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Optical Waveguides Obtained Via Proton Exchange Technology in $LiNbO_3$ and $LiTaO_3$ – a Short Review

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ABSTRACT

Lithium niobate (LN) and lithium tantalate (LT) are nonlinear, birefringent crystals with an important role in optoelectronics. Beside their excellent optical properties, their most prominent feature is the high electro-optical coefficient (r_{33}»30.5 pm/V) which allows the light field to be easily controlled by electric signals. Proton exchange (PE) is a method of obtaining layers of $LiM_{1-x}H_xO_3$ (M = Nb, Ta) on $LiMO_3$ substrates. The PE layers have a significantly higher extraordinary refractive index (n_e) than the non-protonated crystal; the change is Δn_e = 0.120-0.150 for LN and Δn_e = 0.015-0.020 for LT at wavelength 0.633 μm providing a strong waveguide and polarizing effect. The value of x determines the phase composition of the waveguide layer; this value lies within the concentration limits of the different phases of the PE layers (there are 7 possible phases for LN and 5 for LT).
In the most general case, the PE layers may be considered as phase multilayers, which makes their characterization and optical performance somewhat complicated. Since the emergence of the technology, the main efforts have been directed to finding ways to control the phase composition and methods for characterization of the waveguides with regard to their phase composition.

The present paper aims to analyze and summarize the most significant technological modifications of the method of PE, its advantages and disadvantages. Discussed are the methods of characterization of waveguide layers and the most important waveguide structures of $LiM_{1-x}H_xO_3$ for different modulators used in modern optoelectronic devices (navigation equipment, communication systems, biosensors, etc.).
Keywords: Proton Exchange, Optical Waveguides, $LiNbO_3$, $LiTaO_3$, Integrated Optics

I. INTRODUCTION

Due to the wide application of integrated-optical elements and devices in information technologies, transportation, navigation and systems for control, the development of new materials for integrated optics is the subject of particular attention.

Two of the most widely used ferroelectric materials in integrated optics (IO) are lithium niobate - $LiNbO_3$ (LN) and lithium tantalate - $LiTaO_3$ (LT). This is due to their high electro-optical (EO) coefficients ($r_{33}\approx$30.5 pm/V) and the possibility to change the refractive index by modifying their composition in regions where waveguiding of light is required. These features, combined with excellent optical properties and suitability for industrial production, make them key materials for photonics. The application of LN's properties in various devices such as electro-optical modulators, optical parametric oscillators and photonic crystals requires a specific and sometimes complex obtaining of thin layers, waveguides or substrate integrated waveguides.

Proton exchange is a technology with already well-studied advantages and known prospects for the obtaining of optical waveguides in LN and LT, as well as of a wide range of passive elements and active optoelectronic devices.

The design, optimization and production of IO devices require knowledge of the optical properties of waveguides and their relation to technological parameters. As with a number of other modern IO technologies, studying the physics and the chemistry of PE waveguide layers could play a more important role in general for integrated optics than the conventional efforts at miniaturization.

II. METHODS AND MATERIAL

A. Proton Exchange Technology

Proton exchange is one of the main contemporary technologies for obtaining of optical waveguides in LN and LT. It is an induced - at favorable conditions - diffusion of protons into the surface layer of a crystal substrate, whereby the layer's refractive index becomes higher than that of the substrate. The method is interesting with its simplicity and fastness, combined with the possibility of a strong waveguide effect (a significant change of the refractive index), low diffusion temperature (150-300 ^{o}C, of particular importance for LT) and decreased photorefractive susceptibility. Proton exchange increases the extraordinary refractive index (up to 0.15 for LN and 0.02 for LT at 633 nm) and lowers the ordinary refractive index; therefore, depending on the orientation of the substrate, the propagation of only one polarization is sustained (TE for X- and Y-cut samples or TM for Z-cut samples), i.e. PE waveguides guide only light polarized along the optical axis of the crystal.

Proton exchange is a diffusion process, accompanied by a chemical substitution reaction which takes place in the surface layer (at a depth up to several micrometers) of a crystal substrate when it is placed usually in a melt of an appropriate composition and temperature for the necessary time. Protons of the melt diffuse to the crystal and take the places of lithium ions which leave the substrate.

