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Theme Issue on

Photonics with Thin Film Lithium Niobate

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CONTENTS

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Photonics with Thin Film Lithium Niobate

Editorial

News and Commentaries

Reviews

Research Articles

On the cover The image illustrates a roadmap of the development of lithium niobate photonics, from the typical bulk lithium niobate photonics to the newly developed thin-film lithium niobate photonics, as well as various functional devices.

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Photonics with Thin Film Lithium Niobate

Siyuan Yu
Sun Yat-sen University, Department of Electronics and
Information Engineering, Guangzhou, China

Siyuan Yu, Sun Yat-sen University

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_x), silicon dioxide (SiO_2) and indium phosphide (InP), while the refractive index contrast between TFLN waveguide and typical cladding materials such as SiO_2 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 benefitted 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.4.3.034003). We also feature a review article focused on the nonlinear photonics in TFLN to enable an in-depth inspection of this research area (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.4.3.036001) and the other on the generation of optical frequency combs exploiting nonlinear effects (https://doi.org/10.1117/1.APN.1.1.016001), 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.4.3.030503) and a perspective by Zhenda Xie and Shining Zhu (https://doi.org/10.1117/1.AP.4.3.030502).

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LiNbO$_3$ crystals: from bulk to film

Zhenda Xie[a,b,c,*] **and Shining Zhu**[a,b,c,*]
[a]Nanjing University, College of Engineering and Applied Sciences, School of Physics, School of Electric Science and Engineering, National Laboratory of Solid State Microstructures, Nanjing, China
[b]Nanjing University, Ministry of Education, Key Laboratory of Intelligent Optical Sensing and Manipulation, Nanjing, China
[c]Collaborative Innovation Center of Advanced Microstructures, Nanjing, China

Lithium niobate[1,2] is a ferroelectric crystal that features superior electro-optical, nonlinear optical, and acoustic optical performance, and it is thus prominent in various optoelectronic 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-optical modulation,[3–5] the footprint for acoustic wave filtering,[6] and the power requirement for efficient optical frequency conversion.[7–9] TFLN is mainly fabricated using the smart cut technique,[10,11] which was developed for silicon-on-insulator materials[12] and is known for its capability for manufacturing high-quality, large-sized crystalline wafer. 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 computation, 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 drive voltage in a much smaller package. Power consumption as low as 0.37 fj/bit has been demonstrated.[3] These performances make the LNOI EOM not only a direct alternate to the bulk lithium niobate EOM, but also a promising candidate for optical links in/between data centers and local area networks at the data rates of 200-800 Gbps and above, therefore driving the next generation optical communication technology. It is worth noting that laser sources and amplifiers have been demonstrated using rare-earth-ion-doped LNOI chips,[13] 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.[14] Such hybrid integration can also enable simultaneous signal processing and memory operations, leading toward artificial intelligence applications.[15]

Optical computation may change the power-hungry nature of modern electronic computation technology, in both classical[16] and quantum approaches,[17] by demonstration of computation speed acceleration and quantum supremacy. In either approach, larger scale photonic circuitry is required, with phase sensitive optical paths as the interaction mechanism. The low loss nature of lithium niobate qualifies LNOI for such large-scale photonic integration, achieving a level of 2.7 dB per meter in different demonstrations.[18,19] A further crucial challenge for optical computation is circuit reconfigurability, and LNOI is the only mature material to combine fast and accurate phase control using electro-optical modulation, acoustic-optical modulation, or thermal-optical modulation.

Microwave photonics has been a long-chased dream to bring optical accuracy and bandwidth into microwave technology. Photonic integration is key to push complex microwave photonics systems, including high-bandwidth electro-optic modulators, low-noise frequency synthesizers, and chip signal processors, into practice.[20] The LNOI platform contains the most powerful toolbox, including the EOM and dispersive Kerr soliton (DKS) frequency combs.[21] Self-referencing is necessary to further stabilize DKS comb. With high nonlinear coefficients in both $\chi^{(2)}$ and $\chi^{(3)}$, octave-spanning supercontinuum generation[22] and efficient frequency doubling[9] have been reported separately using LNOI, and self-referencing can be expected combining these processes on the same chip. The only missing parts are the photodetector and control electronics in the on-chip signal processing, and their integration relies on the hybrid integration technology.

