Chapter: 7

Conclusions

Chapter outline:

7.1: Conclusions
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7.1: Conclusions

The experimental work, addressed in this thesis, is primarily to study the ferroelectric lithium niobate crystal for optimal photonic device applications. Hence the work includes the study of its electro-optic parameters and also its inherent internal field. Finally, use of bulk lithium niobate crystal to produce effective phase modulation is presented. Conclusion of the entire work is given in the following.

In Chapter: 2 some of the basic physical properties of the crystal as well as some widely used applications are mentioned. From the detailed discussions made there, it is understood that majority of the applications are intimately dependent on the crystallographic properties of the said crystal.

Next in Chapter: 3 domain structure of ferroelectric lithium niobate crystal is addressed to understand various approaches and features of conventional domain inversion techniques. It was concluded that various features of domain inversion such as initiation of domain reversal, nucleation process, domain wall creation and its progress/broadening, pining-depining, etc., are still far from an understanding. Among various poling techniques room temperature electric field poling is employed for domain inversion of the LN crystal. The setup, slightly modified than the conventional one, avoids the complexity of the conventional electric field poling setup. Then to recognize the domain inverted regions of the sample, it is gone through chemical etching with an etchant mixture of $HF + HNO_3$ having a ratio of 1:1. The etched LN samples are then scanned by an optical microscope. From the recorded images a noticeable dissimilarity between the original single domain region and poled region is observed which is a proof of effectiveness of the said poling technique.

In Chapter: 4 the electro-optic property of the crystal is employed to verify the theoretically calculated halfwave voltage with that measured along its $+z$ axis. It is observed that the halfwave voltage is significantly reduced when measured along the $-z$ axis of the crystal due to presence of other interdependent effects of it. The primary observation made there is that a significant decrease of halfwave voltage in domain inverted LN single crystal, followed by no annealing treatment, is detected. The long relaxation time transients and direction dependence of the internal field compensating the spontaneous polarization within the crystal is suggested to be the cause for this variation. Hence, it was predicted that the resulting unstable domains in the bulk of
the crystal might have some effect on $r_{13}$. As the halfwave voltage and the said electro-optic parameter are inversely related with each other, it can be concluded that $r_{13}$ will be increased due to poling (e.g. frustrated or unstable domain inversion) of the LN crystal. An enhancement of $r_{13}$ by 32% is reported there.

Subsequently in Chapter: 5 dependency study of internal field (IF) in LiNbO$_3$ under various domain configurations of the crystal is made. Time and temperature evolution of IF in frustrated/unstable domain inverted LiNbO$_3$ is also performed and reported. It was noted that annealing of the poled LN sample at a temperature of 200 °C for 30 minutes had resulted in stable domain inverted state of the crystal. Though, a detailed and precise time evolution of IF is necessary to understand the features of stable and unstable domain inverted LiNbO$_3$ crystals and also the internal mechanism of electric field domain inversion of ferroelectrics. Again it was found that the strengths of IF for as-bought CLN and annealed domain inverted CLN crystal were same with a visible change of direction of the crystallographic $z$ axis of the crystal. But for frustrated domain inverted CLN crystal the strength of IF was reported to be a function of time elapsed after the previous poling process. A defect model prescribed by V. Gopalan et al [29] was employed there to explain the observed phenomena associated with the ambiguous domain inversion of LN crystals.

Chapter: 5 also concludes from literature that internal field ($E_{IF}$) in CLN is due to the combined effect of effective polarization field ($E_{PS}$) and depolarization field ($E_{PD}$). To realize the strengths of those components, an MZI is utilized to determine the internal fields of CLN single crystal in its single domain state, stable domain inverted state and frustrated domain inverted state. Assuming a linear functional dependency of internal field on effective polarization field and depolarization field, their values are estimated to be 1.65 KV/mm and 0.65 KV/mm respectively. Finally, Chapter: 6 deals with an application based on specially shaped LN crystal block as a differential phase modulating device. For this, analyses of electric field distribution between parallel and non-parallel electrodes are made using Schwarz-Christoffel Mapping method. But for non-parallel electrodes consistent result is only obtained for small angle of inclination only. These types of electrodes are simulated by using simple MATLAB programming and they are computationally very fast. Further the non-parallel electrodes are considered to be placed on the slant surfaces of a trapezoidal shaped LiNbO$_3$ crystal. It is found that variable polarization phase
can be introduced by those electrodes by controlling various geometric parameters of the electrode structure. Optimized dimensional parameters of the device for a particular phase difference between E-ray and O-ray is obtained and it is shown that this phase difference can be made tunable by using multiple strip electrode structure. This is really beneficial, as phase-tunability can be achieved by using a constant voltage source.

