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The Octogenarian Journey of Lithium Niobate: History and Recent Progress
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Abstract: Lithium niobate ($LiNbO_3$) integrates piezoelectric, second-harmonic generation, electro-optic, and photorefractive properties; it is regarded as a model crystal in nonlinear optics and has demonstrated immense practical value. In the nearly one hundred years since its inception, lithium niobate has secured an indispensable position in fields such as homeland security, medical diagnostics, high-energy physics, and industrial inspection. With the advancement of micro- and nano-technologies, research into novel optical effects within lithium niobate micro- and nano-structures has recently become a highly competitive frontier in the international scientific community, playing a pivotal role in the development of new micro- and nano-photonic devices. This paper reviews the developmental history of lithium niobate with a focus on its optical properties, outlines the current state of research in the field of micro- and nano-optics, and offers an outlook on its future development. Keywords: lithium niobate; research history and progress; thin film; waveguide modulator; microcavity; metasurface
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Long-Lived Lithium Niobate: History and Progress
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Abstract: Lithium niobate is considered a model crystal in nonlinear optics, combining piezoelectric, frequency-doubling, electro-optic, and photorefractive properties, and has demonstrated significant practical utility. In the nearly one hundred years since its inception, lithium niobate has played an indispensable role in fields such as national security, medical diagnostics, high-energy physics, and industrial inspection. With the advancement of micro-nano technology, the study of novel optical effects within lithium niobate microstructures has emerged as a frontier hotspot in recent years; such research plays a crucial role in driving the development of new micro-nano photonic devices. This paper summarizes the history of lithium niobate with a focus on its optical properties, introduces recent research progress—particularly in the field of nano-optics—and offers an outlook on future developments. Key words: lithium niobate; history and progress; thin film; waveguide modulator; microcavity; metasurface
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0 Introduction

Lithium niobate is an optoelectronic crystal with excellent properties [1–3] and is currently the ferroelectric material with the highest Curie temperature (1,210 °C) discovered to date. In the ferroelectric phase, the centers of positive and negative charges within the crystal lattice are separated, resulting in strong spontaneous polarization (approximately 0.70 C/m² at room temperature). The symmetry of the lattice point group enables ferroelectric materials to spontaneously exhibit a wide range of optoelectronic properties, such as pyroelectricity, piezoelectricity, the electro-optic effect, birefringence, the photovoltaic effect, and second-harmonic generation. Additionally, lithium niobate's exceptionally wide bandgap (~4 eV) results in extremely low optical absorption loss across the visible to mid-infrared spectral range (0.4–5 μm). Furthermore, lithium niobate possesses stable physicochemical properties and allows for the relatively easy growth of high-quality, large-sized single crystals; it also features a rich defect structure, enabling effective tuning of its properties through methods such as adjusting crystal composition, elemental doping, and valence state control. These characteristics make lithium niobate a versatile "all-rounder" crystal in the field of optoelectronics, widely used in the fabrication of devices such as surface acoustic wave (SAW) filters, electro-optic Q-switches, optical frequency converters, and terahertz waveguides [4–7]. The rapid development of micro- and nanotechnology in recent years—along with the localized effects observed at these scales and the resulting new physics and phenomena—has created fresh opportunities for the research and development of novel lithium niobate optoelectronic devices. Breakthroughs have already been achieved in areas such as the fabrication of lithium niobate nanofilms, integrated photonic circuits, and metasurfaces, laying the foundation for new applications in lithium niobate micro- and nanophotonics and devices [8–10].

This article reviews lithium niobate from three perspectives: its development history, current research status, and future prospects.

1 History

Research into lithium niobate spans nearly a century. In 1928, the mineralogist Zachariasen—then a doctoral candidate at the University of Oslo in Norway—conducted a preliminary study on the structural characteristics of lithium niobate in his doctoral thesis, titled *Crystal Structure Studies of Sesquioxides and Compounds of the Type ABO3* [11]. In 1937, Sue and colleagues experimentally synthesized lithium niobate [12–13] by melting Nb_2O_5 and Li_2CO_3, though the material did not initially attract widespread attention. It was not until 1949, following the research and reporting by Matthias and Remeika at Bell Labs on its high-temperature ferroelectric properties [14], that lithium niobate truly came into the spotlight. Earlier in the 20th century, materials such as Rochelle salt ($KNaC_4H_4O_6·4H_2O$) and phosphates (e.g., KH_2PO_4) were found to exhibit ferroelectric properties; notably, their piezoelectric performance far surpassed that of non-ferroelectric materials like quartz and tourmaline [15].

Although the underlying mechanisms of these ferroelectric properties and their superior piezoelectric responses were not yet understood at the time, the urgent demands of submarine warfare during World War II led to the rapid adoption of phosphate ferroelectrics for high-performance anti-submarine sonar, where they played a crucial role [16]. The discovery in 1949 of titanate (perovskite) ferroelectrics—exemplified by barium titanate—marked the entry of piezoelectric materials into the "ferroelectric" era, driven by advantages such as high piezoelectric coefficients and resistance to deliquescence. However, these ferroelectrics possessed relatively low Curie temperatures (e.g., approximately 120°C for barium titanate) [14]; consequently, they were prone to losing their ferroelectric—and thus piezoelectric—properties due to temperature rises during mechanical processing. This prompted a subsequent search for ferroelectrics with higher Curie temperatures. At the time, the ferroelectricity of barium titanate was attributed to the presence of oxygen octahedra in its structure. Lithium niobate, which is chemically similar to barium titanate, also possesses oxygen octahedra, though its crystal lattice belongs to the lower-symmetry ilmenite structure; furthermore, prior research on perovskite ferroelectrics suggested that niobates (and tantalates, such as $NaNbO_3$) exhibited superior ferroelectric properties [15]. Consequently, in late 1948, Matthias grew lithium niobate crystals using the flux method and, together with Remeika, investigated their ferroelectric characteristics. Although the resulting crystals were small and contained small single-domain regions—exhibiting distinct banded structures (growth striations)—the characteristic ferroelectric hysteresis loop and polarization saturation were clearly measured. While experimental limitations of the era prevented precise determination of the Curie temperature, it was found to exceed 450°C, marking a new starting point for research into high-temperature ferroelectrics [14, 17].

