# Various Fabrication Techniques of Optical Waveguides in Lithium Niobate

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***Abstract* :** Optical waveguide fabrication in lithium niobate is a beautiful art which is reviewed in this article. There are several methods to fabricate optical waveguide in lithium niobate such as Ti in-diffusion, proton exchange, periodically poled lithium niobate waveguide and laser light written like femtosecond laser, Continuous Wave Ultra Violet (CW UV) laser etc. Nano-waveguide in lithium niobate is also discussed in it. The main interest is recently developed fabrication processes such as CW UV written waveguide and it is analyzed by the effective index-based matrix method (EIMM). Most stable techniques such as Ti in-diffusion and proton exchange are discussed as a reference standpoint with modern advancement. As there is growing demand to minimize the size of the optical devices, nano-waveguide is also reviewed in this article.

***IndexTerms* - *Waveguide, CW UV written, femto-second laser written.***

## I. INTRODUCTION

Lithium niobate is a pillar of the photonic industry due to its versatile application and its commercial availability. It is used to fabricate a lot of optical devices like optical mode filter, electro and acousto-optical modulators, switches, diffraction grating, second harmonic generators, wavelength converter and terahertz generator due to its versatile optical and acoustical properties. These capabilities have become possible due to the development of fabrication methods of waveguides and integrated optical interconnection on lithium niobate substrate since the last 7 decades. There are well-established methods such as local doping by Ti in-diffusion and proton exchange. Then there also are recently developed direct writing techniques such as femtosecond laser written and continuous wave UV written. Without lithography, waveguide can be fabricated by direct writing technique. Periodically poled LiNbO3 waveguides also play a vital role to fabricate specific devices like frequency converter and second harmonic generator etc.

In this article, fundamental aspects of lithium niobate waveguide fabrication are reviewed and CW UV written waveguide is analyzed by the effective index-based matrix method. Device applications of this waveguide are mentioned for various techniques in this article. Nano waveguide in lithium niobate was also reviewed in fundamental aspects.

## II. TITANIUM DIFFUSED LITHIUM NIOBATE WAVEGUIDE

Thermal Ti in-diffusion is the best technique to fabricate low loss, high bit rate and low-driver power modulators, deflectors and switches based on $LiNbO_3$ optical waveguide. To fabricate Ti diffused waveguide, at first Ti film near about 10-100 nm thickness is deposited on the surface of the $LiNbO_3$ by electron beam evaporation or sputtering method. Then substrate with thin film layer of Ti on its surface is placed in a furnace nearly at 1000°C in flowing dry Ar and $O_2$ gas through $H_2O$ bubbler chamber [1]. Hence Ti in-diffusion takes place along with $Li_2O$ out-diffusion. Titanium in-diffusion increases the extraordinary as well as ordinary refractive index. Hence both TM and TE mode are guided by Ti diffused waveguide. $Li_2O$ out-diffusion from lithium niobate along with Ti in diffusion is the serious problem because the Li out-diffusion increases the extraordinary refractive index throughout the crystal surface. As a result, polarized light along z axis is not well confined in Ti diffused channel waveguide. There are several methods to suppress the out-diffusion process, such as, immersing $LiNbO_3$ crystal in powders of $Li_2CO_3$ or $LiNbO_3$. To suppress $Li_2O$ out-diffusion completely moistened Ar or $O_2$ gas is passed through the furnace during diffusion [1]. Electron microprobe and X-ray microanalysis showed that Ti concentration profile along depth direction is Gaussian when diffusion time is longer than the time interval required for the metal film to enter the crystal [2]. The refractive index profile is also Gaussian in nature with typical index change, $\Delta n_e=0.022$ and diffusion depth $d_e=2.6\mu m$ [1]. The refractive index change can be precisely controlled by the Ti-film thickness. When the Ti film thickness is less than 200Å, the diffused waveguide supports only the fundamental TE and TM modes. The Ti in-diffusion yields the larger extraordinary index change compare to the ordinary index change.

## III. PROTON EXCHANGE LITHIUM NIOBATE WAVEGUIDE

In this technique $Li^+$ in $LiNbO_3$ is replaced by $H^+$ which is reported first by Jack et al. [3]. Proton exchange takes place when lithium niobate crystal is immersed in the molten benzoic acid in the temperature range 121°C to 250°C. Proton exchange between the crystal and acid depends on the concentration of the acid medium. To fabricate waveguide proton exchange is controlled in the range 65% to 75% because complete replacement of protons between them causes the structural modification and cracks in the substrate [4]. This process produces higher index layer of $H_xLi_{1-x}NbO_3$ [1] near the crystal surface where usually $x>0.5$. To fabricate proton exchange waveguides X-cut and Z-cut $LiNbO_3$ are used. In this technique only the extraordinary refractive index increases by a typical amount of 0.13 and ordinary refractive index decreases by nearly 0.04. So the $LiNbO_3$ waveguide made by this process support only the TM modes in Z-cut crystal.

