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Electro-optic properties of indium/erbium-codoped lithium niobate crystal for integrated optics

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ABSTRACT

Clamped and unclamped electro-optic coefficients γ_{13} and γ_{33} of In^{3+}/Er^{3+}-codoped $LiNbO_3$ crystals, which were grown by Czochralski method from the melts containing 0.5 mol% Er_2O_3 while varied In_2O_3 contents of 0.0, 0.5, 1.0 and 1.5 mol%, were measured by Mach-Zehnder interferometry. The results show that In^{3+}/Er^{3+} codoping does not cause change of γ_{13} and γ_{33}, and both γ_{13} and γ_{33} can be regarded as unchanged in the studied In^{3+} concentration range of 0–2.6 mol% (in crystal) within the experimental error of 3%. The small doping effect is desired in light of the electro-optic application of the crystal. A qualitative, comprehensible explanation for the small effect is given on the basis of the EO coefficient model of $LiNbO_3$ and doping effect on the defect structure of $LiNbO_3$.

1. Introduction

Er^{3+}-doped $LiNbO_3$ (LN) is a promising host material for integrated optics as it combines Er^{3+} laser properties with excellent electro-optic (EO), acousto-optic and nonlinear optical properties of LN. Such an effective combination, together with the possibility of fabricating a low-loss waveguide using well-established techniques, enables broadband amplification and lasing at 1.5 μm. Over the past years, people has demonstrated a family of Ti- or vapor Zn-diffused Er: $LiNbO_3$ waveguide lasers (amplifiers) and integrated devices [1–8], including some active EO devices such as pulsed, mode-locked, Q-switched Ti-diffused Er^{3+}-doped LN (Ti:Er:LN) waveguide lasers, which were implemented by utilizing the excellent EO property of LN [1,2,7,8]. However, these devices suffer from serious photorefractive effect. It is well known that addition of > 4.6 mol% MgO into the growth melt can effectively suppress the photorefractive effect [9]. In addition to the widely Mg^{2+} dopant [9], some other optical-damage-resistant dopants have been reported too. These include divalent Zn^{2+}[10], trivalent Sc^{3+}[11,12], Tm^{3+}[13] and In^{3+}[14–16], and tetravalent Hf^{4+}[17], Zr^{4+}[18,19] and Sn^{4+}[20]. Among these dopants, In^{3+} doping requires a relatively low optical-damage-resistant threshold concentration, ~3 mol% for an LN with a congruent composition [14–16]. The threshold is about 1.7 times lower than that of Mg^{2+} doping, ~5 mol % in crystal. Moreover, as the composition approaches the Li-rich boundary, the threshold lowers significantly. Low concentration threshold of optical-damage-resistant dopants is desired to improve the material homogeneity and the optical quality of crystal when codoped with rare-earth ions such as Er^{3+}, and to increase the diffusivity and solid solubility of codoped rare earth ions. Therefore, an In^{3+}/Er^{3+}-codoped LN is a more promising substrate than the Er^{3+}-only doped LN for developing a photorefractive-damage-resistant active device.

An important issue concerning an EO device is the precise knowledge about the EO coefficients of LN. It is unclear if In^{3+}/Er^{3+} codoping affects the EO property of LN, and if so, it is essential to know what is the relation to the In^{3+} and Er^{3+} doping concentration. In this work, a systematic study is carried out on In^{3+}/Er^{3+} codoping effect on the EO property of LN. The related study could not be found in the previous literatures (previous studies focus more on Er^{3+} spectroscopic properties [21–25]).

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Table 1
Summary of sample cut, In^{3+} and Er^{3+}(data in parentheses) concentrations in growth melt or crystal, interaction length y between applied electric field and light wave propagated in crystal, spacing z of electrodes, and clamped and unclamped EO coefficients γ_{13} and γ_{33} (data outside/inside the parentheses correspond to the unclamped/clamped case).

