Theme Issue on
Photonics with Thin Film Lithium Niobate
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Thin film lithium niobate (TFLN) has the potential to revolutionize photonic integrated circuit (PIC) technology, due to its ability to combine low optical loss, tight optical confinement, and active optical functions. In particular, the readily available electro-optic effect and 2nd order nonlinear effect afford more unique functionalities to TFLN compared to other, more mature, PIC materials, including silicon (Si), silicon nitride (SiN), silicon dioxide (SiO2), and indium phosphide (InP), while the refractive index contrast between TFLN waveguide and typical cladding materials such as SiO2 is sufficiently large to support relatively tight bending, leading to small component sizes.

Over the past few years, research on TFLN-based PICs has blossomed. TFLN electro-optic modulators in particular have benefited hugely from the natural advantage of its electro-optic effect and are now being commercialized, with several start-up companies worldwide already publicizing small-size, low-drive voltage prototypes. The research attention is now moving on to other, more challenging aspects of TFLN technology. These include on-chip laser sources and devices based on its nonlinear optical effects. In addition to the classical optical information applications including communications and sensing, TFLN PICs exploiting high quality on-chip laser sources and nonlinear devices are also promising candidates for integrated quantum photonics.

To spotlight advances in TFLN technology, we present a special collection published across Advanced Photonics and its sister journal Advanced Photonics Nexus. This collection includes two review articles and two original research articles. We feature a wide-ranging review article which we hope may help those new to the field to attain a comprehensive overview of photonics based on TFLN (https://doi.org/10.1117/1.AP.4.3.034001). The two research articles, one combining the generation of very narrow linewidth laser emission with tunability provided by the electro-optic effect (https://doi.org/10.1117/1.AP.4.3.035001) and the other on the generation of optical frequency combs exploiting nonlinear effects (https://doi.org/10.1117/1.AP.4.3.035003), represent distinctive progress in light sources based on TFLN.

We hope our readers enjoy these articles and find them useful. For greater insight and enrichment, we also offer an interview with TFLN innovator and pioneer Marko Lončar (https://doi.org/10.1117/1.AP.4.3.036003) and a perspective by Zhenda Xie and Shining Zhu (https://doi.org/10.1117/1.AP.4.3.030502).
**LiNbO₃ crystals: from bulk to film**

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Lithium niobate (LiNbO₃) is a ferroelectric crystal that features superior electro-optical, nonlinearity, and acoustic optical performance, and it is thus promising in various applications. Recent breakthroughs in the fabrication of thin film lithium niobate (TFLN) combine the unique features of the bulk crystal onto an integrated platform with submicron light confinement, driving new records in reducing the energy consumption for high-speed electro-optic modulation. The footprint for acoustic wave filtering, and the power requirement for efficient optical frequency conversion. TFLN is mainly fabricated using the smart cut technique. This was developed for silicon-on-insulator materials and is known for its capability for superfast high-quality waveguide growth. Revolutionary performances are expected by moving from bulk to TFLN, e.g., in the form of lithium niobate-on-insulator (LNOI) optical communication and wireless communication devices, and this trend may also lead to fundamental breakthroughs in optical communication, microwave photonics, and quantum optics, as discussed below.

Lithium-niobate-based electro-optical modulators (EOMs) have been the choice of long-distance optical communication for decades. However, their relatively large size and high cost make them only applicable for the backbone connections. LNOI EOM, however, is capable of the same high modulation speed and CMOS-compatible low voltage in a much smaller package. Power consumption as low as 0.37 fJ/bit has been demonstrated to make the LNOI EOM not only a direct alternate to the bulk lithium niobate EOM, but also a promising candidate for optical links between data centers and local area networks at rates of 200 Gbps and above, therefore driving the next generation optical communication technologies. Therefore, after more than 50 years of development, the laser sources and amplifiers have been demonstrated using rare-earth-ion-doped LNOI chips, which may enable a fully integrated optical communication module. Hybridization with laser-active materials or silicon is another attractive approach towards full integration that adds a light source or driving electronics capabilities. Such hybrid integration can also enable simultaneous signal processing and memory operations, leading towards a new fabricable architecture.

Optical communication can change the power-hungry nature of modern electronic communication technology, which is both classical and quantum approaches. For example, demonstration of speed acceleration of transistors and quantum supremacy. In either approach, larger scale photonic circuits provide optimal ways to manage the 3D waveguide architecture. Hybrid integration with laser-active materials or silicon is another attractive approach towards full integration that adds a light source or driving electronics' capabilities. Such hybrid integration can also enable simultaneous signal processing and memory operations, leading towards new fabricable architectures.