7.2: Limitations and future scope

Though lots of researches had been made on ferroelectric lithium niobate to explore its internal crystallographic structure and properties, it remains as a mysterious material which is not well understood till date. It is found from literature that the phase transition between ferroelectric and paraelectric phases of the crystal is not well defined as well. So the phase transition temperature or the Curie point of the crystal is not a constant but varies with composition of the crystal from its stoichiometric (SLN) form to its congruent (CLN) form. Again significant variations of forward/reverse poling voltage, coercive field and internal field of the crystal are reported in the literature. In this work direction dependency of halfwave field and its modification due to incomplete poling, resulting in frustrated domain state of the crystal, are reported. From a significant reduction of halfwave voltage measured immediately after poling it was concluded that an enhancement of electro-optic parameter $r_{13}$ by 32% is possible. But it is well known that the frustrated state of the crystal tends to obtain the stable state after some relaxation time. So the enhancement of the said parameter is not constant but time dependent. Obviously maximum value of the parameter will be obtained just after the poling. Hence the reported enhancement is not a unique one. Again it is known that at higher temperature the stability of the poled crystal is obtained relatively faster. So, lower crystal temperature ensures much longer relaxation time and the enhancement of the electro-optic parameter for an extended period.

Again the Mach-Zehnder interferometric method employed for the study is only applicable for $r_{13}$ only. To detect any significant change of other electro-optic parameters of the LN crystal, the used technique is to be modified accordingly. Study of this effect, for example for $r_{33}$, is very important and can be done by fabricating waveguides on the LiNbO$_3$ samples.

Another critically addressed problems in LiNbO$_3$ and LiTaO$_3$ are the properties of coercive field ($E_c$) and inherent internal field ($E_{int}$), particularly their dependence on the crystal composition
and temperature. It is noted that $E_C$ is generally reducing when approaching the phase transition condition of a ferroelectric crystal, but for LiNbO$_3$ and LiTaO$_3$ both of $E_C$ and $E_{int}$ start to decrease far below the Curie temperature, $T_C$. These properties were studied only at room temperature condition and expected to be dependent on the pining effect due to the defect distribution inside the crystal. Detailed and precise studies on these parameters should be made with some experimental results.

The present work also reported the detection of internal field of the LN crystal using the earlier mentioned Mach-Zehnder interferometer. Though the explored property is not setup dependent, but the results should be verified by using other appropriate interferometers.

Again in this work, two main components contributing internal field of the crystal are reported. Though, the proposed model requires experimental verification, but at this instant it can be claimed that the model is good enough to estimate the values of the components, i.e., spontaneous polarization field and defect state depolarization field. Effect of other associated properties and their contribution to the internal field of the crystal should be examined for complete inside view of the crystal.

Studies of $E_C$ and $E_{int}$ for PPLN are not considered in the thesis. Relevant experiments may be conducted for the study of those parameters. Again enhancement of $r_{13}$ in PPLN if any should be examined. It is expected that the periodic variation of $r_{13}$ in PPLN will have some critical effects on the performance of the devices based on it. This also requires some experimental verification which may be conducted in future.

Finally the tunable polarization phase modulating device is simulated using MATLAB and device performance is estimated. But those results should be cross-checked by other numerical or GUI based simulators. Also the trapezoidal shaped LN crystal block with non-parallel electrode pairs on its slant surfaces should be tested so that the simulated data can be verified.