Going by the scheme:

$$\mathbf{LiMO_3 + xH^+ \Rightarrow Li_{1-x}H_xMO_3 + xLi^+ \ (M=Nb,\ Ta)}$$

PE modifies the surface layer (several μm in depth) by Li-H ion exchange at a relatively low temperature (160÷250 ^{o}C), usually in acidic melts. The diffusion is anisotropic and the value of the diffusion coefficient depends on the substrate crystallographic orientation. This process changes the structure and the composition of the exchanged area. The PE layers show complex phase behavior depending on the hydrogen concentration (the value of x). The value of x indicates the extent of PE and determines the concentration limits of the different phases that could form in the waveguide layer (up to 7 in LN and 5 in LT) [1, 2]. The formation of phases depends on the crystallographic orientation and the rate of Li^+-H^+ substitution which is determined in a complex way by the diffusion parameters. Each phase forms a separate sublayer of submicron thickness, and differs from the others by its structural and optical properties. The phases also have different lattice parameters. At the interface of two phases, a rapid change of the extraordinary refractive index (Δn_e) and the deformation perpendicular to the surface is observed. Within each phase, Δn_e is proportional to x. The phase composition determines the properties and the quality of the obtained waveguides. Strong protonation considerably worsens the electro-optical properties of the waveguide layer [3], causes higher losses and some instability of the parameters over time [4]. However, taking into consideration that other methods exist for the adjustment of x (melt buffering and/or annealing) [5], these drawbacks can be corrected or even turned into an advantage for the possibility to adjust (modify) the electro-optical properties. These can also be avoided by using the methods for optimization of proton concentration [6].

The advantages and disadvantages of PE technology could be summarized as:

<u>*Advantages*</u>: a fast and simple waveguide formation procedure; non-toxic and inexpensive method; possibility of thermal tuning of the refractive index; a strong waveguide and polarizing effect; an increased photorefractive resistivity; flexibility and compatibility with other technologies; a large variety of optimization steps.

<u>*Disadvantages*</u>: multiphase composition of the waveguide layer; deterioration of electro-optical properties in strongly protonated layers; anisotropy of diffusion; some instability over time.

Thus, despite the initial excitement over its undisputed advantages, the technology turned out to have serious problems with the quality of the obtained waveguides, owing mainly to the simultaneous formation of different phases in the diffusion-modified layers. These problems have been gradually solved. Different modifications of the method have been used to restore the crystal lattice disorder which is caused by proton exchange, with efforts to optimize the process in order to ensure high EO coefficients and to improve the optical properties by reducing optical losses. Both need control of the phase composition and thorough study on the identification and the properties of each phase.

The main technological versions and optimization steps of the obtaining of optical waveguides via proton exchange in LN and LT include:

PE – proton exchange [7] – a one-step process which takes place when LN or LT substrate is immersed in an appropriate proton source, usually acidic melt (most popular acids being benzoic, pyrophosphoric, cinnamic, oleic, palmitic, sulfuric, adipic). PE waveguides usually have step-like optical profile and nearly vanished EO-coefficients [8].

DPE – deep proton exchange [9] – proton exchange in pyrophosphoric acid for achieving a large change of the refractive index (Δn_e=0.15). Optical profile is almost step-like, better approximated by two rectangular steps (or truncated parabolic profile shape) [10].

ADPE – DPE with subsequent long time and high temperature annealing (two-step process) applied for obtaining deeper (over 20 μm thick) waveguides. High-quality planar waveguides suitable for EO spatial light modulators for 355 nm UV wavelength have been obtained this way [9].

VPE – proton exchange in vapors (one-step process) [11, 12]. VPE allows highly homogeneous monophase waveguides with very low propagation losses to be obtained. By using this low-temperature method with an appropriate proton source, high quality optical waveguides have been obtained by proton exchange and reverse diffusion within a single chemical reaction [11].

SPE – soft proton exchange in buffered melts (i.e. lithium benzoate added to the benzoic acid) - one-step process. It allows the formation of monophase waveguides (α) with preserved EO properties [5] and better quality than those obtained by APE.

HTPE – high temperature proton exchange (one-step process). Stearic acid which has a higher boiling point and lower vapor pressure has been used as a proton source [13]. High quality α-phase waveguides (similar to these made by SPE) have been obtained directly (with no phase transitions) for a short time.