Sample no.	Sample cut	$In^{3+}(Er^{3+})$ concentration (mol%)		y (mm)	z (mm)	γ_{13} (pm/V)	γ_{33} (pm/V)
		In melt	In crystal				
1	Z	0.0 (1.0)	0.0 (1.53 ± 0.09)	14.0	4.5 (1.6)	10.1 ± 0.3 (9.6 ± 0.3)	31.6 ± 0.9 (30.5 ± 0.8)
2	Y	1.0 (1.0)	1.20 ± 0.06 (0.95 ± 0.04)	8.2	4.9 (4.9)	9.8 ± 0.3 (9.4 ± 0.3)	30.8 ± 0.8 (29.7 ± 0.8)
3	Z	2.0 (1.0)	1.91 ± 0.09 (0.93 ± 0.04)	9.6	4.5 (1.3)	10.3 ± 0.3 (9.9 ± 0.3)	31.4 ± 0.9 (30.9 ± 0.8)
4	Z	3.0 (1.0)	2.60 ± 0.10 (0.92 ± 0.04)	8.6	4.5 (1.3)	10.0 ± 0.3 (9.6 ± 0.3)	29.9 ± 0.8 (29.7 ± 0.8)

2. Experimental description

The In^{3+}/Er^{3+}-codoped LN crystals used for present study were grown by the Czochralski technique. The molar percent of Er_2O_3 added into the growth melts was fixed at 0.5 mol%, while that of the In_2O_3 added varies from zero to 0.5, 1.0 and 1.5 mol%. The growth procedure is detailed in Ref. [21]. Table 1 summarizes the samples used for present study. The sample plates are either Z-cut (samples # 1, 3 and 4) or Y-cut (sample # 2). Both surfaces and side-faces of each plate were optically polished. The Er^{3+} and In^{3+} concentrations in crystals were determined by neutron activation analysis [23]. The results are shown in Table 1, together with the contents added into the growth melts, for reader's convenience. The In^{3+} concentration in crystal is 0.0, 1.20, 1.91 and 2.60 mol% for the samples 1, 2, 3 and 4, respectively, and the Er^{3+} concentration in crystal is 1.53, 0.95, 0.93 and 0.92 mol%, respectively.

Mach-Zehnder interferometry was used to measure the EO coefficients of the In^{3+}/Er^{3+}-codoped LN crystals. Fig. 1 shows the schematic of the measurement on a Z-cut LN sample. An X-Y-Z Cartesian coordinate system with Z axis parallel to the optical axis *c* of crystal is considered. An He-Ne laser was used as the light source. After spatially filter and polarized, the light was split into two beams. One beam, as the signal arm, is incident onto the Z- or Y-cut sample plate to be measured along the direction parallel to the crystallographic X axis of the crystal. The other beam acts as the reference arm. The phase of the light wave propagated in the crystal was modulated by a DC voltage applied along the direction parallel to the optical axis *c*, which is parallel to the crystallographic Z axis of the crystal. Both clamped and unclamped EO coefficients were measured. In the case of clamped measurements, the voltage was applied to the crystal through the Al films coated onto the two Z-surfaces of the crystal. In the case of unclamped measurements, the crystal was placed in an electric field environment created by a pair of external Cu slab electrodes as shown in Fig. 1. The signal and reference beams were recombined by another beam splitter where the interference fringe is generated. The interference pattern was detected by a power meter. The detection focuses on the zero-order fringe. From the power plot of the zero-order fringe versus the voltage, one can obtain the half-wave voltage U_π and the EO coefficient $\gamma_{13}=\lambda_0 z/(n_o^3 U_\pi)$ and $\gamma_{33}=\lambda_0 z/(n_e^3 U_\pi)$, where λ_0 is the working wavelength, y is the interaction length between the electric field and the light wave propagated in the crystal, z is the spacing of the two electrodes, n_e (n_o) is the extraordinary (ordinary) refractive index. Table 1 summarizes the parameters z and y for each sample to be measured.

