 1). This band centered at
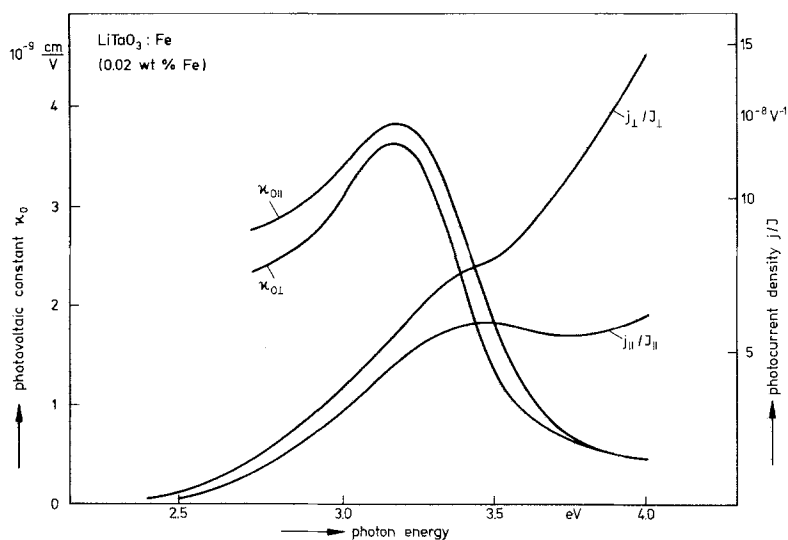
Fig. 2. Spectra of photovoltaic constanc $\varkappa_0$ and photocurrent density j/I of a partially reduced $LiTaO_3$:Fe-crystal (0.02 wt-% Fe, $c_{Fe^{2+}}/c_{Fe^{3+}} = 0.15$) for light polarized parallely ($\parallel$) and perpendicularly ($\perp$) to the c-axis

about 4 eV decreases by reducing treatments, the decrease is correlated to an increase of the Fe^{2+}-bands, e.g. $\Delta\alpha_{\perp}(4\,eV)/\Delta\alpha_{\perp}(3\,eV) \approx -3$ (Fig. 1). For this reason we attribute the 4 eV band to charge transfer processes from oxygen π-orbitals to Fe^{3+}-ions.

The interplay of Fe^{2+}- and Fe^{3+}-bands allows estimations of the oscillator strengths f and of the concentration ratios $c_{Fe^{2+}}/c_{Fe^{3+}}$. In the case of strongly oxidized $LiTaO_3$:Fe-crystals the absorption coefficients at 1.1 and 3 eV are very small supporting the assumption that the Fe-ions are almost completely present in the trivalent state. Then we obtain for the oscillator strength of the 4 eV band: $f_{\perp}(4\,eV) = 5 \cdot 10^{-2}$. For the small lines at 2.6 and 2.9 eV we estimate $f < 10^{-5}$.

The decrease of the 4 eV band by reducing treatments furthermore yields the number of Fe-ions transferred into the divalent state. Then we obtain for the oscillator strengths of the Fe^{2+}-bands: $f_{\perp}(1.1\,eV) \approx 5 \cdot 10^{-4}$ and $f_{\perp}(3\,eV) \approx 10^{-2}$. Within the measuring accuracy these values completely agree with those of the corresponding Fe^{2+}-bands in $LiNbO_3$ [6]. By the reducing treatments described above the concentration ratio $c_{Fe^{2+}}/c_{Fe^{3+}}$ can be increased to values on the order of one.

A further possibility for changes of the ratio $c_{Fe^{2+}}/c_{Fe^{3+}}$ is exposure of the $LiTaO_3$:Fe-crystals to x-ray irradiation. In strongly oxidized samples about 10% of the Fe-ions have been transferred into the divalent state. However, by these means only transient changes are possible, the relaxation time decreases considerably with increasing temperature.

2.2. Photovoltaic Writing

When no external field is applied the hologram writing is mainly determined by a bulk photovoltaic effect [7].

The photorefractive sensitivity $S = d(\Delta n_f)/d(I \cdot t)|_{t=0}$, i.e. the refractive index change per incident light energy, is then given by the relation $[8,7,6]$: $S = \varkappa_0 \cdot \alpha \cdot n^3 rm/(2\varepsilon\varepsilon_0)$, where $\varkappa_0$ is the photovoltaic constant, r the corresponding electro-optic coefficient and m the modulation index.