APE – proton exchange with subsequent annealing (two-step process) for obtaining monophase (α) waveguides with restored EO properties after phase transitions from phases of high values of x to the phase with lower value of x [6].

PEAPE – two-step proton exchange with intermittent annealing (three-step process) [14, 15]. This method is appropriate for obtaining deep waveguides with high refractive index change in Y-cut LN.

RPE – reverse proton exchange (two-step process) [16] for obtaining buried waveguides with different properties depending on the phase composition of PE-waveguide. Takes place when PE-waveguide is immersed in eutectic mixture of $LiNO_3$, KNO_3 and $NaNO_3$. The method is used for obtaining minimal loss when connecting the waveguide to optical fiber.

RAPE – reverse proton exchange in APE waveguides (three-step process) [17]. The method is used to bury the waveguide under the crystal surface, increasing that way the circular symmetry of the optical mode.

Some opportunities for controlling the optical profile shape by using appropriate technology modification of PE are shown in Fig. 1.

A predetermined phase composition that meets particular requirements – a high refractive index, high electro-optical coefficients, low optical losses, stable parameters over time, decreased photorefractive susceptibility, or combinations thereof – can be achieved with an appropriate selection of PE conditions.

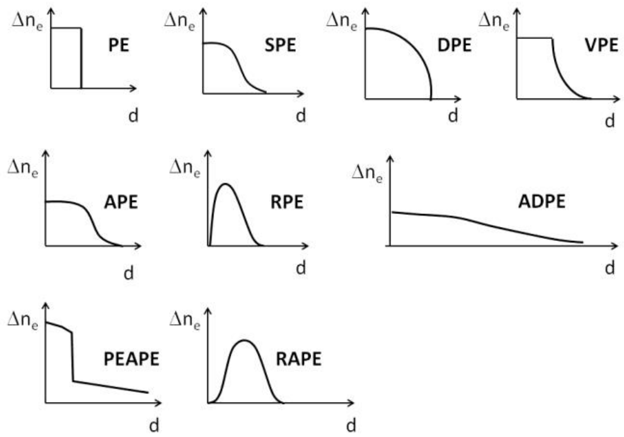

Figure 1. Qualitative representation of optical profiles of waveguide layers obtained by using different modifications of PE

Having a great flexibility, PE is easily combined with other technologies:

<u>Titanium in-diffusion</u> combined with PE (TIPE) [18]. The method is of interest mainly due to the quite wide

range in which the refractive index changes and the shape of the optical profile may be modified.

Ion implantation of PE waveguides [19] for reducing losses and photorefractive effect as well as for designing devices with complicated refractive index profiles.

Ion implantation, metal in-diffusion and PE [20] for obtaining optically isolated waveguides with high photorefractive susceptibility for various recording applications.

Plasma etching of PE waveguides [21] allowing ridge waveguides of very low propagation losses to be fabricated.

Rare earth doping of PE waveguide layers [22] for obtaining waveguide solid state lasers capable to be integrated monolithically with other elements on a common substrate.

Combination of PE and nanotechnology [23] by photodeposition of silver or gold nanoparticles on a lithium niobate substrate patterned periodically with PE stripes. This technology is prospective for applications in cellular biosensing.

Photonic crystals on PE waveguides [24] obtained by engraving of photonic crystal structure (air holes for example) on APE waveguide.

Combining of PE and LNOI (LN on insulator) for building PIC (photonic integrated circuit) on LNOI by PE [25, 26]. PE waveguides in LNOI can have very low propagation losses. It could be a way for obtaining advanced photonic devices in future.

B. Characterization of the Waveguide Layers

The development of technologies inspires the search for methods for characterization of the materials used in contemporary IO elements and devices. Since the conditions at which PE waveguides are obtained - type and composition of the proton source, temperature and duration of diffusion, additional procedures, stoichiometry and orientation of the substrate - affect the phase formation, the establishment of this relationship contributes to a deeper understanding of the processes behind the features of PE layers. The control of the phase composition of proton-exchanged layers is the subject of extensive studies, and a number of methods and combinations thereof have been used for the characterization of the layers.