3. Results and discussion

3.1. Verification of measurement system

The experimental system was used to measure a congruent pure LN and the measured results are compared with those values reported previously so as to examine its accuracy. The datasheet of specifications and parameters of congruent LN, which is provided by Gooch & Housego Inc. (original Crystal Technology Inc.), indicates that the EO coefficients γ_{13} (γ_{33}) at the 632.8 nm wavelength is 10 (33) pm/V in the unclamped case and 9 (31) pm/V in the camped case, without the error specified [26]. Cabrera group [27] and Kitamura group [28] have also reported the unclamped EO coefficients of the congruent LN at the 632.8 nm wavelength. The Cabrera group has reported that the unclamped γ_{13} is 10.5 ± 0.1 pm/V and γ_{33} is 31.5 ± 0.3 pm/V. The Kitamura group has reported that the unclamped γ_{13} is 10.0 ± 0.8 pm/V and γ_{33} is 31.5 ± 1.4 pm/V. Our measurements show that γ_{13}=10.4 ± 0.3 pm/V and γ_{33}=33.0 ± 0.8 pm/V in the unclamped case, and γ_{13}=10.0 ± 0.3 pm/V and γ_{33}=31.0 ± 0.8 pm/V in the clamped case. By taking into account all of the possible factors, our data have a relative error of ± 3%. One can see that our results are consistent with those reported previously within the error for both the clamped and unclamped cases, showing that the results measured using our system are sound.

3.2. EO coefficients of In^{3+}/Er^{3+}-codoped LNs

Table 1 collects the clamped and unclamped EO coefficients γ_{13} and γ_{33} measured from the In^{3+}/Er^{3+}-codoped LNs. Each coefficient was given from the average over twenty measurements on U_π. The data outside/inside the parentheses correspond to the unclamped/clamped case. Fig. 2 shows the dependence of the EO coefficients on the In^{3+} concentration in crystal. The red/blue balls represent the unclamped/clamped coefficients. Error bar is indicated for each data. One can see that both γ_{13} and γ_{33} reveal small dependence on the In^{3+} concentration. Both can be regarded as unchanged in the studied In^{3+} concentration range of 0–2.6 mol% (in crystal) within the experimental error of 3%, and this is the case for both the clamped and unclamped coefficients.

Subsequently, we explain why only the In^{3+} doping effect on the EO coefficient is considered in Fig. 2 while the Er^{3+} doping effect is ignored. Recently, we have also studied Er^{3+}-only doping effect on the electro-optic property of LN. The experimental results show that both γ_{13} and γ_{33} show small dependence on Er^{3+} concentration. The γ_{13} does not change within the error in the studied Er^{3+} concentration range of 0–2 mol% (in growth melt). Although the γ_{33} reveals a degradation tendency with a rise in Er^{3+} concentration, the degradation is no more than 5% in the considered Er^{3+} concentration range 0–2 mol%. Actually, the small Er^{3+} doping effect is also verified by the present data of the Er^{3+}-only doped crystal (i. e., sample # 1), for which γ_{13}=10.1 ± 0.3 pm/V and γ_{33}=31.6 ± 0.9 pm/V in the unclamped case, and γ_{13}=9.6 ± 0.3 pm/V and γ_{33}=30.5 ± 0.9 pm/V in the clamped case. A comparison with those values of the pure LN given above shows that two results have a small difference (< 5%). In addition, the weak Er^{3+} doping effect on EO property of LN is also indirectly verified by previous experimental results that the performance of an EO device based on the Ti^{4+}-diffused Er^{3+}-doped LN waveguide is not influenced noticeably by the Er^{3+} dopants, and the voltage used to drive an EO device based on an Ti^{4+}-doped Er:LN waveguide is low, only ~28 V for a Q-switched Ti:Er:LN waveguide laser [8]. In words, the Er^{3+} dopants have a small contribution to the EO coefficients. This is the reasons why only the In^{3+} doping effect is considered in Fig. 2 while the Er^{3+} doping effect is ignored. Such consideration is also supported by the small Er^{3+}