Above all the sensitivity S depends on the photovoltaic constant $\varkappa_0$. This quantity can be determined from photocurrent measurements under uniform illumination in a short-circuited configuration. Then the current density j along the c-axis is given by $j = \varkappa_0 \alpha I$ [7].

The experimental results confirm this relation for the photocurrent density. To a first approximation the photovoltaic constant depends on the absorbing centers and on wavelength only. Small additional influences of impurity concentration and valence states will be described below.

The largest $\varkappa_0$-values are obtained for Fe-dopants. Figure 2 shows the photocurrent spectrum of a $LiTaO_3$:Fe-crystal and the corresponding $\varkappa_0$-spectrum obtained by taking into account the entire absorption α. As in the case of $LiNbO_3$ the photocurrent is directed along the polar c-axis with the $+c$-end negative.

The values of $\varkappa_0$ are also very similar to those of $LiNbO_3$:Fe. Furthermore $\varkappa_0$ again increases with increasing photon energies, reaches a maximum around 3.2 eV and decreases again [9]. The $\varkappa_0$-values for photon energies larger than about 3.3 eV, however, should be handled with care, especially for Fe-concentrations larger than 0.01 wt-%. The absorption used with the evaluation of the $\varkappa_0$-values may contain transitions which are inefficient for the photovoltaic effect. Because of the small influence of light polarization the following results are confined to unpolarized light.
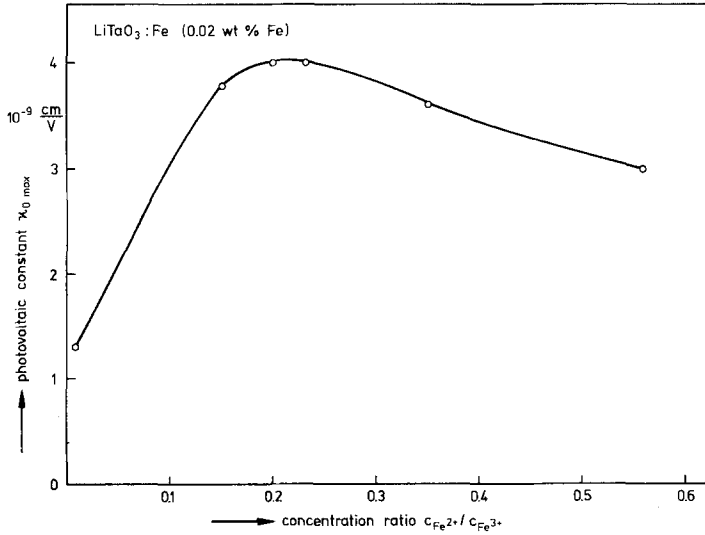
Fig. 3. Dependence of the maximum value $\varkappa_{0\,max}$ of the photovoltaic constant on the concentration ratio $c_{Fe^{2+}}/c_{Fe^{3+}}$ for LiTaO$_3$:Fe(0.02 wt-% Fe)
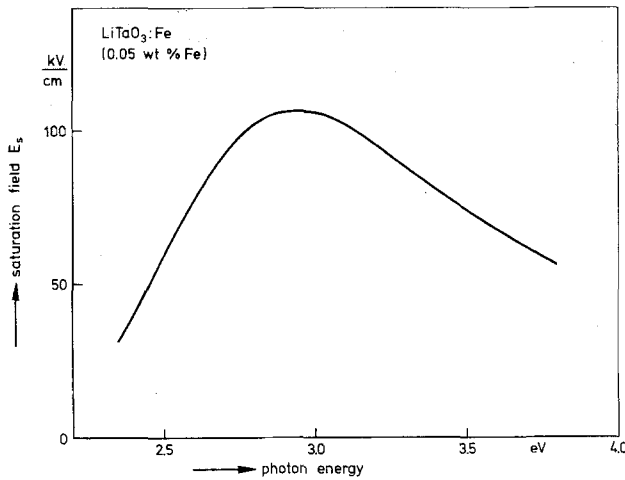