For the analysis of the composition and the structure of PE layers, various methods have been used, such as SIMS (Secondary Ion Mass Spectrometry) for obtaining concentration profile of protons [27], RBS (Rutherford Back Scattering) [28], IR (Infrared) [29, 30] and Raman [31, 32] spectroscopy, XPS (X-ray Photoelectron Spectroscopy) for the analysis of the first few atomic layers below the waveguide/air interface in PE waveguides in LN [33, 34], X-ray diffraction for finding out the crystalline phase change [25, 35], measurement of the tensions in the layer [36]. A theoretical model has been created for the mechanism of the refractive index change in PE waveguides which is confirmed by experimental results [37].

The main questions when modifying of LN and LT crystals takes place are: how the doping elements get into the lattice (doping mechanism) and how they change the structural – and hence the optical – properties of the crystal.

The answers to these questions can come from the combination of different methods for optical and structural characterization of these essentially new materials, with an emphasis on the search for non-destructive methods: mode spectroscopy, IR absorption and reflection spectroscopy, Raman spectroscopy, atomic absorption spectroscopy in the visible and near ultraviolet (UV-VIS), LFM-method (line-focus-beam acoustic microscopy), etc.

Mode spectroscopy

Optical methods for studying waveguides enable the determination of the refractive index of the waveguide layer, the field distribution in it, the electro-optical and thermo-optical coefficients, the losses, etc. A crucial point in these measurements is the obtaining of the mode spectrum (the set of effective mode indices) of the waveguide by a known method (usually prism coupling method [38]). The processing of the obtained values with a numerical method gives the distribution of the refractive index toward the depth (optical profile of the waveguide).

Numerical methods

A common approach to restore the optical profile is the IWKB-method (Inverse Wentzel–Kramers–Brillouin) [39] which precisely enough describes the function of distribution of the refractive index by the depth of the layer, i. e. determines the waveguide parameters – depth (thickness), maximal value of the refractive index and profile shape. For modeling of the optical field distribution, Fourier transformation-based methods could be used.

LFB-method

The line-focus-beam acoustic microscopy [40] is based on the change in acoustic properties caused by PE and APE in LN and has been used for obtaining of the optical profile of the waveguide layer. Being a non-destructive and non-contacting method, LFB acoustic microscopy provides also a capability of higher measurement accuracy than that of more popular methods like SIMS and the prism coupler.

Vibration spectroscopy

When a proton diffuses in the crystal lattice of LN or LT and takes the place of a lithium ion during PE or crystal growth, it forms a hydroxyl (OH) group with the respective oxygen ion, thus influencing the vibrations of the crystal lattice. Precisely the substitution of lithium ions with hydrogen ions and the formation of OH groups in the lattice is what causes the strong waveguide effect of the diffused layers – through a change in the spontaneous polarization, the molecular refraction and the introduction of elastic deformation. Since PE involves the formation of hydroxyl groups, infrared and Raman spectroscopy are powerful tools for characterization of waveguide layers formed via proton exchange. The physical processes behind the phonons active in vibration spectra are also the ones that determine the electro-optical and non-linear dielectric properties of materials. Proton exchange causes new phonons to appear in the vibration spectra of the lattice of LN and LT. This means a change in the parameters of the chemical bond (length and orientation) as well as the formation of new chemical bonds. Thus, vibration spectra provide information which allows the characterization of PE layers regarding phase transitions, deformations of the crystal lattice and change of the positions of ions in it. Vibration spectroscopy is one of the most informative methods in physics and chemistry.

Infrared absorption spectroscopy provides information for structural changes due to PE through the position, polarization and relative intensities of the main bands in the spectrum (polarized one peaked at about 3500 cm^{-1}, and a large unpolarized band centered at about 3800 cm^{-1}) [29, 30, 41]. It could be used for monitoring of PE process [42, 43], for phase composition analysis [10, 11, 44, 45] and dynamics of phase formation [12, 46], evaluation of the waveguide parameters [47 - 49], technology adjustment [50, 51], studying of proton redistribution during annealing [52, 53], etc. The formation of long-living metastable phases in PELN and PELT waveguides could be detected by following the evolution of the refractive index change and the parameters of the OH bands in IR absorption [54, 55].