A significant breakthrough in lithium niobate research occurred in 1964 when Ballman at Bell Labs successfully grew centimeter-scale lithium niobate crystals using the Czochralski method [18] (around the same time, Fedulov et al. in the Soviet Union achieved similar success using the same technique [19], and the technology was subsequently mastered in the UK [20]). Despite the observation of piezoelectricity, subsequent measurements—including pyroelectric testing, wet etching, and phase-matched second-harmonic generation experiments—revealed the presence of antiparallel multi-domain structures within the crystals [21]; consequently, ferroelectric hysteresis loops could not be observed, even under conditions of high temperature and strong electric fields. At that time, there was no known method to achieve ferroelectric domain reversal, making it impossible to convert the as-grown multi-domain crystals into single-domain ones. In 1965, Nassau and Levinstein at Bell Labs developed a method to achieve single-domain lithium niobate at high temperatures using a low electric field, thereby obtaining high-quality single crystals. They discovered that when the crystal temperature rose to 1,200°C, the electrical resistance of lithium niobate dropped rapidly; applying an electric field of 1 V/cm at this stage enabled domain reversal and yielded high-quality single-domain lithium niobate. They also determined the Curie temperature of lithium niobate to be 1,210°C [22-23]. This preparation technique laid a crucial foundation for subsequent research; for many years thereafter, the lithium niobate used in Bell Labs' studies was largely supplied by Nassau. Meanwhile, understanding of the lithium niobate crystal structure was also deepening. Zachariasen proposed that the point group of lithium niobate was C3i and the space group was R3 [11, 24]. This view persisted until 1952, when Bailey (UK) confirmed via X-ray diffraction that

the space group was R3c. This finding refuted the notion that lithium niobate possessed an ilmenite-type structure; however, as he was unable to determine the precise position of Nb relative to Li and O, he proposed two possible crystal lattice models [25-26]. In 1963, Shiozaki and Mitsui used neutron diffraction on polycrystalline lithium niobate powder to reconfirm the R3c space group and proposed a new crystal structure model [27], though that model remained imperfect. In 1965, Abrahams et al. conducted a systematic study of large-sized lithium niobate single crystals (grown by Nassau) and polycrystalline powders using techniques such as X-ray and neutron diffraction. They precisely measured and calculated lattice constants and atomic positions, establishing a new structural model for the lithium niobate lattice in both its ferroelectric and paraelectric phases—a model that remains in use today [4, 28–30]. Given the intrinsic link between lattice symmetry and material parameter tensors, an accurate understanding of the lattice structure was crucial for research—both contemporary and subsequent—into the ferroelectric, dielectric, piezoelectric, and even nonlinear optical properties of lithium niobate [31].

By overcoming material growth challenges and securing an optimal lattice model, Bell Labs rapidly took the lead in lithium niobate research. Between 1964 and 1967, they investigated a range of properties—including electro-optic, second-harmonic generation, piezoelectric, and photorefractive effects—thereby establishing the overall framework and disciplinary scope for future research in the field. my country began its own lithium niobate research in the 1970s research on lithium niobate crystal growth, defects, properties, and applications [32].

In 1980, a collaboration between Nankai University and the Southwest Institute of Technical Physics discovered the high resistance to optical damage in magnesium-doped lithium niobate; this crystal became known internationally as the "Star of China" [33]. Meanwhile, Nanjing University achieved a breakthrough in the growth process of periodically poled lithium niobate (PPLN), experimentally realizing quasi-phase matching [34]. The following section outlines the development history of lithium niobate, focusing on research areas such as electro-optics, frequency doubling, piezoelectricity, and photorefraction.

1.1 Electro-optic properties

Following the invention of the laser, it was quickly recognized that this light source held immense potential for applications in optical communication and optical routing. However, realizing this potential required a method for the high-speed modulation of laser amplitude, phase, frequency, and propagation direction. Modulation techniques based on mechanical shutters or moving mirrors suffered from excessive inertia, making it impossible to achieve modulation speeds in the MHz or GHz range. Consequently, researchers proposed utilizing nonlinear interactions between light waves and modulating electric, magnetic, or acoustic fields to control light wave characteristics. However, some of these nonlinear interactions—such as free-carrier absorption and the Franz-Keldysh effect—entailed significant optical losses [35]. Research efforts subsequently shifted toward processes involving reactive electrical parameters, such as the electro-optic Pockels effect.

As early as 1906, Pockels and others investigated the electro-optic effects in materials with various point-group symmetries (e.g., quartz, tourmaline, potassium chloride, and Rochelle salt) [36], establishing a fundamental understanding of the relationship between point-group symmetry and the presence or absence of electro-optic properties. In 1964, Peterson at Bell Labs conducted the first measurements of the electro-optic properties of lithium niobate;

however, the single-crystal quality of the samples grown by Ballman was poor, resulting in unstable electro-optic signals and significant relaxation issues [37]. Following the breakthrough in lithium niobate single-crystal technology achieved by Nassau et al. in 1966, further research was conducted on the electro-optic properties of the material [38]. That same year, Turner re-examined the high-frequency electro-optic characteristics of lithium niobate and successfully measured the complete set of electro-optic tensor coefficients at a wavelength of 633 nm [39]. In 1967, Kaminow et al. demonstrated electro-optic modulation at 4 GHz using lithium niobate [40]. By this time, a fundamental understanding of the electro-optic properties and applications of lithium niobate had been established.

By the mid-1960s, dozens of electro-optic materials had been identified, including KH_2PO_4 and its isomorphs, ABO_3-type compounds, and AB-type semiconductors. Although the physical origins of the electro-optic effect remained unclear at the time, practical application requirements led to the establishment of selection criteria for these materials. Key requirements included high optical transparency in the relevant wavelength range, a piezoelectric point group symmetry to ensure the existence of a linear electro-optic effect, a cubic or uniaxial crystal structure to facilitate device calculation and design, low dielectric loss to minimize thermal stress and modulation power, and high electrical resistivity to mitigate space-charge and thermal effects [41]. Under the constraints of these standards, many materials are excluded; for instance, although $BaTiO_3$ possesses a large electro-optic coefficient (r_{51}) [42], its excessively high piezoelectric coefficient causes acoustic resonances to significantly impact the electro-optic response [43–44]. KH_2PO_4 and KD_2PO_4 exhibit weaker electro-optic effects and are prone to deliquescence, resulting in instability after fabrication; furthermore, achieving optical-grade processing is difficult, and the required electrical drive power is high, limiting their use to applications with modest requirements for power consumption and performance [45]. Potassium Tantalate Niobate (KTN) demonstrates a strong quadratic electro-optic effect and high efficiency, yet growing high-quality, large-sized KTN crystals remains a major challenge; additionally, its extreme temperature sensitivity—requiring temperature fluctuations to be controlled within approximately 0.01°C for most applications—makes it inconvenient to use [46]. Meanwhile, semiconductors such as GaAs, ZnSe, and CdS are limited to infrared applications due to their narrow bandgaps. Lithium niobate (along with lithium tantalate) offers comprehensive advantages in terms of stability, ease of processing, transparency, single-crystal quality, and electro-optic strength; consequently, it has gained widespread favor and remains in use today. Currently, lithium niobate is a primary material for commercial bulk electro-optic modulators and is widely employed in Q-switching for pulsed lasers (see Fig. 1(a)) [47–49]; it also holds a dominant position in fiber-optic communication systems (see Fig. 1(b)). In the realm of on-chip integrated optoelectronics, while silicon-based carrier injection mechanisms currently dominate electro-optic modulation—owing to the compatibility of silicon photonics with traditional microelectronics—lithium niobate-based high-speed electro-optic modulation technologies may soon find new opportunities as bandwidth demands approach and surpass the limits of silicon-based modulators. Fig. 1 Lithium niobate electro-optic modulator: (a) Q-switch for pulsed laser (provided by Nankai University); (b) fiber-coupled electro-optic modulator [50].