**New opportunities with an old optical material: an interview with Professor Marko Loncar**

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Marko Loncar, Tsantalis Lab Professor of Electrical Engineering at Harvard’s John A. Paulson School of Engineering and Applied Sciences (SEAS).

Chang: How did you become interested in researching nanoscale optical devices?

Loncar: I obtained my bachelor’s degree in electrical engineering from University of Belgrade in 1997 and the same year I went to Caltech to pursue my PhD. I initially wanted to conduct research in power electronics. However, after meeting friends who were taking quantum and photonics-related courses I was intrigued... These courses sounded very interesting to me, so at the end of my first year, I switched to the group of Axel Scherer, who was working on nanofabrication and integrated optics. I started working in the field of photonic... first waveguides then nanolasers, and finally nanodevices for sensing and quantum electronics applications.

Chang: Thank you! Our topic today is lithium niobate. It’s an old optical material, in use for more than 50 years. Recently, you started to work on thin-film lithium niobate (TFLN). How did you start to work on this material?

Loncar: When I was studying at Caltech, I attended my first CLEO conference in 2000. There, I saw a talk by Rick Osgood’s group at Columbia University, focused on making thin lithium niobate films... they were slicing bulk LN crystals into slabs and doing fun stuff with it. A few years later, when I was in a position with Fordic Capasso at Harvard, I reached out to Rick and he was kind enough to send me some of their LN material. I was curious to see if I could etch this material and make devices. This is the work that has been in developing nanomanufacturing strategies for materials that have unique optical properties but are hard to fabricate devices in. And lithium niobate... certainly satisfies both of these criteria: it is a very important electric-optic material, but also a very hard material to etch!

I have to say that my initial efforts largely failed... I also wanted to use some photonic materials using focused ion beam milling but devices never really worked properly. Still, integrated lithium niobate photonics was an important part of my research proposal and I was applying for faculty positions in 2005/06 and I was determined to continue research in this direction. Several years later, I learned about a new company in China—Nanolight... that was commercializing thin film LN. I believe they were emailing everybody trying to sell their wafers, but most people ignored them at the time, it seems. My student Cheng Wang (now a professor at City University of Hong Kong) happened to be going back to China for summer vacation that year and I asked him to visit Nanolight to see if they were legitimate. Cheng visited the company and was impressed! They had been making a series of products related to thin-film crystals. At that time, we decided to purchase a few TFLN wafers. But procuring wafers was only half of the job. The biggest challenge was to develop nanofabrication techniques for TFLN that can make ultra-low-loss devices. Cheng worked for 2-3 years in Harvard’s clean room, exploring the processing methods and trying to figure out the fabrication recipes. I have to give credit to Harvard’s Center for Nanoscale Systems that is very open to new materials and processes, unlike more traditional shared-user-on-campus. The later, by now my partner Pian Zhang (now CEO of HyperLight corporation) and together we were able to figure the fabrication recipe that can result in ultra-low loss TFLN photonic devices. The rest is history.

Chang: What are the advantages of TFLN over bulk LN? TFLN? I will first identify the main advantages, which is my original motivation, is to reduce the driving voltage for modulators. In bulk LN, waveguides are made by either proton exchange or doping to locally change the refractive index. This results in a very low index contrast between the core and the cladding. It’s a similar situation to what you’d have if an optical fiber. For example, since the index contrast is very small, it would be very difficult to... when you want to change the refractive index using electric-field, you need to apply a large voltage to get an appreciable electric field. The benefit of TFLN is that you can make tightly confined waveguides with... very large, because matching between phase velocity of applied...
1 Introduction

The excellent electro-optic (EO) and nonlinear optical properties of lithium niobate (LiNbO₃, LN) have long established it as a prevailing photonic material for the long-haul telecom modulator and wavelength-converter markets. Indeed, the first nonlinear experiment in any waveguide platform was a demonstration of Cherenkov radiation from titanium-diffused LN. Conventional LN waveguides are most commonly formed by the electro-optic effect, as well as optical wavelength converters based on second-order nonlinear effects, such as spontaneous parametric downconversion for quantum optics. Recent progress in nonlinear integrated photonics on TFLN for all these applications, their current trends, and future opportunities and challenges are reviewed.

Keywords: lithium niobate; thin-film lithium niobate; nonlinear integrated optics; photonic integrated circuits.