## IV. PERIODICALLY POLED LITHIUM NIOBATE WAVEGUIDE

Lithium niobate is versatile material due to its electrooptic, acousto-optic, ferroelectric and nonlinear properties. One of the most essential properties is the optical nonlinear property which yields frequency doubling, wavelength conversation, sum-frequency generation, and difference frequency generation devices based on quasi-phase-matched (QPM). A wavelength conversion device based on LiNbO3 is mainly used in a telecommunication system. Periodic poling of ferroelectric single crystal-like LiNbO3 is an useful method to achieve efficient parametric processes by application of QPM [5]. It is a trigonal structure with R3c space group and 3m point group. Lithium and niobium cations are situated on either side of the oxygen octahedral plane [6] which gives rise to spontaneous polarization with an approximate value of 70 μC/cm-2 [6] Therefore, it contributes to ferroelectric property, each unit cell act as a domain and contributes dipole moment. The application of an intense electric field can flip the orientation of the electric dipole. This electric field is the order of kV/mm and is applied for only a few milliseconds, thereafter inverted domains are permanently imprinted into the crystal structure. It is called poled lithium niobate (PLN). Then to produce periodically poled lithium niobate, a periodic electrode structure is incorporated into the wafer. Therefore, the electric field is applied to invert the domain underneath the electrodes. Lithium niobate poled in this way is called periodically poled lithium niobate (PPLN). There are several methods to fabricate PPLN waveguides like Ti in diffusion, proton exchange, ion implantation, zinc diffused [7], electron beam bombardment [8] and presently developed femtosecond laser written process [9]. Periodically polled lithium niobate has wide applications in the photonic industry like parametric oscillator based blue laser source [10], second harmonic generation based on QPM [11], wavelength conversation [12] etc. It is also used to generate narrowband (0.11 THz bandwidth at 1.7 THz) terahertz radiation [13].

## V. LITHIUM NIOBATE WAVEGUIDE IN NANO SCALE

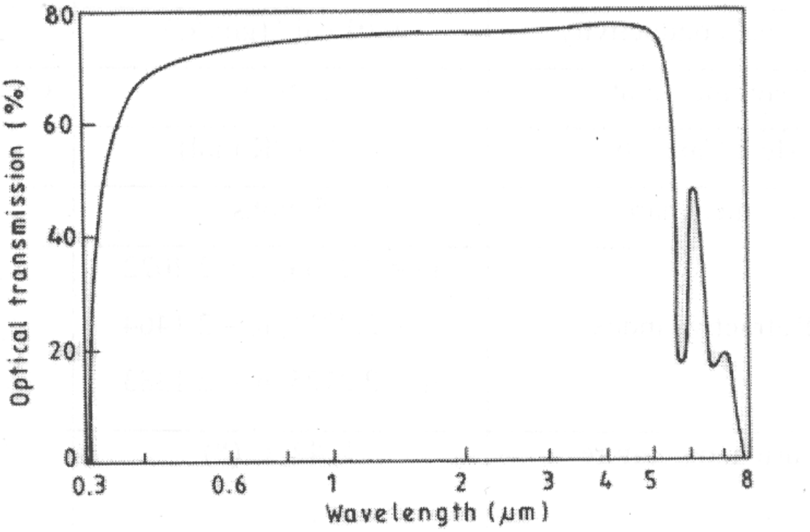
The spatial modulation of the nonlinear optic and electro-optic characteristics of the ferroelectric crystals in the micron-scale domain is used to fabricate various photonic devices like optical switches, modulators and resonators etc. It is essential to reduce the size below 20 nm due to optical wavelength conversion with high efficiency. The creation of the tailored domain structures with nanometer precision needs to understand the domain evaluation mechanism on the nanoscale. From the fundamental concept of domain kinetics, periodically poling technology-enabled to fabricate grating and tailored 1D and 2D structures for photonic application. Some of the research groups [14, 15, 16] showed ferroelectric domain patterns with nanoscale dimensions. There was no experimental evidence of ferroelectric domain structure in nanoscale precision for a long time. But in the present decade, gradual development of ferroelectric domain engineering and application abled to visualize domain size with enough spatial resolution. Consequently, the key role of the "invisible" nanodomain information of the self-assembled nanoscale domain structures has been discovered. [17] Periodically poled lithium niobate (PPLN) waveguides are an efficient tool for wavelength conversion with high precision. Long device lengths and high pump powers are required for conventional PPLN converters due to the limited nonlinear interaction strength. Nanostructured PPLN waveguide is demonstrated with normalized efficiency of 2600%⁄W − cm2 [12] due to the second-harmonic generation of 1.5 μm radiation which is 20 times higher than that in state-of-the-art diffused waveguides. The lithium niobate nanostructure is fabricated by the spin-coating technique [18]. It has been observed by SEM picture that the diameter of grain size is in the range 64 to 167 nm [18]. Optical properties of the nanostructure yield high values of transmission which is about 89 - 96% and energy band gaps were in the range 3.6 eV to 4.2 eV. The estimated value of the refractive index from the transmission spectrum [18] is useful for application in optical waveguides with perfect accuracy. As lithium niobate exhibits electro-optic properties and high second-order nonlinearity, an efficient single-photon detector on thin-film LiNbO3 enable to fabrication of a small-scale integrated quantum photonic chip, which yields single-photon sources, filters, tuneable quantum gates, and detectors [19].