Domain engineered bulk lithium niobate crystal, also known as optical superlattice,[23] has been a great success for nonclassical light generation and photon state manipulation, for quantum optics research. However, photonic integration is the key to the practical application of quantum information technology. Compared to other photonics integration platforms, LNOI features high nonlinearity in $\chi^{(2)}$ and fast EOM for photon state modulation. Ultrabright photon pair generation has been reported in both straight waveguide and micro-resonator using LNOI to achieve revolutionary photon generation rates of 2.79×10^{11} Hz/mW[24] and 2.7 MHz/μW,[25] respectively. Together with the low-loss waveguide and other passive devices, larger scale on-chip photon state manipulation can be expected.

On one hand, the above important advances may be seen as incremental steps toward practical application of quantum information technology that are expected directly from the high nonlinearity of LNOI. On the other hand, the practical application of quantum information relies on sources of the deterministic multiqubit state, which is the multiphoton state in photonics quantum systems. While such a problem is yet to be resolved, a theoretical study shows that LNOI may be the only candidate for such deterministic multiphoton state generation considering the material limitations.[26] Deterministic nonlinear interaction is possible at single photon level, and the required quality factor is on the order of 10^7 to 10^8 for domain engineered micro-ring resonators, within the reach of existing fabrication limits.[26]

In summary, from bulk devices to chips, LNOI technology has shown its capability to push the performance of optoelectronic devices to new heights, for electro-optical modulation and acoustic wave filtering functions in next-generation optical and wireless communications. In conjunction with hybrid integration, LNOI can also be an enabling technology for optical computation, microwave photonics, and quantum information, with large-scale photonic integration, high optical reconfigurability, and strong nonlinear interaction at the single photon level. To make these happen, large-size low-defect TFLN wafer and high-performance device fabrication techniques are key areas of future research.

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*Address all correspondence to Zhenda Xie xiezhenda@nju.edu.cn; Shining Zhu zhusn@nju.edu.cn

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New opportunities with an old optical material: an interview with Professor Marko Lončar

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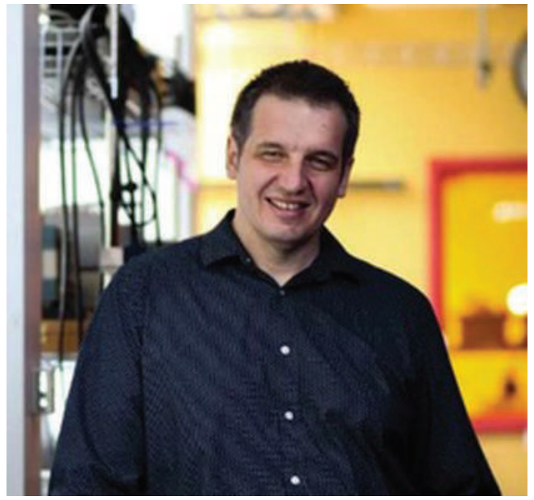
Guoqing Chang
Chinese Academy of Sciences, Institute of Physics, Shanghai, China



Marko Lončar, Tiantsai Lin Professor of Electrical Engineering at Harvard's John A. Paulson School of Engineering and Applied Sciences (SEAS).

Guoqing Chang spoke with Marko Lončar of Harvard University about his innovative work in thin film lithium niobate.

Chang: How did you become interested in researching nanoscale optics?
Lončar: 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 crystals, first waveguides then nanolasers, and finally nanocavities for sensing and quantum electrodynamics 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?
Lončar: 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 a postdoc with Federico Capasso at Harvard, I reached out to Rick and he was kind to send me some of their LN material. I was curious to see if I can etch this material and make devices in it. Then, as well as now, my interest has been in developing nanostructuring 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 electro-optic material, but also a very hard material to etch!

I have to say that my initial efforts largely failed… I was able to make some photonic crystals using focused ion beam milling but devices never really worked properly. Still, integrated lithium niobate photonics was an important part of my research proposal as 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—NanoLN—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 NanoLN to see if they were "legit."