1.2 Frequency-doubling characteristics

Following Franken's first observation of the laser frequency-doubling effect in quartz crystal in 1961, nonlinear optics rapidly developed into an independent scientific field. In 1962, Maker invented the angle phase-matching technique based on material birefringence (i.e., critical phase matching) and subsequently developed the Maker fringe method for measuring nonlinear coefficients [51]. That same year, Bloembergen published the paper "Interactions between Light Waves in a Nonlinear Dielectric," in which he described nonlinear optical processes using quantum mechanical perturbation theory and formulated the coupled-wave equations for three-wave (and four-wave) nonlinear interactions; this work laid a crucial theoretical foundation for subsequent research in nonlinear optics. The paper also proposed three phase-correction techniques—one of which evolved into the "quasi-phase-matching technique"—thereby paving the way for the emergence of PPLN [52].

In the years that followed, a significant amount of research in nonlinear optics focused on the search for materials with high nonlinear coefficients. Against this backdrop, in 1964, Boyd and colleagues at Bell Labs conducted the first study on the second-harmonic generation (SHG) characteristics of lithium niobate using a pulsed $CaWO_4$:Nd^{3+} laser. They employed the Maker fringe method to measure the material's nonlinear coefficients, finding the d_{31} and d_{22} values to be 11.9 and 6.3 times that of KDP crystals, respectively; additionally, applying Kleinman symmetry conditions, they estimated that the d_{33} coefficient could reach 107 times that of KDP [21]. Compared to other contemporary crystals (such as quartz, ZnO, and $NH_4H_2PO_4$), lithium niobate exhibited significantly larger nonlinear coefficients. Although its coefficients were smaller than the d_{14} coefficient of GaP or GaAs, the d_{14} component was impractical for use due to polarization configuration constraints that resulted in low out-of-plane radiation efficiency [53]. Furthermore, lithium niobate's exceptionally broad transparency range highlighted its importance for SHG applications spanning the visible to infrared spectral regions.

While angle phase matching could enhance SHG efficiency, it remained limited by issues such as spatial walk-off, optical beam divergence, and the finite spectral width of the incident light. To address this, Miller proposed a method in 1965 to achieve phase matching for SHG in lithium niobate by varying the temperature—a technique later known as temperature phase matching (or non-critical phase matching). Due to the ferroelectric nature of lithium niobate, its dielectric constant (and thus its birefringence) is highly temperature-dependent. By heating the crystal to approximately 200°C, Miller achieved perfect phase matching at a 90° angle, attaining an SHG efficiency of around 5% [54]. Building on this work, he subsequently demonstrated parametric down-conversion oscillation in lithium niobate—converting visible light to infrared light—a development crucial for generating widely tunable coherent light sources [55]. In 1966, he further extended the output of down-conversion parametric oscillation to the visible light range [56].

After mastering crystal growth technology in 1965, the UK Ministry of Defence also began investigating the temperature-dependent birefringence characteristics of lithium niobate [20, 57]. Building on this foundation,

in 1967, Midwinter and colleagues at the Royal Radar Establishment (UK Ministry of Defence) achieved parametric up-conversion (sum-frequency generation) in lithium niobate for the first time using temperature-based phase matching [58]; subsequently, in 1968, they demonstrated the conversion of infrared images into visible light images using this technique [59–60]. Although the up-conversion efficiency was relatively low, the availability of high-performance

detectors and cameras in the visible light range effectively compensated for this limitation. This technology held significant value for infrared imaging detection and played a pivotal role in advancing research and applications in fields such as infrared remote sensing, infrared spectroscopy, astronomy, and long-range monitoring [61–63].

Research into nonlinear difference-frequency generation in lithium niobate was also conducted during the 1970s [64–65]. At the same time, experimental attempts were made to achieve quasi-phase matching—such as by stacking thin plates of GaAs or lithium niobate [66] or by growing GaAs-AlGaAs layered structures using molecular beam epitaxy [67]—but these efforts yielded poor results due to issues like a limited number of stacked layers or imprecise control of the periodicity. In 1980, a research team led by Feng Duan and Min Naiben at Nanjing University successfully grew periodically domain-inverted lithium niobate crystals (i.e., periodically poled lithium niobate, or PPLN) by adjusting doping and off-axis rotation during the growth process to enhance growth striations. This achievement experimentally validated the theory of quasi-phase matching for the first time and pioneered the use of periodic ferroelectric domain structures as a novel class of microstructured functional materials [34, 68–69]. In previous research on lithium niobate, polarization configuration constraints associated with birefringent phase matching limited usage to the non-maximal tensor element d_{31}. Through quasi-phase matching technology, the largest nonlinear tensor element, d_{33}, could be fully utilized, resulting in a boost in second-harmonic generation efficiency by factors of tens to hundreds. Today, quasi-phase matching has become the standard technique for lithium niobate frequency converters (see Fig. 2).

Fig. 2 Lithium niobate frequency converter: (a) lithium niobate crystal with periodic ferroelectric domain structure [70]; (b) high-power red-green-blue laser source [71]

1.3 Piezoelectric Properties

To this day, the piezoelectric effect remains one of the most widely utilized physical properties of ferroelectric materials. As early as 1949, while investigating the ferroelectric properties of lithium niobate, Matthias and Remeika reported its piezoelectric response [14]. However, it was not until Ballman successfully grew lithium niobate using the Czochralski method in 1964 that its piezoelectric coefficients were first measured; at that time, due to the multi-domain nature of the crystal, an electromechanical coupling efficiency of only 30% was achieved. Following breakthroughs in crystal single-domain processing technology, Warner raised this figure to 50% in 1965 [72]. Although this parameter was the highest among water-insoluble crystals at the time, it did not garner widespread attention or application; this was because PZT piezoelectric ceramics—which offered superior performance—had already emerged in the 1950s [73] and captured the primary market for piezoelectric materials, a position they have held unchallenged ever since.