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Electro-optic tuning of a single-frequency ultranarrow linewidth microdisk laser

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Abstract. Single-frequency ultranarrow linewidth on-chip microlasers with a fast wavelength tunability play a game-changing role in a broad spectrum of applications ranging from coherent communication, light detection and ranging, to metrology and sensing. Design and fabrication of such light sources remain a challenge due to the difficulties in making a laser cavity that has an ultrahigh optical quality (Q) factor and supports only a single lasing frequency simultaneously. Here, we demonstrate a unique single-frequency ultranarrow linewidth lasing mechanism on an erbium ion-doped lithium niobate (LN) microdisk through simultaneous excitation of high-Q polygon modes at both pump and laser wavelengths. As the polygon modes are sparse within the optical gain bandwidth compared with the whispering gallery mode counterpart, while their Q factors (above 10 million) are even higher due to the significantly reduced scattering on their propagation paths, single-frequency lasing with a linewidth as narrow as 322 Hz is observed. The measured linewidth is three orders of magnitude narrower than the previous record in on-chip LN microlasers. Finally, enabled by the strong linear electro-optical effect of LN, real-time electro-optical tuning of the microlaser with a high tuning efficiency of ~50 pm/100 V is demonstrated.

Keywords: lasers; lithium niobate; microcavities; integrated optics.

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1 Introduction

Broad transparency window and high piezoelectric, acousto-optic, second-order nonlinear, and electro-optic (EO) coefficients characterize crystalline lithium niobate (LN) as the “silicon in photonics.” Recent breakthroughs in the nanofabrication technology on thin-film LN platforms have given birth to a variety of integrated photonic devices such as high-performance EO modulators, broadband optical frequency combs, and high efficiency frequency converters.2,3 To build a monolithic integrated photonic system on an LN chip, the capacity of microlaser

Ultra-broadband and low-loss edge coupler for highly efficient second harmonic generation in thin-film lithium niobate

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Abstract. Thin-film lithium niobate is a promising material platform for integrated nonlinear photonics, due to its high refractive index contrast with the excellent optical properties. However, the high refractive index contrast and correspondingly small mode field diameter limit the attainable coupling between the waveguide and fiber. In second harmonic generation processes, lack of efficient fiber-chip coupling schemes covering both fundamental and second harmonic wavelengths has greatly limited the overall efficiency. We design and fabricate an ultra-broadband tri-layer edge coupler with a high coupling efficiency. The coupler allows efficient coupling of 1 dB/facet at 1550 nm and 3 dB/facet at 775 nm. This enables us to achieve an ultrahigh overall second harmonic generation normalized efficiency (fiber-to-fiber) of 1027 W cm−1 (on-chip second harmonic efficiency ~3256% W cm−2) in a 5-mm-long periodically-poled lithium niobate waveguide, which is two to three orders of magnitude higher than that in state-of-the-art devices. Keywords: thin-film lithium niobate; ultra-broadband coupler; second harmonic generation.

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1 Introduction

Lithium niobate is an ideal material for nonlinear photonics due to its exceptional nonlinear-optic properties, wide transparency range, and ferroelectric properties. Periodically poled lithium niobate (PPLN) waveguide inversion allows for a quasi-phase-matched (QPM) second-order nonlinear process, have been widely used in wavelength conversion, optical parametric oscillation, photon pair generation, and supercontinuum generation. The strong optical nonlinearity in PPLN waveguides is based on weakly coupled modes with index contrasts of ~0.02, leading to low nonlinear interaction strengths. Therefore, the traditional PPLN device requires a long interaction length for high conversion efficiency, making it difficult for large-scale photonic integrated circuits. In recent years, thin-film lithium niobate (TFLN) has emerged as an attractive platform for compact and high-performance optical modulators and non-linear optical devices due to the high refractive index contrast (~2.5) and non-linear optical devices due to the high refractive index contrast (~2.5). For instance, the efficiency of second harmonic generation (SHG) has been improved over 20 times in TFLN-based PPLN devices. However, TFLN-based PPLN devices face a major challenge of how to achieve efficient and broadband off-chip coupling. For example, in Ref. 29 an on-chip SHG conversion efficiency as high as 37.5% W cm−2 was achieved in a 5-mm PPLN waveguide, but the collected second harmonic (~780 nm) power is only several μW when the input pump (~1560 nm) power is nearly about 100 mW due to the lack of a well-designed coupling mechanism. For SHG, an ideal device requires an efficient coupling scheme...
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