Fig. 4. Spectral dependence of the photo-induced saturation field E_s for LiTaO$_3$:Fe (0.05 wt-% Fe, $c_{Fe^{2+}}/c_{Fe^{3+}} = 0.4$)

As in the case of LiNbO$_3$:Fe the quantity $\varkappa_0$ for LiTaO$_3$:Fe depends slightly on the concentration ratio $c_{Fe^{2+}}/c_{Fe^{3+}}$ [9]. Oxidized crystals show rather small $\varkappa_0$-values, $\varkappa_0$ increases by reducing treatments, and decreases again for concentration ratios $c_{Fe^{2+}}/c_{Fe^{3+}} \gtrsim 0.3$ (Fig. 3). Moreover, $\varkappa_0$ depends on the entire Fe-concentration c_{Fe}, LiTaO$_3$-crystals containing 0.05 wt-% Fe show $\varkappa_0$-values larger by about a factor of two than those of crystals containing 0.002 wt-% Fe.

The photovoltaic constant can be increased also by raising the temperature. At 250 °C the $\varkappa_0$-values are larger by about a factor of two compared to room temperature values.

Another quantity important for the photorefractive properties, especially for the storage capacity, is the

photo-induced saturation field E_s obtained in an open circuit configuration under uniform illumination. The field E_s determines the saturation value of refractive index change Δn_{fs} via electro-optic effect: $\Delta n_{fs} = n^3 r E_s/2$.

The saturation field is given by the relation [7]: $E_s = \varkappa_0 \alpha I/\sigma$. The conductivity during illumination $\sigma = \sigma_l + \sigma_d$ contains contributions of photo- and dark conductivity. Because σ_d is very small compared to σ_l and the quantity σ_l is proportional to I, the E_s-values are independent of light intensity.

The spectral dependence of E_s is shown in Fig. 4. The values grow with increasing photon energies because $\varkappa_0$ increases, reach a maximum around 3 eV and decrease again at larger photon energies mainly because $\varkappa_0$ decreases. For the Fe-concentrations investigated (up to 0.05 wt-% Fe) the saturation fields grow weakly with increasing Fe-content. As in the case of LiNbO$_3$:Fe in LiTaO$_3$:Fe photo-induced fields on the order of 100 kV/cm are observed (Fig. 4).

2.3. Photoconductive Writing

Hologram writing can also be performed by utilizing electron drift under the influence of an externally applied field E_{ex}. Then the photorefractive sensitivity S is given by [4]: $S = |\varkappa_0 + \varkappa_1 E_{ex}| \alpha n^3 rm/(2\varepsilon\varepsilon_0)$, where $\varkappa_1 = \sigma_l(\alpha \cdot I)^{-1}$ is the specific photoconductivity. This quantity is most important for the sensitivity in the case of photoconductive writing.

Figure 5 shows the spectral dependence of σ_l/I and $\varkappa_1$ for a LiTaO$_3$:Fe-crystal. The photoconductivity σ_l/I increases monotonically with increasing photon energy, the specific conductivity $\varkappa_1$ reaches a maximum value around 3.5 eV. Besides that the values of σ_l/I and $\varkappa_1$ increase with increasing $c_{Fe^{2+}}/c_{Fe^{3+}}$-ratio. For
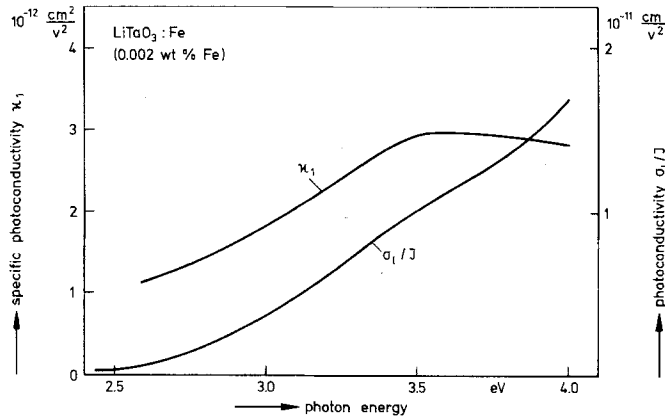
Fig. 5. Spectral dependence of specific photoconductivity $\varkappa_1$ and photoconductivity σ_l/I for LiTaO$_3$:Fe (0.002 wt-%Fe, $c_{Fe^{2+}}/c_{Fe^{3+}} = 1$)

this reason we attribute the photoconductivity mainly to field sensitive electron transfers from Fe^{2+}- to Fe^{3+}-ions.