Cheng visited the company and was impressed! They were indeed 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 nanostructuring 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 clean rooms.) Cheng was later joined by my former postdoc Mian Zhang (now CEO of HyperLight corporation) and together they were able to figure the fab 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?
Lončar: TFLN has many advantages, in my opinion. The main advantage, which was our 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 in an optical fiber, for example. Since the index contrast is very small, the mode is very large. Thus, if you're making a modulator, you need to put the electrodes very far away from the waveguide core, which means that when you want to change the refractive via electro-optic effect, 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 using etching—similar approach that is used in e.g. silicon photonics. This allows us to place electrodes closer to the waveguide thus allowing the same electric field to be achieved using much smaller voltage. This is an old and simple idea, but the main challenge was to figure out an etching process that results in a very low loss waveguide. During this process, we also realized that the bandwidth of the modulator could be very large, because matching between phase velocity of applied

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Review Article

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Applications of thin-film lithium niobate in nonlinear integrated photonics

Milad Gholipour Vazimali[a] and **Sasan Fathpour**[a,b,*]
[a]University of Central Florida, CREOL, College of Optics and Photonics, Orlando, Florida, United States
[b]University of Central Florida, Department of Electrical and Computer Engineering, Orlando, Florida, United States

Abstract. Photonics on thin-film lithium niobate (TFLN) has emerged as one of the most pursued disciplines within integrated optics. Ultracompact and low-loss optical waveguides and related devices on this modern material platform have rejuvenated the traditional and commercial applications of lithium niobate for optical modulators based on the electro-optic effect, as well as optical wavelength converters based on second-order nonlinear effects, e.g., second-harmonic, sum-, and difference-frequency generations. TFLN has also created vast opportunities for applications and integrated solutions for optical parametric amplification and oscillation, cascaded nonlinear effects, such as low-harmonic generation; third-order nonlinear effects, such as supercontinuum generation; optical frequency comb generation and stabilization; and nonclassical 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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1 Introduction

The excellent electro-optic (EO) and nonlinear optical properties of lithium niobate ($LiNbO_3$ or 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.[1] Conventional LN waveguides are most commonly formed by in-diffusion of titanium (Ti) dopants[2] or by the proton exchange process.[3] However, these conventional lithium niobate optical waveguides have a low index-contrast, hence are bulky compared with modern integrated platforms, such as silicon photonics. The bulkiness impedes photonic circuit implementations and imposes high optical power requirements for nonlinear applications.

Achieving thin films of LN (with a thickness of a few hundred nanometers) that reside on an insulator cladding with a much lower index (e.g., silicon dioxide, SiO_2)— along with methods to achieve low-loss ridge or channel waveguides on the thin films—can address the above issues and yield high-contrast waveguides. Thin-film lithium niobate (TFLN) wafers on silicon (Si) substrates and high-contrast waveguides (with submicron cross-sectional dimensions) were developed for the first time at CREOL in 2013.[4] Since the commercialization of TFLN wafers by a few vendors,[5–7] efforts by several research teams have tremendously advanced the field of TFLN-integrated photonics. A plethora of ultracompact linear and nonlinear optical devices and circuits (waveguides, microring resonators, modulators, grating couplers, wavelength converters, entangled photon sources, isolators, supercontinuum, and comb sources) with unprecedented or significantly superior performances than the conventional (bulk) LN counterparts have been demonstrated. The combined efforts have rejuvenated LN for EO, nonlinear-, and quantum-optics applications, and the material is considered to be among the top candidates for heterogeneous integrated photonics. That is when multiple materials are monolithically integrated on the same substrate (preferably silicon), while each material is chosen for the functionalities that it suits the best.

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*Address all correspondence to Sasan Fathpour, fathpour@creol.ucf.edu

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Review Article

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Advances in lithium niobate photonics: development status and perspectives

Guanyu Chen,[a] **Nanxi Li**,[b] **Jun Da Ng**,[a] **Hong-Lin Lin**,[a] **Yanyan Zhou**,[b] **Yuan Hsing Fu**,[b] **Lennon Yao Ting Lee**,[b] **Yu Yu**,[c,*] **Ai-Qun Liu**,[d] and **Aaron J. Danner**[a,*]
[a]National University of Singapore, Department of Electrical and Computer Engineering, Singapore
[b]A*STAR (Agency for Science, Technology and Research), Institute of Microelectronics, Singapore
[c]Huazhong University of Science and Technology, School of Optical and Electronic Information, Wuhan National Laboratory for Optoelectronics, Wuhan, China
[d]Nanyang Technological University, Quantum Science and Engineering Centre, Singapore