However, between the 1960s and 1980s, as the Cold War between the United States and the Soviet Union intensified, the fields of military radar and electronic countermeasures created an urgent need for microwave delay devices capable of storing and processing microwave signals and generating decoys to jam enemy radar. Lithium niobate demonstrated significant advantages in this context. Compared to materials such as CdS, quartz, BaTiO3, and PZT [74],

lithium niobate is more readily produced as large-sized single crystals. It maintains extremely low transmission loss for elastic acoustic waves in the 500 MHz to 5.5 GHz range across temperatures spanning from liquid helium levels to high temperatures [75]. Furthermore, its high piezoelectric coupling coefficient allows it to function simultaneously as both an ultrasonic transducer and a transmission line; this greatly simplifies device fabrication and effectively enhances the integration level of radio-frequency (RF) delay lines (see Figure 3(a)). In the 1980s, with the widespread adoption of radio and color television technologies, lithium niobate became a primary material for intermediate-frequency (IF) filters. In the current era of booming mobile communications, hundreds of tons of 6-inch (1 inch = 2.54 cm) lithium niobate wafers are produced annually, with 80% ultimately destined for the microwave filter market; surface acoustic wave (SAW) filters based on lithium niobate (or lithium tantalate) continue to hold a significant market share in sectors such as smartphones and satellite receivers (see Figure 3(b)).

Additionally, the high-temperature ferroelectric properties of lithium niobate have secured its irreplaceable status in applications involving extreme environments [76], such as the fabrication of ultrasonic imaging transducers for fast-neutron breeder reactors. Liquid metal is typically used as the coolant in fast reactors, with operating temperatures reaching 600–883°C. Because liquid metal is opaque and electrically conductive, conventional optical and electrical detection methods are unsuitable for core imaging and monitoring, making ultrasonic imaging the only viable approach. As early as the 1970s, the U.S. Department of Energy funded a project focused on liquid-sodium-cooled fast reactors, aiming to develop an ultrasonic system for the periodic monitoring and maintenance of the reactor core. Driven by this initiative, countries such as Germany, Japan, Lithuania, and Belgium also launched related research programs. Lithium niobate—valued for its exceptionally high Curie temperature and ability to retain piezoelectric properties at elevated temperatures—was selected by these nations for the fabrication of the necessary components.

...high-temperature ultrasonic transducers to monitor the status of fast-neutron breeder reactors [77]. Additionally, drilling operations—whether in geological extraction or space exploration—face similar high-temperature challenges. For instance, drilling into deep oil and gas fields or geothermal wells, as well as sampling the surfaces of Venus and Mercury (where surface temperatures are extremely high), involves environments exceeding 300°C, thereby posing a challenge to drilling equipment. Researchers such as Bar-Cohen at NASA's Jet Propulsion Laboratory developed a piezoelectric-driven rock-drilling device using lithium niobate crystals; the piezoelectric actuator generates ultrasonic mechanical vibrations that impact the drill bit to fracture the rock, and experiments have demonstrated its effective operation in environments reaching temperatures as high as 500°C [78–80]. Fig. 3 Acoustic wave delay lines and transducers: (a) comparison between an acoustic wave delay line (red elements) developed in 1967 and a contemporaneous microwave cable delay line [81]; (b) lithium niobate ultrasonic transducer array (German-made) for inspection in sodium-cooled fast reactors [77].

1.4 Photorefractive properties

Among the many nonlinear optical properties of lithium niobate, the photorefractive effect is a relatively recently discovered phenomenon, first identified by Ashkin at Bell Labs in 1966 [82]. In the decades that followed, continuous research was conducted on the photorefractive mechanism and the modulation of its properties; this process also deepened the comprehensive

understanding of microscopic properties such as lattice characteristics, charge carrier transport, energy band structure, defect features, and dopant site occupancy.

In 1966, Nobel laureate Ashkin, while conducting second-harmonic generation (SHG) experiments using lithium niobate, unexpectedly discovered that the crystal's refractive index changed under light irradiation. This change disrupted the phase-matching conditions required for SHG and reduced the conversion efficiency. At the time, this undesirable effect was termed "optical damage." This "optical damage" persisted for a considerable time after the light irradiation ceased. Ashkin noted that "although the effect itself is interesting, it is highly detrimental to lithium niobate nonlinear optical devices" [82]. Two years later, Chen took a different approach by successfully utilizing this "optical damage" to achieve optical holographic storage, thereby identifying a "beneficial" application for this otherwise "harmful" effect [83]. Chen further investigated the physical mechanisms underlying this phenomenon and, in 1969, proposed a model of photo-excited carrier migration: photogenerated carriers migrate—driven by concentration diffusion or the crystal's spontaneous polarization field—into dark regions where they are trapped by acceptors; this process separates positive and negative charges, creating a space-charge electric field that subsequently induces a refractive index change within the crystal via the electro-optic effect [84–85]. Building on this foundation, Kukhtarev et al. formulated the "band transport model" in 1979 and derived the dynamic equations governing the photorefractive effect, successfully providing a quantitative description of both its steady-state and dynamic evolution characteristics [86]. Because this "optical damage" could be completely erased—restoring the crystal to its initial state—through uniform irradiation or heating, it was renamed the "photorefractive effect" to distinguish it from permanent optical damage. Unlike other nonlinear optical effects that require high-power optical fields for excitation, the photorefractive effect is classified as a "low-intensity nonlinear effect." Even with weak light beams, a significant nonlinear response emerges provided there is sufficient time for the accumulation of carrier migration and trapping; this characteristic has generated immense interest and research activity surrounding the photorefractive effect. Research into the photorefractive properties of lithium niobate over the past few decades has generally diverged into two distinct directions: suppressing the photorefractive effect to enhance the crystal's resistance to optical damage, and conversely, enhancing the effect to improve saturation diffraction efficiency and response speed.

Improving lithium niobate's resistance to the photorefractive effect is primarily achieved by introducing dopant ions into the crystal lattice. Among all the dopant ions used for this purpose, magnesium is the most well-known. Initially, small amounts of magnesium were doped into lithium niobate crystals to reduce growth striations and improve lattice quality [87]. Later, it was discovered that the introduction of magnesium ions could effectively lower the erasure temperature for "optical damage" (photorefraction) while raising the phase-matching temperature for second-harmonic generation [88]. By simply controlling the magnesium content to raise the phase-matching temperature above the photorefractive erasure temperature, it became possible to eliminate the effects of photorefraction while achieving high second-harmonic generation efficiency. Extensive research was conducted on magnesium doping concentrations and crystal growth conditions; however, the problem of degraded lattice quality associated with high magnesium doping levels remained unresolved [88]. In 1980, a collaborative effort between Nankai University and the Southwest Institute of Technical Physics