The use of reflection spectroscopy has a number of advantages due to the small photometric depth of the surface layer at large angles of incidence (above 60 degrees). Sometimes it is more informative than absorption spectroscopy, especially for multilayer structures such as multiphase PE layers, because each phase has its own reflection spectrum [56], and the determination of the type of the surface phase often allows the entire layer’s phase composition to be found, especially in combination with other characterization methods.

The influence of PE on Raman spectra concerns both vibration modes A1(TO) and E(LO). Raman spectroscopy-based method (waveguide Raman spectroscopy) has been introduced and successfully used for waveguide characterization [57, 58]. These spectra allow study of structural changes in PE layer [57, 59, 60], evaluation of the proton concentration [61], phase identification [59, 62], etc.

The comparative analysis shows that there are significant differences between the main parameters of Raman and infrared spectra of the different phases: such parameters as frequency, polarization, intensity and number of spectral bands depend on the phase composition of waveguides [63 - 65]. The information obtained from these spectra allows the characterization of PE layers in terms of the degree of order/disorder of the crystal lattice, amorphization, mobility of protons, stability of waveguide parameters, EO properties, thickness of the waveguide layer and the phase sublayers, lattice deformation, aging, etc.

A thorough review of the results on vibration spectroscopy of PELN and PELT has been made in [66].

Near UV-VIS absorption spectroscopy

Absorption spectroscopy in the visible and near ultraviolet range has been used to study the EO properties of PELN waveguides, since the shift of the absorption edge (the change in bandgap width) reflects the change of the spontaneous polarization and thus the electro-optical coefficients [67, 68]. Proton exchange leads to a decrease in the spontaneous polarization, different among the phases of PELN [57]. By using absorption spectroscopy, a quantitative evaluation of the change in the EO coefficients of the different phases [68]is possible compared to the virgin crystal's ones. Such data has not been published for LT so far.

Other methods for measuring the EO coefficients in the PE waveguides have also been developed [69] since this is an important part of the characterization of waveguides.

Study on the photorefractive properties and the losses in PE waveguides in LN

The main mechanism of loss depending on the orientation of substrates has been determined [70]: surface scattering (for Z-cut samples) and mode transformation (for Y-cut samples).

Combinations of methods

A combination of methods can be used for the identification of phases: optical, spectral, etc., where the matching of results supports the sole use of a particular method for that purpose. The phase composition of the waveguide layers in PELN and PELT as well as the distribution of different phases by depth have been analyzed by combined spectroscopic studies [34, 44, 11, 10, 64, 36]. A correlation between the methods for studying these layers has been sought.

III. RESULT AND DISCUSSION

Applications in Photonics, Optoelectronics and Sensors

Proton exchange is mainly used for the obtaining of high-quality waveguides for different modulators [71], switches [72], multiplexers and Y-splitters [73] as main elements of modern optoelectronic devices for navigation equipment, communication systems, in a number of sensors (detectors of molecules in fluids, biosensors, contamination detectors, temperature sensors [74], etc.) and many devices for interferometric control. It is favored for applications where visible light is required and the restriction to the linear polarization is not an obstacle. The fact that only the extraordinary refractive index changes can be used to control polarization [75] and to create fundamentally new modulators [76]. Proton-exchanged LN and LT waveguide devices are favored over Ti-diffused LN ones in cases where high optical powers are to be transmitted and/or single polarization operation is desired. APE and RPE waveguides are mostly used for applications in integrated and quantum optics for obtaining modern devices, such as photonic crystals [24], second harmonic generation devices [77, 78] and devices with more complicated architecture [79, 80] .

Some examples illustrating the use of the PE technology in modern optoelectronics are given below.

1. Phase modulator

Phase modulation originates from the EO properties of LN (LT) when the refractive index changes, causing phase variation. This is brought about by applying electric signal to the waveguide via electrodes deposited on the crystal, usually by photolitography. Principle schemes of three modifications of the phase modulator are shown in Fig.2. The phase modulator consists of a stripe waveguide (2) formed in the crystal substrate (1) and electrode configuration (3) (Fig. 2 a and b).