Abstract. Lithium niobate (LN) has experienced significant developments during past decades due to its versatile properties, especially its large electro-optic (EO) coefficient. For example, bulk LN-based modulators with high speeds and a superior linearity are widely used in typical fiber-optic communication systems. However, with ever-increasing demands for signal transmission capacity, the high power and large size of bulk LN-based devices pose great challenges, especially when one of its counterparts, integrated silicon photonics, has experienced dramatic developments in recent decades. Not long ago, high-quality thin-film LN on insulator (LNOI) became commercially available, which has paved the way for integrated LN photonics and opened a hot research area of LN photonics devices. LNOI allows a large refractive index contrast, thus light can be confined within a more compact structure. Together with other properties of LN, such as nonlinear/acousto-optic/pyroelectric effects, various kinds of high-performance integrated LN devices can be demonstrated. A comprehensive summary of advances in LN photonics is provided. As LN photonics has experienced several decades of development, our review includes some of the typical bulk LN devices as well as recently developed thin film LN devices. In this way, readers may be inspired by a complete picture of the evolution of this technology. We first introduce the basic material properties of LN and several key processing technologies for fabricating photonics devices. After that, various kinds of functional devices based on different effects are summarized. Finally, we give a short summary and perspective of LN photonics. We hope this review can give readers more insight into recent advances in LN photonics and contribute to the further development of LN related research.

Keywords: lithium niobate; etching; photonics; integrated optics; nanotechnology; devices.

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1 Introduction

Lithium niobate ($LiNbO_3$, LN) is one of the most important artificial materials and has been widely used in the photonics area since it was first discovered to have a ferroelectric property in 1949.[1] Compared with other material systems, LN has various superior characteristics, such as a wide transparency window (400 nm to 5 μm) and large electro-optic (EO)/nonlinear-optic (NLO)/acousto-optic (AO)/pyroelectric coefficients, as well as stable chemical and physical properties.[2–9] Based on these effects, various kinds of photonics devices have been demonstrated. For example, the large EO property of LN can be used for the realization of high-speed modulators. As there is no carrier dynamic process involved, such as the case in its counterparts including silicon (Si)[10] and indium phosphide (InP),[11] both the speed and linearity of LN modulators show advantages compared with other kinds of modulators. Therefore, in current fiber-optic communication systems, LN-based modulators have been widely used.[3] The second- and third-order nonlinear effects

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*Address all correspondence to Yu Yu, yuyu@mail.hust.edu.cn; Aaron J. Danner, adanner@nus.edu.sg

Research Article

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

Jintian Lin,[a,b,†] Saeed Farajollahi,[c,†] Zhiwei Fang,[d,†] Ni Yao,[e,f] Renhong Gao,[a,b] Jianglin Guan,[d,g] Li Deng,[d,g] Tao Lu,[c,*] Min Wang,[d,g] Haisu Zhang,[d,g] Wei Fang,[f,h,*] Lingling Qiao,[a,b] and Ya Cheng[a,b,d,g,i,j,k,*]

[a]Chinese Academy of Sciences (CAS), Shanghai Institute of Optics and Fine Mechanics (SIOM),
State Key Laboratory of High Field Laser Physics and CAS Center for Excellence in Ultra-Intense Laser Science, Shanghai, China
[b]University of Chinese Academy of Sciences, Center of Materials Science and Optoelectronics Engineering, Beijing, China
[c]University of Victoria, Department of Electrical and Computer Engineering, Victoria, British Columbia, Canada
[d]East China Normal University, School of Physics and Electronic Science, XXL—The Extreme Optoelectromechanics Laboratory, Shanghai, China
[e]Research Center for Intelligent Sensing, Zhejiang Lab, Hangzhou, China
[f]Zhejiang University, College of Optical Science and Engineering, The Interdisciplinary Center for Quantum Information,
State Key Laboratory of Modern Optical Instrumentation, Hangzhou, China
[g]East China Normal University, State Key Laboratory of Precision Spectroscopy, Shanghai, China
[h]Jiaxing Institute of Zhejiang University, Intelligent Optics & Photonics Research Center, Jiaxing, China
[i]Shanxi University, Collaborative Innovation Center of Extreme Optics, Taiyuan, China
[j]Shandong Normal University, Collaborative Innovation Center of Light Manipulations and Applications, Jinan, China
[k]Shanghai Research Center for Quantum Sciences, Shanghai, China

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-optic 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."[1–7] Recent breakthroughs in the nanofabrication technology on thin-film LN platforms[4] gave birth to a variety of integrated photonic devices such as high-performance EO modulators,[8,9] broadband optical frequency combs,[10–12] and high efficiency frequency converters.[13–15] To build a monolithic integrated photonic system on an LN chip, the capacity of microlaser

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*Address all correspondence to Tao Lu, taolu@ece.uvic.ca; Wei Fang, wfang08@zju.edu.cn; Ya Cheng, ya.cheng@siom.ac.cn.