## VI. FEMTOSECOND LASER WRITTEN LITHIUM NIOBATE WAVEGUIDE

Among the various methods for fabricating two dimensional waveguides such as Ti in-diffusion, proton exchange, etc., direct laser written technique is also popular due to its single step process to fabricate channel waveguides. Without photolithography one can fabricate waveguides using this method at any depth of the substrate. At first K. M. Davis et al. [20] in 1996 have demonstrated the refractive index modification in glass by laser writing. Soon it was not restricted to glass but it is extended to $LiNbO_3$, first fabricated by L. Gui et al. [21]. When femtosecond laser pulses are tightly focused into the bulk of a transparent material ($LiNbO_3$) and the material is translated along the beam direction or perpendicular to the beam direction, nonlinear absorption in focal volume will take place which forms channel waveguides due to local modification of refractive index. This channel acts as a waveguide by suitable writing parameters. By femtosecond laser writing, there are three type of waveguides, such as, type-I directly written waveguide [22] , type-II stress induced waveguide [23] and type-III depressed cladding waveguides [24] can be fabricated. It is found that for $LiNbO_3$ crystal femtosecond laser induced refractive index change may be positive or negative in the damage track region depending on the laser intensity [25, 26]. Positive index change occurs only in extraordinary refractive index in which weak damage induced by femtosecond laser pulse with low intensity [25] is predominant. In this case core is formed just along the laser written track due to slight increment of $n_e$. This is type-I waveguide. The type-II waveguides were formed in volumes immediately adjacent to the laser damage tracks supported both polarization perpendicular to the sample surface denoted by TM and parallel to the sample surface referred to as TE. The laser damage tracks are found due to compressive stresses in the surrounding crystalline media that leads to this polarization dependent refractive index change. Recently developed depressed cladding waveguides (type-III) are popular due to its flexible diameter and shape which is feasible to construct fibre waveguides and integrated photonic chip. One group of researchers [24] has fabricated depressed cladding waveguide with diameter of 50 μm and 110 μm supported guidance along both TM and TE polarization at wavelength 0.633 μm, 1.064 μm and 4 μm. They were able to reduce the loss to0.5 dB/cm after thermal annealing.

## VII. CW UV LASER WRITTEN LITHIUM NIOBATE WAVEGUIDE

In spite of emerging advantages of fs laser written, it cannot be used abruptly due to very high cost of laser source. Continuous wave ultraviolet laser writing is another method for fabricating waveguides in congruent lithium niobate. For congruent lithium niobate the transparency region is around 0.4 μm to 5 μm shown in figure-1. When CW UV laser of wavelength less than the left boundary of transmission window is scanning on the $LiNbO_3$ crystal, it gets heated due to nonlinear absorption.