led to a breakthrough in the growth technology for heavily magnesium-doped lithium niobate. Researchers discovered that when the magnesium doping level exceeded a threshold of 4.6% (molar fraction), the crystal's resistance to photorefraction improved by more than two orders of magnitude. This achievement attracted widespread attention from scholars both domestically and internationally, and the crystal was hailed abroad as the "Star of China" [33]. This breakthrough opened up new avenues for crystal applications; for instance, magnesium-doped, photorefraction-resistant crystals are now commercially used in nonlinear devices such as Q-switches and optical frequency doublers. Additionally, these crystals have been utilized to fabricate titanium-diffused integrated waveguide electro-optic modulators, which entered the market in the 1980s and are widely employed in fiber-optic communication systems. Beyond magnesium, researchers such as Volk [89], Yamamoto [90], and Kong Yongfa [91] discovered—between 1990 and 1994—three other dopants (zinc, scandium, and indium) capable of conferring photorefractive resistance. Subsequently, Kong Yongfa and his team further developed the use of tetravalent dopants—specifically hafnium [92-93], zirconium [94-95], and tin [96]—to enhance photorefractive resistance. Compared to early divalent and trivalent dopants, tetravalent elements require lower doping concentrations to achieve the same level of resistance to photorefraction; notably, lithium niobate crystals doped with 2.0% zirconium exhibit far superior photorefractive resistance compared to those doped with 6.5% magnesium. This reduction in doping concentration facilitates the growth of high-quality single crystals and lays the foundation for fabricating high-performance lithium niobate devices, while also filling the gap for photorefractive-resistant crystals in the ultraviolet spectral range [9].
On the other hand, following Chen's 1968 report on holographic experiments with lithium niobate, the significant potential of this low-light nonlinear effect for optical information processing and storage was recognized. Between the 1960s and 1990s, as information technology advanced, existing storage media—such as magnetic tapes, magnetic disks, and optical discs—could no longer meet the rapidly growing demand for data storage. Holographic storage capacity is proportional to the cube of the reciprocal of the optical wavelength, with a theoretical limit reaching 10^{12} bits/cm³ [97]—far exceeding that of traditional one-dimensional and two-dimensional storage systems. Extensive research led to the development of encoding techniques based on angle [98], space [99], phase [100], and wavelength [101], enabling information to be encoded across different dimensions to enhance storage density. However, it was observed that photorefractive holography is consistently affected by noise arising from light-induced light scattering (specifically, the optical fanning effect) [102]. The research group led by Xu Jingjun and Zhang Guangyin at Nankai University discovered the irradiation spot size effect [103–104] and the "light-crawling" effect [105] associated with light-induced light scattering. These findings provided direct experimental evidence regarding the origins of the "light fanning" phenomenon. By successfully applying these insights to the theoretical analysis of holographic light scattering and achieving noise suppression, the team increased storage capacity to over 10 Tbit/cm²—a thousand times greater than that of 2D disks at the time—and developed a prototype for a 3D holographic mass storage system. In 2000, Xu et al. [106] further discovered the ultraviolet (UV) photorefractive enhancement effect in highly Mg-doped lithium niobate crystals, challenging the prevailing international consensus that magnesium was strictly an anti-photorefractive element. The ability to induce the photorefractive effect in the shorter-wavelength UV range meant that holographic gratings could be made smaller and with

finer resolution. Lamarque et al. [107] utilized the highly Mg-doped lithium niobate crystals provided by Nankai University as the UV photorefractive medium to achieve programmable 2D laser marking via two-wave coupling optical amplification. Unfortunately, in the early 21st century, the application of the giant magnetoresistance (GMR) effect dramatically increased the storage capacity of mechanical hard drives, causing optical holographic storage to fade from public view. However, in recent years, the rapid development of internet technologies—such as cloud computing—has led to a surge in demand for massive data throughput in data centers. Consequently, optical holographic storage technology has regained attention due to its advantages of high capacity and high bandwidth, and it is now considered a viable solution for information access challenges in next-generation cloud networks [108]. Additionally, the recent advancement of technologies such as virtual reality and human-computer interaction has increased the demand for 3D volumetric displays; erasable and rewritable photorefractive holographic technology represents a key method for realizing dynamic 3D displays [109]. This requires photorefractive materials to possess characteristics such as high holographic diffraction efficiency, short response times, and rapid erasure speeds; however, materials simultaneously meeting these requirements have long been lacking. Addressing these needs, the research group led by Kong Yongfa and Xu Jingjun at Nankai University developed novel lithium niobate crystals—such as those co-doped with molybdenum and magnesium [110] or bismuth and magnesium [111]—which significantly enhanced photorefractive sensitivity and response speed, enabling real-time holographic displays with refresh rates of 30 Hz [112] (as shown in Fig. 4).

Fig. 4 A variety of lithium niobate crystals with different doping elements (provided by Nankai University)

2 Current Status

In recent years, the rapid development of micro- and nano-technologies has drawn widespread attention to research in lithium niobate micro- and nano-photonics. This section outlines the current state of lithium niobate research by highlighting progress in this field.

Following the invention of the laser, there was immense interest in utilizing photons for information interconnection and processing. Inspired by microelectronic integration technology, Miller of Bell Labs first proposed the concept of integrated optics in 1969 [113] with the aim of reducing the size and manufacturing costs of optical information systems. Lithium niobate (and lithium tantalate) is considered an ideal substrate material for integrated optical chips due to properties such as low optical absorption loss, a high electro-optic coefficient, strong nonlinearity, and high electrical resistivity (which reduces the power required for electro-optic modulation). Between 1973 and 1982, techniques such as out-diffusion of lithium ions [114], in-diffusion of titanium ions [115], and proton exchange [116] were developed, successfully enabling the fabrication of lithium niobate optical waveguides. These methods have since become the primary techniques for manufacturing commercial lithium niobate waveguides. However, waveguides fabricated using the aforementioned techniques exhibit a small refractive index contrast between the core and cladding, resulting in weak optical confinement and a large mode field area (typically on the order of 10 μm). Furthermore, significant optical leakage loss occurs at small bending radii, which limits the integration density of optical devices. To address these issues, Levy et al. at Columbia University employed the "ion slicing" (or "Smart Cut") technique in 1998 to successfully fabricate 9-μm-thick lithium niobate thin films and bond them to silicon and gallium arsenide substrates using epoxy resin—a structure now known as lithium

niobate-on-insulator (LNOI) [117]. However, because epoxy resin cannot withstand high temperatures, it was impossible to reduce the lattice damage induced during the ion slicing process via high-temperature annealing; consequently, the optical properties of the resulting thin films were far inferior to those of bulk materials. In 2004, Rabiei and Günter successfully fabricated LNOI thin films using SiO_2 as the bonding layer and employed high-temperature annealing to achieve optical properties comparable to those of bulk single crystals [118]. In 2010, Hu et al. successfully applied the "Smart Cut" technology to the wafer-scale fabrication of lithium niobate thin films, producing high-quality single-crystal thin-film wafers with a diameter of 3 inches, thereby laying a solid foundation for subsequent commercialization [119–120]. Lithium niobate crystals possess high hardness, stable physical properties, and chemical inertness; while these characteristics are advantageous for practical device applications, they also pose significant challenges for micro- and nanofabrication. In recent years, novel micro- and nanofabrication techniques for lithium niobate, such as dry etching and laser direct writing, have been developed. In dry etching, patterns are first defined in a photoresist (such as HSQ) or a hard mask (such as Cr, Ni, or SiO_2) using electron-beam lithography or ultraviolet photolithography; subsequently, plasma etching is employed to transfer the mask pattern onto the lithium niobate layer, thereby fabricating the waveguide. Using this technique, the Loncar group at Harvard University successfully fabricated a waveguide with a propagation loss of only 2.7 dB/m in 2017 [121]. In 2019, the same group extended this fabrication process to the visible light spectrum, achieving a waveguide with a propagation loss of approximately 6 dB/m [122]. In 2018, the Cheng Ya group at East China Normal University proposed a waveguide fabrication technique combining femtosecond laser direct writing with chemical-mechanical polishing. This method involves patterning a Cr mask using a femtosecond laser, followed by transferring the pattern to the lithium niobate layer via chemical-mechanical polishing, resulting in an optical waveguide with a loss as low as 2.7 dB/m [123–124]. Due to the significant refractive index contrast (approximately 0.7) between the top lithium niobate thin film and the intermediate insulating layer in LNOI, optical field confinement is greatly enhanced.