†These authors contributed equally to the work.

Research Article

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

Xiaoyue Liu,[a] Shengqian Gao,[a] Chi Zhang,[b] Ying Pan,[a] Rui Ma,[a] Xian Zhang,[a] Lin Liu,[a] Zhenda Xie,[b] Shining Zhu,[b] Siyuan Yu,[a] and Xinlun Cai[a,*]

[a]Sun Yat-sen University, School of Electronics and Information Technology, State Key Laboratory of Optoelectronic Materials and Technologies, Guangzhou, China
[b]Nanjing University, College of Electronic Science and Engineering, School of Physics, Nanjing, China

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 the 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% $\mathrm{W}^{-1}\,\mathrm{cm}^{-2}$ (on-chip second harmonic efficiency ~3256% $\mathrm{W}^{-1}\,\mathrm{cm}^{-2}$) 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; ultrabroadband 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.[1,2] Periodically poled lithium niobate (PPLN) waveguides, where the periodic domain inversion allows for a quasi-phase-matched (QPM) second-order nonlinear [$\chi^{(2)}$] process, have been widely used in wavelength conversion,[3,4] optical parametric oscillation,[5–8] photon pair generation,[9–12] and supercontinuum generation.[13–15] As the strength of the nonlinear interaction is proportional to the optical intensity, the employment of high-contrast waveguides with strong optical confinement can greatly improve nonlinear optical efficiency. Unfortunately, the legacy PPLN waveguides are based on weakly confined waveguides 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[16–18] and $\chi^{(2)}$ nonlinear optical devices[19–24] due to the high refractive index contrast ($\Delta n \sim 0.7$) offered by TFLN waveguides. TFLN-based PPLN devices have been demonstrated that outperform their legacy counterparts in both nonlinear optical efficiency and device footprint.[25–28] For instance, the efficiency of second harmonic generation (SHG) has been improved over 20 times in TFLN-based PPLN devices.[26] 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 3757% $\mathrm{W}^{-1}\,\mathrm{cm}^{-2}$ 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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*Address all correspondence to Xinlun Cai, caixlun5@mail.sysu.edu.cn

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Xiao-Cong (Larry) Yuan is Director of the Shenzhen University Nano Photonics Research Center.

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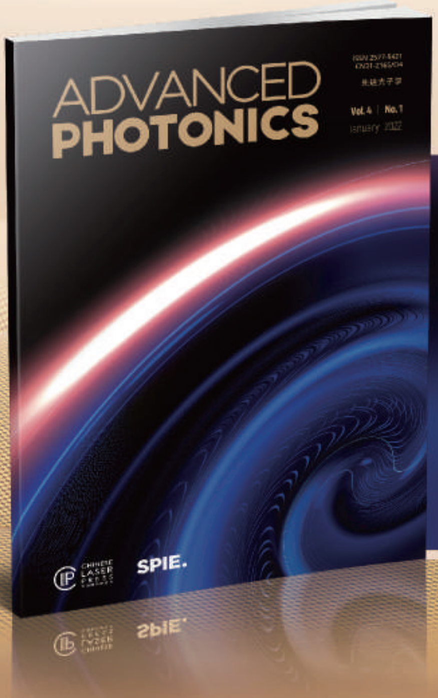
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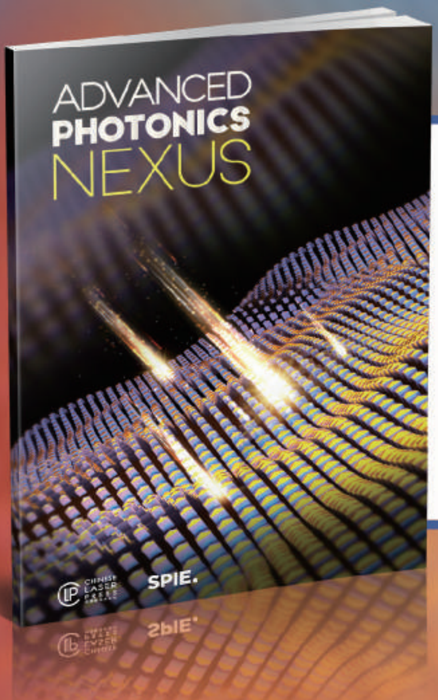
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