In the case of LiNbO$_3$:Fe an increase of photoconductivity in the near uv region with increasing $c_{Fe^{3+}}/c_{Fe^{2+}}$-ratio has been found additionally [9]. The transitions responsible for these contributions are not observed in the case of LiTaO$_3$:Fe in the spectral range investigated.

For Fe-concentrations larger than 0.01 wt-% Fe the $\varkappa_1$-values of LiTaO$_3$- and LiNbO$_3$-crystals are of the same order of magnitude, typically between 10^{-14} and 10^{-13} cm^2/V^2. For smaller Fe-concentrations, however, in the case of LiTaO$_3$:Fe surprisingly large $\varkappa_1$-values have been measured up to $3 \cdot 10^{-12}$ cm^2/V^2 (Fig. 5). For this reason these crystals are especially attractive for photoconductive hologram recording as confirmed by the results described in the following section.

2.4. Holographic Experiments

Because of the large values of the specific photoconductivity $\varkappa_1$ the photorefractive properties under external electric fields have been studied in the near uv region using partially reduced and weakly doped LiTaO$_3$:Fe-crystals (0.002 wt-% Fe, $c_{Fe^{2+}}/c_{Fe^{3+}} \approx 1$).

The qualitative results concerning the photorefractive process are again very similar to those of LiNbO$_3$:Fe [4]. The saturation value of refractive index change Δn_{fs} and the photorefractive sensitivity S depend linearly on the applied field strength. The time constants for writing and erasing of refractive index changes are determined by photoconductivity, the time constants are equal in both cases and not influenced by external fields. The photovoltaic saturation field $E_S = \varkappa_0/\varkappa_1$ is relatively small (about 1.1 kV/cm) and can be easily compensated by external fields. In this case only small refractive index changes due to diffusion currents are obtained.

Table 1. Absorption coefficient α, photovoltaic constant $\varkappa_0$, specific photoconductivity $\varkappa_1$ and energy density $\mathscr{E}$(1%) at $\lambda = 350.7$ nm

Light polarization	α [cm^{-1}]	$\varkappa_0$ [cm/V]	$\varkappa_1$ [cm^2/V^2]	$\mathscr{E}$(1%) [mJ/cm^2]
$\perp$	3.74	$3.0 \cdot 10^{-9}$	$2.7 \cdot 10^{-12}$	115
$\parallel$	3.26	$3.4 \cdot 10^{-9}$	$3.4 \cdot 10^{-12}$	23

From the holographic experiments the basic parameters $\varkappa_0$ and $\varkappa_1$ can also be determined. The values are listed in Table 1. There is an excellent agreement with the results of direct photocurrent and photoconductivity measurements indicating the validity of the description used for the photorefractive process. The direct measurements performed with unpolarized light yield for this crystal: $\varkappa_0 = 3.0 \cdot 10^{-9}$ cm/V and $\varkappa_1 = 3.0 \cdot 10^{-12}$ cm^2/V^2. In comparison we obtain from the holographic measurements (mean values of Table 1):

$$\varkappa_0 = 3.2 \cdot 10^{-9} \text{ cm/V} \quad \text{and} \quad \varkappa_1 = 3.1 \cdot 10^{-12} \text{ cm}^2/\text{V}^2 .$$

Table 1 also shows the exposure energy density $\mathscr{E}$(1%), which is necessary to induce an elementary volume phase grating of 1% diffraction efficiency. For an external electric field $E_{ex} = 15$ kV/cm, a crystal thickness $d = 0.09$ cm and a modulation index $m = 0.83$ we observe rather small values for $\mathscr{E}$(1%), which will be discussed in the following chapter.