...field dimensions can be reduced to the order of 1 μm [125], providing a novel material platform for the fabrication of highly integrated lithium niobate optical waveguides and fueling the rapid development of lithium niobate integrated photonics in recent years. Several review articles have recently detailed these advancements [9-10, 126-134]; this paper highlights selected representative achievements in the field, focusing on waveguide electro-optic modulators, optical microcavities, and metasurfaces.

2.1 Waveguide Electro-optic Modulators

Due to the large mode areas associated with ion-diffused or proton-exchanged waveguides, electrodes must be spaced widely apart to minimize optical absorption losses caused by the electrodes. Consequently, achieving sufficient phase modulation at lower driving voltages often requires long waveguides. However, the disparity in dispersion characteristics between optical waves and microwaves in lithium niobate leads to significant group velocity mismatch, which severely limits waveguide length and hinders increases in modulation frequency. In 2018, the Loncar group at Harvard University successfully addressed the limitations of traditional technologies by using dry etching to fabricate LNOI ridge waveguides, realizing an ultra-high-speed on-chip LNOI electro-optic modulator compatible with CMOS driving voltages.

By optimizing the thicknesses of the lithium niobate and SiO_2 layers to achieve group velocity matching between optical waves and microwaves, they demonstrated an electro-optic modulator with a half-wave voltage of 1.4 V, an electrode length of 20 mm, a 3 dB bandwidth of 45 GHz, and a total insertion loss of less than 0.5 dB. When the electrode length was further reduced to 5 mm, the device's 3 dB bandwidth increased to 100 GHz (see Fig. 5(a)) [135]. Around the same time, the research groups of Cai Xinlun and Yu Siyuan at Sun Yat-sen University realized a silicon-based hybrid-integrated lithium niobate electro-optic modulator featuring a modulation bandwidth exceeding 70 GHz, an insertion loss of 2.5 dB, and a figure of merit of 2.2 V·cm. This modulator employs a dual-layer waveguide structure in which the silicon waveguide handles optical transmission while the lithium niobate waveguide performs modulation; optical modes couple efficiently from the silicon waveguide to the lithium niobate waveguide, thereby enabling effective modulation (see Figure 5(b)) [136]. In 2019, Wu et al. fabricated multiple cascaded Mach-Zehnder interferometer waveguides on a single LNOI wafer using femtosecond laser direct writing assisted by chemical-mechanical polishing, realizing a multifunctional, reconfigurable photonic chip based on the electro-optic effect. The chip comprises seven Mach-Zehnder interferometers, four electro-optic phase shifters, and a micro-electrode array, with an overall footprint of 6.5 cm × 0.2 cm. It demonstrated functionalities including a high-extinction-ratio (~28 dB) beam splitter, a 1×6 optical switch, and a 3×3 balanced interferometer, thereby proving the feasibility of realizing large-scale photonic integrated circuits using low-loss waveguides (see Figure 5(c)) [137]. However, the lengths of the aforementioned electro-optic modulators remain on the order of millimeters to centimeters, making high-density integration difficult to achieve. In 2020, Li et al. at the University of Rochester fabricated a lithium niobate photonic crystal waveguide and realized an electro-optic modulator with dimensions on the order of the wavelength; the device exhibited a modulation bandwidth of 17.5 GHz, a tuning efficiency of 16.0 $pm \cdot V^{-1}$, and an electro-optic mode volume of only 0.58 μm^3, providing a technical foundation for achieving low-energy, high-density integrated photonic circuits (see Fig. 5(d)) [138].

Fig. 5 LNOI-based waveguide electro-optic modulators: (a) on-chip electro-optic modulator compatible with CMOS driving voltage [135]; (b) silicon/lithium niobate heterostructure electro-optic modulator [136]; (c) reconfigurable multifunctional photonic integrated chip [137]; (d) compact electro-optic modulator based on lithium niobate photonic crystal [138].

2.2 Optical Microcavities

An optical microcavity is an optical resonator capable of confining an optical field within a region on the micrometer scale. It utilizes the reflection, scattering, or diffraction of light at interfaces with dielectric constant discontinuities to confine optical energy within a tiny region, where it oscillates back and forth. Characterized by small mode volumes and high quality factors, this structure significantly extends the photon lifetime within the cavity and enhances light-matter interaction. It plays a crucial role in applications such as narrowband filtering, low-threshold lasing, nonlinear frequency conversion, high-sensitivity optical sensing, and quantum optics, serving as a vital functional unit in integrated optical circuits [139–142]. In 2015, the research group led by Ya Cheng at East China Normal University successfully fabricated lithium niobate microdisk cavities using femtosecond laser direct writing combined with focused ion beam etching; a quality factor of 2.5×10^5 was achieved at a wavelength of 1,550 nm [143]. That same year, the group led by Fang Bo at Nankai University also successfully fabricated lithium niobate

microdisk cavities using a combination of ultraviolet lithography and dry etching, achieving a quality factor of 1.19×10^6 [144]. In 2019, the group led by Xianfeng Chen at Shanghai Jiao Tong University successfully fabricated bilayer microdisk cavities with quality factors on the order of 10^5 [145].

