Summary of Habilitation Thesis

Development of nonlinear integrated optical devices for quantum communication

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Summary

Since the antiquity, the control of the light propagation path is a fascinating thing. After first experiment of light guiding in a water jet (reported in 1841 by J.D. Colladon), the advent of cleanroom technologies in the early 1940's and the advances in fabrication technologies in the 1950's and 1960's have progressively opened-up pathways toward nowadays Integrated Optics (IO), offering the possibility of light guiding in small devices while controlling its flux. In the development of this fascinating research field, the lithium niobate $LiNbO_3$ single crystal (LN) platform always played a noteworthy role. The success of this ferroelectric material is due to its excellent nonlinear optical (NLO) and electro-optical (EO) properties while benefiting from the fabrication maturity based on Czochralski process, so that numerous suppliers can be found around the world. Moreover, its physical properties are compatible with cleanroom technological steps, heat treatments, dicing-polishing and packaging processes respectively. For example, its high Curie temperature (~1200°C) allows preserving the NLO and EO properties even during annealing steps, which is not the case for other materials. Additionally, LN single crystal offers a wide transparency range (340nm - 4.6µm) which opens the way to applications from visible to mid-infrared. The very low absorption loss (<0.15%/cm @ 1.06µm) and its weak optical dispersion in the transparency band also contribute to its success. On top of these, periodically-poled lithium niobate substrates (PPLN) linking the ferroelectric domain reversal and the second-order nonlinear effect, played a key role to the development of numerous nonlinear applications and devices. As a result, LN/PPLN crystals are exploited in various applications and devices such as laser frequency doublers, wideband tunable light sources, light amplification, quasi-phase-matched frequency converters, Q-switches for lasers, information and image storage, surface acoustic wave, electromagnetic sensors, precision gyroscopes, optical switches, optical modulators for long-haul high-bit-rate, multiplexors, entangled photon-pair sources for quantum optics applications and quantum communications and also for many others optical processing devices. For each of these applications, the challenge is to provide integrated configurations that are easy to implement, with *low propagation losses*, *high efficiency*, *stability*, robustness and, if possible, *compactness* and *low power* consumption.

In this context, this habilitation thesis presents some of the most important scientific results published by dr. Sorin Tascu since obtaining the title of doctor in Physics, based on the lithium niobate $LiNbO_3$ single crystal (LN) platform, in an attempt to address above-mentioned requirements.

The thesis is divided in three chapters. The ***first chapter*** outline the main concepts and techniques used through the presented studies such as Quasi-Phase Matching (QPM), e-field" poling used for the fabrication of the periodically inverted ferroelectric domains, the most usual techniques for waveguides fabrication in LN and techniques for optical waveguides characterization.

The ***second chapter*** consists of presenting some of the author's contributions to the development of integrated nonlinear optics and integrated optical devices. These devices fulfill a certain optical function such as "optical funnel" for example. In this case we are talking about segmented channel waveguides and tapers in order to realize the best tradeoff between the propagation losses and the coupling efficiency. Also, the continuous advance of

optical telecommunication systems requires characterization techniques to measure the most important parameters that determine device or component performances. In this way an all-in-one experimental setup for executing accurate measurements on propagation losses, effective group index and mode size of integrated optical devices and optical fibers is presented. The possibility to use a single setup, instead of three separate ones, enables faster measurements, improvements in terms of reproducibility and precision, and reduction of systematic errors.

Also, the problems that can occur during the fabrication of periodically inverted ferroelectric domains such as abnormal domain kinetics or self-organized formation of quasi-regular nanodomain patterns are tackled in two presented studies. These studies are very important both for understanding the domain structure evolution with high spatial resolution, and for creation of the nanoscale domain structures with controlled geometry, which is still problem challenging domain engineering in ferroelectrics.