The dark storage time was also determined from the holographic measurements. An exponential decay of refractive index change Δn_f was observed experimentally. The dark relaxation time constant is given by $\varepsilon \varepsilon_0/\sigma_d$ [6], the static dielectric constant ε is 45 for LiTaO$_3$. At room temperature we extrapolate from our measurements a dark storage time larger than 10 years corresponding to σ_d smaller than 10^{-20} (Ωcm)$^{-1}$ for the LiTaO$_3$:Fe-crystal (0.002 wt-%Fe, $c_{Fe^{2+}}/c_{Fe^{3+}} \approx 1$).

In the case of $LiNbO_3$:Fe a fixing process has been discovered [10]. A hologram is written at room temperature and then the crystal is heated up to a temperature at which ions in the lattice become relatively mobile, while the trapped electronic charges remain still thermally stable. The ions are hence allowed to drift in this field until they nearly completely compensate the trapped electronic charge. The original phase hologram disappears, but information remains stored as a weak absorption hologram corresponding to the distribution of Fe^{2+}- and Fe^{3+}-ions. Then the crystal is cooled down to room temperature and the ionic pattern is frozen in. When the crystal is again exposed to light, the trapped electronic charges redistribute, leaving an electric field pattern that mirrors that of the original hologram. The initial electronic charge pattern is then partially converted into an optically stable ionic charge pattern.

We have observed this fixing process in $LiTaO_3$:Fe, too. A crystal with a hologram was heated to about 150 °C and cooled down to room temperature again. After this treatment the hologram was nearly erased, but would be quickly brought back by incoherent illumination with visible light. The new pattern was stable against light and could only be erased by heating the crystal again.

3. Discussion

The experiments described above clearly indicate that $LiTaO_3$ is a very attractive material for the photorefractive storage of volume phase holograms. Qualitatively the results are very similar to those of the isomorphous compound $LiNbO_3$. The storage properties depend characteristically on transition metal dopants, especially efficient are Fe-ions. In the crystals Fe^{2+}- and Fe^{3+}-centers are present, the ratio $c_{Fe^{2+}}/c_{Fe^{3+}}$ can be easily controlled by chemical annealing treatments.

The quantitative comparison of the storage properties of Fe-doped $LiNbO_3$- and $LiTaO_3$-crystals also shows close agreement in most cases. The oscillator strengths of the absorption bands, the photovoltaic constants and the electro-optic coefficients are similar. In the case of photovoltaic writing in $LiTaO_3$:Fe as well as in $LiNbO_3$:Fe [9] a concentration of about 0.05 wt-% Fe and a ratio $c_{Fe^{2+}}/c_{Fe^{3+}}$ between 0.2 and 0.3 seem to be most favourable.

Differences occur in the specific photoconductivity and the dark resistivity of weakly doped crystals, the values in the case of $LiTaO_3$:Fe are larger by more than one order of magnitude compared to those of $LiNbO_3$:Fe.

For this reason $LiTaO_3$ is especially attractive for photoconductive writing. The properties storage time, capacity and sensitivity will be discussed in this case.

The dark storage time (about 10 years) is extremely large due to the dark resistivity values, which are the largest of all electro-optic materials investigated up to now. The problem of optical erasure during read-out may be partially overcome by the thermal fixing processes observed in these crystals.

The storage capacity is determined by the number N of individual holograms which can be superimposed in the same volume. This number is given by [11]: $N = \Delta n_{fs}/\Delta n_{fi}$, where Δn_{fs} is the saturation value of refractive index change and Δn_{fi} the refractive index change of an individual hologram. Using the relation for Δn_{fs} [4] we obtain $N = 0.5 n^3 rm (E_{ex} + \varkappa_0/\varkappa_1)/\Delta n_{fi}$. In the case of photoconductive writing $(E_{ex} \gg \varkappa_0/\varkappa_1)$ the number N is determined by the external field only and independent from photoconductivity. Thus, using large external fields multiple storage with large storage capacity should be possible in crystals with large photoconductivity as well as in crystals with small photoconductivity using large photovoltaic fields.