Recently, continuous advancements in lithium niobate micro/nanofabrication technologies have led to steadily increasing microcavity quality factors, enabling the realization of various photonic functions such as nonlinear frequency conversion, optical frequency combs, and laser sources. For instance, in 2019, Ya Cheng's group boosted the microdisk cavity quality factor to 9.61×10^6 and utilized the natural quasi-phase-matching mechanism to achieve second-harmonic generation with an efficiency of 9.9%/mW and cascaded third-harmonic generation with an efficiency of 1.05%/mW². That same year, Cheng Wang and colleagues at Harvard University successfully demonstrated a lithium niobate third-order Kerr optical frequency comb (see Figure 6(a)) [146] using a microring resonator with a quality factor on the order of 10^6; the generated TE-mode comb spectrum spanned the 1,400–2,100 nm wavelength range. By integrating an electro-optically tunable add-drop filter with the frequency comb generator on a single chip, the device simultaneously achieved tunable filtering and intensity modulation of the comb, with a filtering suppression ratio of 47 dB and a modulation rate of up to 500 Mbit/s. However, the physical process of generating optical frequency combs based on the Kerr effect is complex, suffers from poor stability, and makes spectral bandwidth control difficult. To address these issues, researchers have successfully utilized second-order electro-optic phase modulation to generate optical frequency combs. Although this method offers high stability and excellent controllability, previously reported electro-optic frequency combs exhibited spectral widths of only a few nanometers due to weak nonlinear interactions and a lack of dispersion control. To overcome this, Mian Zhang and colleagues at Harvard University fabricated an LNOI (lithium niobate-on-insulator) microracetrack resonator with a quality factor on the order of 10^6 to enhance the electro-optic effect; they successfully demonstrated a broadband electro-optic frequency comb with over 900 lines and a spectral width exceeding 80 nm, covering the entire L-band and parts of the C- and U-bands. Furthermore, by driving the device with two microwave signals of different frequencies, researchers realized a "dual-comb" system on a single microring containing two pulse repetition rates simultaneously, with the difference between the repetition rates continuously tunable from 10 Hz to 100 MHz [147]. Meanwhile, research into lithium niobate microcavity lasers has also recently achieved breakthroughs; by doping with rare-earth elements, lithium niobate can serve as a gain medium to achieve laser emission. Research groups led by Chen Xianfeng, Bo Fang, and Cheng Ya have successively succeeded in fabricating erbium-doped LNOI micro-disk cavities. By employing a 980 nm pump laser and utilizing the radiative transition of Er^{3+} ions from the $^4I_{13/2}$ energy level to the $^4I_{15/2}$ level, they realized on-chip integrable laser sources operating in the 1550 nm telecommunications band—results that hold significant potential for applications in fiber-optic communications (see Fig. 6(b)) [148–151].

Fig. 6 LNOI-based optical microcavities: (a) Kerr optical frequency comb and electrically tunable add-drop filter based on an LNOI microring resonator [146]; (b) erbium-doped lithium niobate micro-disk laser [149].

2.3 Metasurfaces

Metasurfaces are a novel class of artificial sub-wavelength micro-nano structured materials. Through the design of artificial constituent elements and their spatial arrangement, they achieve light-field manipulation capabilities far exceeding those of natural materials, enabling flexible control over the phase, amplitude, and polarization state of electromagnetic waves [152]. With thicknesses on the order of the wavelength or even less, metasurfaces offer excellent integration capabilities for micro-nano optics and provide novel design principles for developing compact optical devices. Research into metasurfaces has garnered widespread attention in recent years, leading to the realization of innovative optical devices such as metalenses, ultrathin waveplates, and holograms. Furthermore, the scope of metasurface research has expanded from linear optics to nonlinear optics [153–154] and from classical optics to quantum optics [155], demonstrating immense application potential. Metal metasurfaces based on surface plasmons typically exhibit significant losses, particularly in the visible light range, which severely limits their transition to practical applications. Consequently, attention has shifted toward dielectric metasurfaces based on Mie resonances. These metasurfaces are generally composed of dielectric or semiconductor materials—such as Si, GaAs, and TiO_2—characterized by low loss, high refractive indices, and high nonlinear coefficients. Silicon-based metasurfaces [156–158] have attracted widespread interest due to their fabrication compatibility with CMOS processes; however, Si possesses centrosymmetry and lacks second-order nonlinear effects such as frequency doubling and the electro-optic effect. GaAs has a narrow bandgap, making it unsuitable for visible-light applications, and its symmetry limits the efficiency of second-order nonlinear excitation and out-of-plane radiation [159–160]. While TiO_2 exhibits low loss in the visible range, it lacks electro-optic and acousto-optic effects, making it difficult to realize metasurface components with dynamically controllable performance [161–162]. Lithium niobate crystals, possessing a combination of properties—including high transparency, electro-optic, acousto-optic, thermo-optic, and photorefractive effects—serve as ideal substrate materials for realizing high-efficiency dielectric metasurfaces. In 2018, the research group led by Mengxin Ren and Jingjun Xu at Nankai University theoretically designed a gradient metasurface composed of lithium niobate nanopillars, demonstrating excellent capabilities for wavefront splitting and manipulation [163]. In 2019, the research group overcame fabrication challenges associated with lithium niobate (LN) nano-metasurfaces. By employing focused ion beam (FIB) etching with a novel "high-energy bombardment plus low-energy cleaning" process—which mitigated lattice damage caused by the ion beam during fabrication—they successfully produced sub-wavelength LN nanograting metasurfaces that exhibited excellent resonant spectral filtering and structural color characteristics (see Fig. 7(a)) [164]. Subsequently, addressing the issue where traditional methods (such as the Maker fringe technique) could not accurately measure the nonlinear coefficients of LN micro/nanostructures—due to their thickness being far less than the nonlinear coherence length—the group invented a new second-order nonlinear measurement technique named "PolariSH." This enabled the complete measurement of the nonlinear susceptibility tensor of LN nanofilms [165]. Building on this, the group utilized LN metasurfaces to achieve resonant enhancement and spectral control of optical second-harmonic generation (SHG); compared to unstructured LN films, the conversion efficiency was enhanced by up to fivefold (see Fig. 7(b)) [166–167]. Fedotova et al. from the University of Jena (Germany) investigated resonant SHG enhancement and polarization-dependent properties of LN metasurfaces in the 1550 nm wavelength range (see

Fig. 7(c)) [168]. That same year, Carletti et al. from the Australian National University used FIB etching on bulk LN material to fabricate nonlinear nanopillar metasurfaces, experimentally observing a significant enhancement of the SHG effect driven by structural magnetic dipole resonance [169]. In 2020,
Li Tao's research group at Nanjing University integrated a metasurface with a lithium niobate slab waveguide. By utilizing the reciprocal lattice vector phase matching provided by a nanograting metasurface,
they directly converted fundamental-frequency light from free space into second-harmonic light within the waveguide mode and demonstrated functionalities such as beam focusing and Airy beam generation [170],
offering a new design approach for the multifunctional integration of related metasurface devices (see Fig. 7(d)).
Lithium niobate has a bandgap of approximately 4 eV, and its low-loss characteristics extend into the near-ultraviolet spectral range [171–172]. In 2019, Timpu et al. [173]
synthesized lithium niobate nanocubes with dimensions of approximately 200–300 nm using a solvothermal method; these nanocubes
are capable of producing efficient linear and nonlinear scattering in the near-ultraviolet range.
...emission. Experimental results indicate that the second-harmonic conversion efficiency at a wavelength of 360 nm can reach
Fig. 7 Lithium niobate metasurfaces: (a) structural color from lithium niobate metasurfaces (top panel: SEM image; bottom panel: optical photograph) [164]; (b–d) control of second-harmonic signals by lithium niobate metasurfaces [166–168, 170]; (e) electro-optic lithium niobate metasurface and phase modulation of light waves [174]