*Optical transmission spectra of a 50 µm-thick $LiNbO_3$ sample.*

Fig.1. Transmission spectra of $LiNbO_3$

There are different processes of absorption due to defects such as internal transition (charge state of impurity ion is unchanged), intervalence transitions (charge state of impurity ion is changed), optical transfer of free and bound small polarons and phonon relaxation. When the UV laser light in the form of energy incident on the crystal, lattice vibration is set up in the crystal and produced quantized energy of lattice vibration (acoustic wave) known as phonon. This energy transfers to the lattice by phonon relaxation. Hence Li diffusion takes place due to absorption of light which increase the extraordinary refractive index in the exposed region. This can be used as an optical waveguide by total internal reflection in the expose region and surrounding acts as a cladding. The schematic diagram of scanning laser beam is shown in figure-2. In this technique crystal properties will remain unchanged. This type of waveguide was first demonstrated by S. Mailis et al [27]. They used frequency doubled $Ar^+$ laser of wavelength 244 nm, 60-600w/cm$^2$ laser intensity, 20-60 mW power, 1.75 µm to 3.25 µm spot size and 0.017 cm/s to 1.33 cm/s scanning speed, to fabricate single as well as multimode waveguides. They showed that it guided the visible and infrared light (0.6328 µm and 1.523 µm) with 0.7-2 dB/cm loss depending on the other writing parameters. This type of waveguide support only TM mode in Z-cut $LiNbO_3$ due to increase of extraordinary refractive index only. The extra ordinary refractive index profile is nearly Gaussian in nature shown in figure-3 [28] and its full width half maxima and maximum refractive index change depends on the writing parameter such as laser power, wavelength, spot size and scanning speed [29] . The figure-3 represents the lateral extraordinary refractive index profile for 305 nm UV laser writing wavelength for 35 mw power and 2.25-micron spot radius with 0.1 mm/s writing speed. To obtain smooth refractive index profile from near field intensity profile, the high spatial frequency noise of the measured amplitude pattern and its 2nd derivative is eliminated by using 3rd order low pass Butterworth filter with 200 mm$^{-1}$ cut-off frequency. The effective index or mode index of the waveguide is determined by adjusting the refractive index change outside the waveguide boundary to zero. The typical value of mode index is 2.206136.

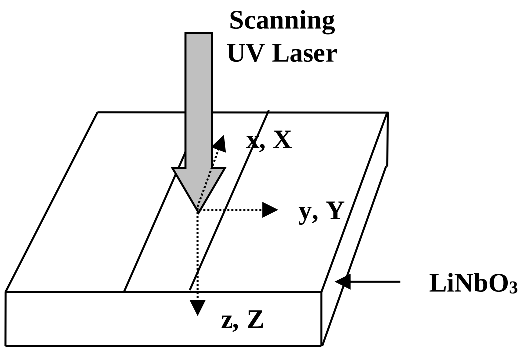


Fig.2. Schematic of the scanning laser beam

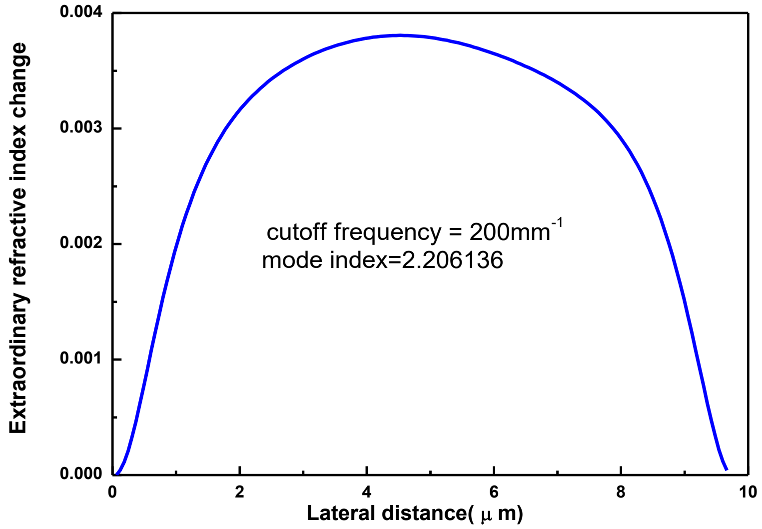


Fig.3. Lateral extraordinary refractive index change profile at 305 nm writing wavelength for 35 mw power, 2.25-micron spot radius, and 0.1 mm/s writing speed,

This CW UV written waveguide is analysed by effective index-based matrix method [30]. The electric field in the guiding layer has been determined in terms of the incident electric field in the 1st layer by simple matrix multiplication, and excitation efficiency (η = $\left|E_g^+ / E_1^-\right|^2$) has been computed for different incident angles. This prism coupling approach indicates the guided mode propagation constants (β) in terms of Lorentzian resonance peaks in η versus β plot. From the peak positions we can get the real part of the propagation constant of the guided modes and its full-width at half maximum (FWHM) (imaginary part) is related to radiation loss of the guided mode of the waveguide [30].The figure-4 represents two no of modes present in the waveguide. From this figure it is obvious that out of two modes flat one is lossy and sharp one is guided mode. Therefore, single mode is guided by this waveguide.