A further quantity critically influencing the optical storage properties is the sensitivity. Besides the photorefractive sensitivity $S = d(\Delta n_f)/d(I \cdot t)|_{t=0}$ the figure of merit $\mathscr{E}(1\%)$, i.e. the energy density for recording an elementary volume phase grating of 1% read-out efficiency, is of particular interest. Using the relation for S with constant external field [4] the quantity $\mathscr{E}(1\%)$ is given by [11]

$$\mathscr{E}(1\%) = \frac{2\lambda\varepsilon\varepsilon_0\cos\theta}{\pi n^3 rm} \cdot \frac{1}{(\varkappa_0 + \varkappa_1 E_{ex})}$$
$$\cdot \frac{\arcsin(0.01 \cdot e^{\alpha d/\cos\theta})^{1/2}}{(1 - e^{-\alpha d})},$$

where λ is the light wavelength, θ the half interference recording angle and d the crystal thickness. This equation requires the following conditions to be fulfilled: Linear recording region $[\Delta n_{fs} \gg \Delta n_f(\eta = 1\%)]$, small reflection losses, negligible diffusion currents and small mean transport length of charge carriers compared to fringe spacing.

The energy density $\mathscr{E}(1\%)$ is mainly determined by the term $(\varkappa_0 + \varkappa_1 E_{ex})$, representing the influence of the photovoltaic effect and of externally applied electric field. For photoconductive writing $\left(E_{ex} \gg \dfrac{\varkappa_0}{\varkappa_1}\right)$ the quantity $\mathscr{E}(1\%)$ is reciprocally proportional to $\varkappa_1$.

We have measured in the near uv region $\varkappa_1$-values of about $3 \cdot 10^{-12}$ cm^2/V^2 (Fig. 5 and Table 1). For light polarized parallely to the c-axis and an external field of 15 kV/cm we then calculate from the above equation: $\mathscr{E}(1\%) = 23$ mJ/cm^2. This value is in excellent agreement with that obtained from direct measurements:

Table 2. Energy density $\mathscr{E}(1\%)$ and dark storage time of various electro-optic storage materials

Material	$\mathscr{E}(1\%)$	Storage time	Remarks		Reference
	[mJ/cm²]	[years]	λ [nm]	E_{ex} [kV/cm]	
LiTaO₃:Fe	11	10	351	15	This work
LiNbO₃:Fe	200	1	351	15	[13]
	300	0.1	488	0	[11]
Sr₀.₇₅Ba₁.₂₅Nb₂O₆:Ce	1.5	0.1	488	0	[14]
Bi₁₂SiO₂₀	0.3	0.003	514	6	[15]
KTa₀.₆₅Nb₀.₃₅O₃	0.05	0.001	530 two-photon absorption	6	[16]

$\mathscr{E}(1\%)=22\,\text{mJ/cm}^2$ (Table 1). A further improvement can be obtained by optimizing the crystal thickness so that $\alpha d=1$ and by choosing a modulation index of one. In this case we obtain the optimum value $\mathscr{E}(1\%) = 11\,\text{mJ/cm}^2$.

The term $(\varkappa_0 + \varkappa_1 \cdot E_{ex})$ is correlated to the effective mean drift length $l=(\varkappa_0 + \varkappa_1 E_{ex})h\nu/e$. For a photon energy $h\nu = 3.55\,\text{eV}$, $E_{ex} = 15\,\text{kV/cm}$ and $\varkappa_1 = 3\cdot10^{-12}$ cm²/V² we obtain $l = 20\,\text{Å}$ in LiTaO₃:Fe. The comparison with the corresponding value of about $1\,\text{Å}$ in LiNbO₃:Fe again indicates the more efficient charge transport in LiTaO₃:Fe.

The ultimate sensitivity is obtained when the drift length is comparable to fringe spacing [12], in this case $\mathscr{E}(1\%)$-values on the order of $50\,\mu\text{J/cm}^2$ are possible.

As shown in Fig. 5, the specific photoconductivity decreases only slightly with decreasing photon energy. For this reason efficient writing using the argon laser lines (514 and 488 nm) should be possible, too. A difficulty, however, arises from the small absorption coefficient in this spectral region. To obtain αd-values on the order of one rather thick crystals have to be used.

Table 2 gives a comparison of the energy density $\mathscr{E}(1\%)$ and the dark storage time of various electro-optic storage materials, which represent at the moment the most promising examples. The data indicate that the most sensitive materials show rather short storage times. LiTaO₃:Fe-crystals represent a fairly good compromise considering the combination of sensitivity and storage time.

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