7.6×10^{-7} W^{-1}, representing a seven-order-of-magnitude enhancement compared to bulk lithium niobate. Notably, Ren Mengxin [167], Carletti [169], and others have also observed second-harmonic enhancement near the 400 nm wavelength. It is anticipated that as research into lithium niobate micro-nano photonics deepens, the material's low-loss advantage can be fully leveraged to realize high-efficiency ultraviolet second-harmonic generation devices.
Recently, Gao Bofeng and colleagues at Nankai University experimentally investigated the electro-optic modulation characteristics of resonant lithium niobate metasurfaces (see Fig. 7(e)). Under oblique incidence, lithium niobate nanograting metasurfaces can generate quasi-bound states in the continuum (Q-BIC) resonance modes. By leveraging the high-Q nature of this resonance mode to enhance the nonlinear electro-optic interaction between the optical field and the lithium niobate, researchers achieved dynamic control over the phase of transmitted light. The modulation performance significantly surpassed that of unstructured thin films of the same thickness, thereby validating the feasibility of using lithium niobate metasurfaces for novel micro/nano electro-optic modulation [174].

3 Conclusion and Outlook

Lithium niobate crystals possess a unique combination of excellent optoelectronic properties, making them highly valuable among optoelectronic materials. After nearly a century of development, lithium niobate has secured an indispensable role in fields such as national security, medical diagnostics, high-energy physics, and industrial inspection. my country has

established a stable research workforce—comprising senior, mid-career, and young researchers—dedicated to crystal preparation, property tuning, and device development, while also gradually cultivating a complete industrial chain spanning upstream, midstream, and downstream sectors. With the rapid rise of microelectronics and optoelectronics technologies, the demand for lithium niobate materials and their associated core devices is poised for explosive growth. To maintain my country's existing advantages in lithium niobate research and application and to secure a more strategic position in the future, it is essential to take proactive measures in the following areas:

First, regarding raw material acquisition: According to the *Annual Review of World Mineral Resources*, lithium and niobium are relatively abundant in nature, ranking 27th and 33rd respectively among all chemical elements, with natural crustal reserves of approximately 11 million tons and 4.2 million tons. According to China's *Handbook of Industrial Requirements for Mineral Resources* (2010), the country possesses abundant lithium resources. Three major production bases have been established in Xinjiang, Sichuan, and Jiangxi, with a combined production capacity exceeding 20,000 tons (in lithium carbonate equivalent); meanwhile, lithium resources in the salt lakes of Tibet and Qinghai are also under development. Furthermore, the deepening implementation of new energy strategies in recent years has driven up the demand for lithium batteries and focused attention on the development and utilization of lithium resources—trends that are likely to simultaneously stimulate the growth of the lithium niobate raw material industry. On the other hand, niobium ore deposits are primarily located in countries such as Brazil and Canada; these two nations have been the largest producers of niobium concentrate since 1950. The world's two largest deposits are situated in the Brazilian states of Minas Gerais (operated by CBMM) and Goiás (owned by Anglo American), with their combined output accounting for 75% of the global total. As of 2013, CBMM controlled 85% of global niobium production. In contrast, China faces a disadvantage regarding niobium reserves; proven deposits are mainly distributed across Inner Mongolia, Xinjiang, and Jiangxi, and are typically found in association with tantalum ores. To secure my country's strategic position in the field of lithium niobate for the future, it is essential to explore new deposits and maintain close cooperation with raw material-producing nations.

Secondly, there is an urgent need to establish unified and practical standards and specifications for crystals to rectify the current issue of inconsistent quality across different manufacturers and production batches. For instance, current lithium niobate crystal growth involves various techniques—such as the Czochralski method, gradient growth, and the edge-defined film-fed growth (EFG) method—resulting in varying quality and defect levels. Significant fluctuations in mechanical, optical, and electrical properties hinder large-scale, production-line applications. Drawing on the development experience of the microelectronics industry, future efforts should focus on formulating standards covering growth processes, crystal dimensions, defect levels, doping types, flatness, surface particles and metal contamination, inspection methods and rules, as well as marking, packaging, transportation, and storage. Establishing such standards will enhance crystal growth quality and stability, thereby enabling a foothold in the high-end international market.

Furthermore, cost factors must be considered to facilitate the translation of lithium niobate research into the consumer optoelectronics industry. Based on the current state of development, optoelectronic hybrid integration is expected to remain the primary technological pathway for the

coming decades. Lithium niobate supports the transmission of visible light at shorter wavelengths and theoretically offers higher carrier bandwidths than silicon-based optoelectronic devices; indeed, current research indicates that lithium niobate can achieve modulation speeds far exceeding those of silicon devices, suggesting promising opportunities for the technology. However, due to immature fabrication processes and a refractive index lower than that of silicon, lithium niobate devices remain relatively large and suffer from low integration density, which significantly drives up the cost per bit of information per unit area. Furthermore, lithium niobate technology is not yet fully compatible with current silicon-based microelectronics processes, and manufacturing costs remain high. To address these challenges, it is essential to refine fabrication processes, bridge the gap between lithium niobate and existing microelectronics technologies, and achieve process compatibility. Simultaneously, developing new theories for optical information processing and computing—while leveraging advanced technologies such as metasurfaces, nanophotonic waveguides, and optical neural networks—will enable optimized device designs. Such designs can push the material's properties to their limits, increase information processing bandwidth, enhance processing efficiency within a given footprint, and ultimately reduce the cost per bit.

Finally, critical challenges regarding specific optoelectronic devices—such as electrically pumped light sources and photodetectors based on lithium niobate—remain to be resolved. In the foreseeable future, electrical energy will continue to be the primary medium for information generation and storage. Consequently, developing lithium niobate-based light sources and detectors to facilitate the conversion between photons and electrons is a crucial step in establishing a comprehensive lithium niobate photonic device ecosystem. However, as an indirect bandgap material, lithium niobate exhibits extremely low light-emission efficiency via bandgap transitions, making direct electrical-to-optical conversion via electrical injection impossible. At the same time, its exceptionally wide bandgap—while responsible for its remarkably low optical loss—prevents the efficient photon absorption required for photodetection. To address the aforementioned issues, it is necessary to develop novel nanotechnology and doping science, modify the band structure of lithium niobate, and achieve electrically injected luminescence and photodetection in the material.

Lithium niobate has already surpassed the age of eighty and is approaching its centennial; with the advancement and refinement of micro/nano-material science, fabrication processes, and novel device science, this "classic" crystal is certain to exert a "new" influence on the world in the future. References

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