The device can be used as a phase shifter in different waveguide structures. Its main advantages are high speed of operation and small drive power. When electric field is applied via electrodes, a phase change ($\Delta\varphi$) takes place in the light travelling along the electrodes (longitude L). The phase shifting is expressed by

$$\Delta\varphi = k\Delta nL$$

where k is a wave factor $k=2\pi/\lambda$ (λ is the light wavelength in vacuum and Δn is the refractive index change). For distance d between the electrodes and applied voltage U, the phase shifting is given by

$$\Delta\varphi = -\pi\,(n_{eff})^3\, r_{33}\, J_m UL/\lambda d$$

where J_m is the factor of overlapping between optical field of the propagating mode and the applied electrical field.

As a phase shifter, this modulator is an important component in many EO lightguiding structures, due to its simplicity, efficiency and high speed, e.g., in different interferometric systems for phase deviation or compensation in the two arms. The phase shifter in such systems allows much less stringent restrictions on the structural parameters than in the constructions fabricated without a phase balanced element. Many optical switches (directional couplers) utilize EO phase tuning to achieve operations at very low losses. The EO phase shifters are very popular in fiber optic sensor technology because of the advantage that the phase measurements are not influenced by amplitude variations.

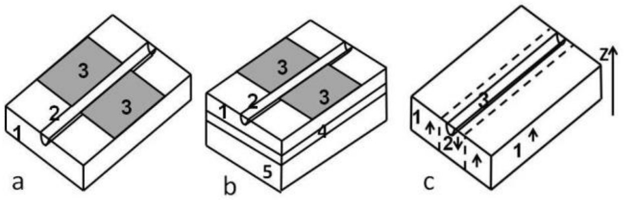

Figure 2. A principle scheme of a phase shifter (a); PE LNOI phase modulator (b): 1 – substrate, 2 – PE stripe waveguide, 3- electrodes, 4 – SiO_2 layer; schematic representation of a DI PE element for electric field sensor (c): 1, 2 – DI regions, 3 – PE stripe

An example of the application of combined advanced technologies for obtaining a phase modulator is discussed in [25, 26]. A proton-exchanged stripe waveguide (near cut-off) is formed in the LNOI film (Fig. 2b). The lithium niobate on insulator technology is attractive due to the high optical confinement and enhanced lightguiding capability. The structure has a low driving voltage and could be used in high sensitivity sensors.

Another example of a device based on DI PELN is an all-optical electric field sensor proposed in [81, 82]. A proton-exchanged stripe waveguide (3) near cut-off is fabricated in the central DI region (2) of a Z-cut LN substrate (Fig. 2c). When external electric field is applied parallel to the z-axis of the substrate, the refractive index in the DI region increases/decreases but that in the surrounding domains (1) decreases/increases causing mismatch of the guided modes between active and passive regions and thus produces a loss after a sufficient propagation length. Electric field intensities up to 20 MV/m could be measured this way (below the value of the coercive field of LN along the Z-axis E_c = 21.4 MV/m). A three-dimensional measurement of the field intensity could be easily achieved by orthogonal arrangement of three sensors.

2. Mach-Zehnder (MZM) modulator/interferometer

The Mach-Zehnder interferometer structure is the most frequently used type of EO amplitude modulator and is a basic structure in a variety of IO devices. As in the classical bulk configuration of the MZ interferometer, light splits into two optical paths with no possibility of interaction. The key point in the interferometric modulators working on the Mach-Zehnder principle from classic optics consists of (in their integrated-optical version) two Y-junctions which perform the function of beam splitting and coupling into the stripe waveguides which represent the interferometer's channels (Fig. 3a). The refractive index (i.e. the propagation velocity) in each arm could be modified by applying electric field, changing that way the interferometric pattern at the output. The performance of the device strongly depends on the electrode configuration and waveguide architecture.

An efficient MZM in PELN with specially designed quasi-smooth (tapered) Y-branches has been demonstrated in [83]. A special feature of this kind of modulator is the utilization of monomode waveguides, which permits great modulation depth (88%) for PELN to be reached under comparatively low drive voltages.