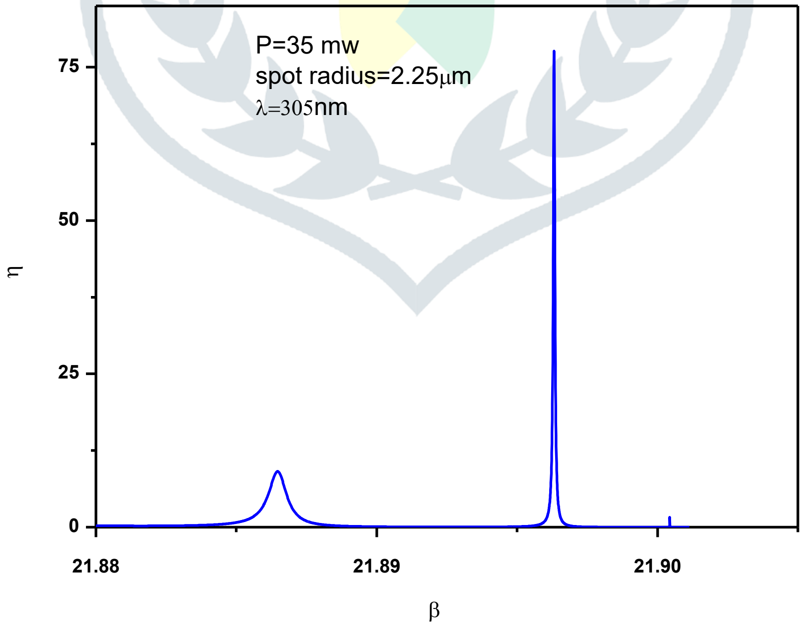


Fig-4. Variation of excitation efficiency as a function of β, for 305 writing wavelength 35 mw power, scan speed 0.1mm/s and 2.25-micron spot radius laser writing wavelengths,

Table 1 Comparison of Fabrication Techniques

| | **Ti diffused** | **Proton Exchange** | **Fs Laser written** | **UV Laser Written** |
|---|---|---|---|---|
| Advantages | **1.** In this technique waveguides are more stable than other methods.<br>**2.** Waveguide supports both TE and TM polarization.<br>**3.** This type of waveguide has lowest reported propagation loss (0.1 dB/cm) . [3], higher thermal, electrical and chemical stabilities.<br>**4.** The fabricated waveguide retains the crystalline property of the substrate. | **1.** In this process waveguide supports only TM modes which can be used as polarizer.<br>**2.** Low loss propagation loss (0.5 dB/cm) has been reported . [3].<br>**3.** The photorefractive damage is low for these waveguides. | **1.** Waveguides can be fabricated at any depth of the substrate.<br>**2.** Process is simple due to direct writing single step process.<br>**3.** Without lithography one can fabricate channel waveguide. | **1.** Process is simple due to direct writing single step process.<br>**2.** Without lithography one can fabricate it.<br>**3.** This process is of lower cost than the fs written waveguides.<br>**4.** Waveguides have reliable stability up to 200°C.<br>**5.** Crystal properties remain unchanged. |
| Disadvantages | **1.** This process is complicated due to its multistep fabrication process.<br>**2.** Clean room environment is required.<br>**3.** It suffers from photorefractive damage even at longer wavelengths, such as, 0.85µm. | 4. Crystal properties gets changed (electro-optic and acousto-optic coefficients are reduced). | **1.** This process is costly due to high price of Ti: Sapphire fs laser source.<br>Waveguide propagation loss is comparatively high. | **1.** At high temperature waveguides are erased.<br>**2.** Waveguides suffer photorefractive damage.<br>Electro-optic coefficient gets reduced at some writing wavelengths due to space charge effects. |

## VIII. CONCLUSION

Lithium niobate plays a key role in modern technology of optical devices due to its versatile properties. Different fabrication methods of the waveguide in LiNbO$_3$ have been discussed in this article. Titanium in-diffusion technique is the most popular and well established but the fabrication process is complicated due to its multistep process. Due to direct writing single-step process, CW UV written waveguide is a simple technique. In this method, crystal properties remain intact and it yields reliable stability up to 200°C. Its fabrication cost is comparably lower than the femtosecond laser written. In this method, the refractive index change profile in the UV laser exposed region at 305 nm writing wavelength for 35 mw power, 2.25-micron spot radius, and 0.1 mm/s writing speed is discussed in this article. CW UV written waveguide in LiNbO$_3$ with above mentioned writing parameters is single mode waveguide which is analysed by EIMM. Now a days lithium niobate waveguide in nanoscale is used in quantum photonic integrated circuits which play an important role in ultra-fast and secure communication.

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