As it was said above, almost for all nonlinear optical applications, the challenge is to provide integrated configurations that are easy to implement, with low propagation losses, high efficiency, stability, robustness and, if possible, compactness and low power consumption. The primary element of almost all optical integrated applications and devices, essential to meet these requirements, is the so-called optical waveguide (OWg). Even if for decades the fabrication of optical waveguides has been the subject of tremendous research studies, the actual techniques remains insufficient to meet the demands of modern integrated photonics – low propagation losses, high index contrast for tight confinement, high nonlinear efficiency, stability and robustness, small device footprints, low power consumption, etc. In this context, we have proposed and experimentally validated for the first time, as far as we know, the fact that diminishing as much as possible the water content of the acidic bath used in proton exchange leads to *new fabrication techniques* that was name *High Vacuum Proton Exchange (HiVacPE)* and *High Vacuum Vapor-phase Proton Exchange (HiVac-VPE)* respectively. These new techniques are very promising offering a solution to straightforwardly address all the demands of modern integrated photonics. The role of the high vacuum in Proton Exchange techniques was very well described in a study in which it was experimentally validated the excellent control and reproducibility of the index contrast and index profile of optical waveguides.

The technological efforts concerning the fabrication of OWgs in LN for NLO applications are oriented toward the lowest propagation losses, while seeking the highest refractive index contrast without degrading the nonlinear efficiency and of course, a compatibility with PPLN substrates. Nonetheless, knowing the index contrast (IC) at telecom wavelengths is not straightforward. For tackling this the author and co-workers proposed and tested a new hybrid (experimental and numerical) method to determine the IC at 1310 nm and 1550 nm for typical low-IC lithium niobate waveguides by fitting the experimental in-depth optical mode profiles with the Finite Element Method simulated ones. This original and very useful new method can be used to all surface graded-index waveguides fabricated in low IC range for which the propagation is single-mode and makes no longer possible to use the M-lines technique that requires a multi-mode propagation.

Waveguides fabricated on periodically poled lithium niobate (PPLN) substrates are already one of the most widely used devices for many nonlinear optical applications based on the quasi-phase matching (QPM) process. An efficient nonlinear process such as second harmonic generation (SHG), spontaneous parametric down conversion (SPDC) or different variants of optical frequency conversion, requires, among others, waveguide fabrication techniques that allow preserving both the nonlinear coefficient and the domains orientation of the substrate. The α-phase waveguides directly produced in one fabrication step only are well known for preserving both the excellent nonlinear properties and the ferroelectric domains orientation of lithium niobate substrates. However, by using the piezoresponse force microscopy (PFM), dr. Sorin Tascu and co-workers show that there is a ferroelectric dipoles switching induced by the fabrication process of α-phase waveguides on Z-cut congruent lithium niobate (CLN) substrates. The obtained results show that the proton exchange process induces a spontaneous polarization reversal and a reduction in the piezoelectric coefficient d_{33}.

Another study presented in this chapter is consecrated to the results obtained on the investigation of a broadband beam splitter that provides two output beams in phase independently of the wavelength dispersions. This integrated photonic chip was implemented by using telecom waveguides fabricated on lithium niobate by using *our HiVacPE technique*.

The end of this chapter is devoted to showing how PPLN structures, beam splitters, couplers and electro-modulators have been harnessed simultaneously on a monolithic LN chip for generating heralded configurable, two-photon states. It gathers five different integrated elements to enable successively photon pair production, wavelength demultiplexing of the pairs and two-photon interference on a tunable coupler. Each optical function of the chip shows high-level performances in terms of losses and efficiency. The monolithic configuration ensures high stability, low power consumption, and low operating voltage. This study is an authentic example of how the integrated nonlinear optics is at the service of quantum communications.

The ***last chapter*** is dedicated to the most important achievements, in the framework of the research activities, that marked the professional trajectory of dr. Sorin TASCU since 2003, as well as the perspectives of career development, with emphasis on some new devices based on ***counter-propagating*** type-0 spontaneous parametric down-conversion (SPDC) in Periodically Poled Lithium Niobate Waveguides (PPLN/Ws) where signal and idler propagate collinear but in opposite directions.