A fundamentally new, technologically simpler broadband IO modulator (Fig.3b) has been designed: a single-stripe MZM based on the polarizing action of PELN [76]. The waveguide structure is formed in the LN X-cut wafer (1) and consists of a single-mode channel waveguide (2) whose central region (4) is deeper (produced via double PE), has a higher value of refractive index change and supports two modes. This new construction uses the simplest electrode configuration consisting of two parallel driving electrodes (3). Upon reaching region (4), light divides into two orthogonal modes which propagate independently, and after voltage is applied to the electrodes, the phase for each optical mode changes in a different way because the overlapping integrals for electric and optic fields are different for each mode. Reaching the end of the two-mode region, these two modes interfere and the light continues propagating as a single mode whose intensity depends on the phase difference between modes in the central region, i.e. on the voltage applied. This way, amplitude modulation of the light takes place with the depth of modulation being proportional to the driving voltage. The simple construction, together with the advantages of PE technology, lead in this case to minimization of radiation losses caused by splitting as well as to the simplification of the procedure of preparation of driving electrodes. The experimental investigations of the intensity modulation and high-frequency response showed low optical losses for large frequency bandwidth. The new construction together with the technology used allows easier control of the geometry and the composition of waveguiding regions as well as further device minimization (long Y-splitter's length being avoided). Further optimization is possible.

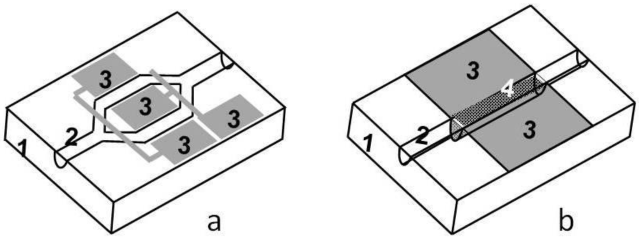

Figure 3. Principle schemes of MZM: (a) - classical configuration; (b) – single-stripe MZM; 1 – substrate, 2-PE-stripe (supports single mode), 3 – electrodes, 4 – deeper stripe (supports 2 modes)

3. Quantum optics

Waveguide structures in PPLN (periodically poled LN) are commonly used in integrated quantum optics applications since the efficiency of the nonlinear interactions is enhanced that way. A parametric down- and up-conversion have been obtained in PELN [84] in single photon emitters at a telecom wavelength. The IO wavelength convertors with the advantage of polarization control provided by the PE technology could be integrated for example in quantum relay chips or other more complicated future quantum systems.

The PE technology has left its laboratory research level and reaches the manufacturing stage. Integrating single components and structures on a common chip allows a great variety of IO devices to be obtained. Some of the commercially available mono-blocks (IOCs) containing PE modulators are described in Table 1.

Table I. Examples of commercially available IOCs

Supplier	Device model	Technolog y	Application
ixBlue (Photline)	Y-JPX_LN series (Polarizing Y-junction Phase Modulator)	PE based waveguide	FOGs (Sagnac interferometer based sensors)
Broadray Techno-logy	LN Modulator (MZ and Electro-absorption modulator (EAM))	APE	Fiber optic communication systems
Photline Technolo-gies	NIR-MPX800-series (Phase modulators, 800 nm band)	PE based waveguide	Interferometric sensors, quantum optics, frequency shifting
	NIR-LN series (Intensity and phase modulators for Near Infrared region)	PE based waveguide	Pulse shaping, pulse picking, lidar-based sensing
Optolink	MIOC	HTPE	IO components on LN, FOGs, navigation systems

IV. CONCLUSION

Due to the importance of PELN and PELT for integrated optics, a variety of methods have been developed for fabrication of waveguides in these materials but none of them is universally applicable. Very promising appear to be the combined methods, and the efforts are aimed at the introduction of some technological modifications of the existing methods. Further improvements are sought as well in terms of new methods for characterization and accumulation of fundamental knowledge on the material science of these waveguide materials. The combination of structural and optical methods for studying the waveguides obtained by diffusion is a powerful approach to understanding the reasons behind their properties, as well as for characterization of the waveguides themselves.

The systematic and thorough data on the dependence of phase composition and thickness of phase sublayers on technological parameters is needed for a better understanding of the processes of phase formation during PE in the discussed electro-optical crystals and for a controllable modification of their properties used for obtaining of optical waveguides and waveguide structures by proton exchange, with regard to their future application. Since the main difficulty in the application of IO devices is the input and output coupling, future developments will tend to attract new technologies like photonic crystal technologies and nanotechnologies for solving that problem. The achievement of higher data processing speeds and an increased level of integration are also among the current objectives of the development of PELN and PELT based optoelectronics.

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