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Advances in Thin-Film Lithium Niobate High-Speed Electro-Optic Modulators

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Abstract

The thin-film lithium niobate (TFLN) platform, with high refractive-index contrast and a strong linear electro-optic effect, offers a viable pathway to overcoming the performance limitations of conventional bulk-material electro-optic modulators. This paper systematically reviews key technological advances in TFLN high-speed electro-optic modulators. In terms of synergistic optimization of modulation efficiency and electro-optic bandwidth, three technical routes are summarized: microstructured electrode design, waveguide mode engineering, and velocity-matching strategies, encompassing periodically capacitively loaded T-electrodes, slow-wave electrodes, buried dual-capacitor structures, slot waveguides, and high-permittivity cladding. These approaches have reduced the half-wave voltage-length product ($V\pi L$) to 1–2.5 V·cm and pushed the 3 dB electro-optic bandwidth beyond 140 GHz. In terms of functional expansion and heterogeneous integration, polarization-independent modulation, Si/SiN, and chalcogenide glass heterogeneous integration technologies are reviewed, along with application-specific designs for ultrashort pulse generation, laser ranging, and fully packaged devices. Different technical routes exhibit distinct performance trade-offs: microstructured electrodes and optical mode engineering can significantly enhance modulation efficiency but at the cost of increased fabrication complexity, higher coupling loss, and enhanced high-frequency dispersion; heterogeneous integration offers advantages in bandwidth extension and functional convergence, yet faces challenges in thermal management, interfacial defects, and material compatibility. Currently, the development of TFLN modulators is transitioning from single-parameter performance enhancement toward comprehensive optimization of efficiency, bandwidth, loss, and manufacturability. Multi-objective co-design and optoelectronic co-packaging will represent important future directions.

Keywords

thin-film lithium niobate, electro-optic modulator, Mach–Zehnder interferometer, half-wave voltage-length product

1. Introduction

With the rapid growth of global data traffic, high-speed optical communication and microwave photonic systems impose increasingly stringent requirements on the bandwidth, power consumption, size, and integration density of electro-optic modulators [1]. Conventional bulk lithium niobate modulators form waveguides via titanium diffusion or proton-exchange processes, resulting in low refractive-index contrast and weak optical field confinement. A relatively large spacing must be maintained between the electrode and waveguide to avoid metal-induced optical absorption loss, resulting in a half-wave voltage-length product (VπL) typically exceeding 10 V·cm and a device length beyond 5 cm, rendering these devices ill-suited for next-generation photonic integrated chips that demand compact footprint, low power consumption, and high bandwidth [2].

The thin-film lithium niobate-on-insulator (TFLN) platform has fundamentally overcome the performance constraints of conventional bulk materials by virtue of its high refractive-index contrast and strong linear electro-optic effect [1,2]. In 2018, Wang et al. reported the first X-cut TFLN-based MZI electro-optic modulator, achieving VπL = 2.2 V·cm and a 3 dB electro-optic bandwidth of 100 GHz [3], marking a critical step from proof-of-concept toward high-performance practical devices. In 2020, Cai Xinlun et al. demonstrated a TFLN IQ coherent modulator operating at 320 Gbit/s, marking the transition of the TFLN platform from simple intensity modulation to coherent modulation [4]. In 2025, Yu et al. leveraged a ridge-top transparent electrode to dramatically reduce VπL to 0.33 V·cm while maintaining an extrapolated bandwidth of 145 GHz, achieving an order-of-magnitude improvement in modulation efficiency [5]. In the same year, Kakolaki et al. employed a segmented coaxial transmission line electrode to realize a simulated electro-optic bandwidth of 1 THz, pushing the frequency of TFLN modulators into the terahertz regime for the first time [6]. This paper systematically reviews key technological advances in TFLN high-speed electro-optic modulators, focusing on two principal directions: synergistic optimization of modulation efficiency and electro-optic bandwidth, and functional expansion and heterogeneous integration. The technical costs within the efficiency–bandwidth–loss trade-off triangle are analyzed, and future development trends are discussed.

2. Theoretical Foundations

2.1 Mach–Zehnder Interferometer Structure and Operating Principle

Thin-film lithium niobate electro-optic modulators predominantly adopt the Mach–Zehnder interferometer (MZI) configuration. Input light is split equally by a first-stage multimode interference coupler into two beams that respectively enter the two modulation arms. A traveling-wave coplanar waveguide electrode applies a push-pull modulation voltage, exploiting the linear electro-optic effect (Pockels effect) of the lithium niobate crystal to alter the waveguide refractive index. After the two arms accumulate a phase difference, the beams are recombined by a second-stage coupler to achieve intensity modulation. For X-cut TFLN, the refractive index change for TE-mode propagation satisfies [1,7]:

$$\Delta n_e = -\frac{1}{2} n_e^3 \gamma_{33} E_z \quad (1)$$

where n_e is the extraordinary refractive index, γ_{33} is the maximum electro-optic coefficient, and E_z is the electric field component along the crystal Z-axis.

2.2 2.2 Key Figure of Merit for Modulation Efficiency

The key figure of merit for modulation efficiency is the half-wave voltage-length product VπL, defined as the product of the drive voltage Vπ required to switch the modulator output intensity from maximum to minimum and the modulation region length L. For a push-pull MZI electro-optic modulator, VπL can be expressed as [1,8]:

$$V_\pi L = \frac{\lambda G}{2 n_e^3 \gamma_{33} \Gamma} \quad (2)$$

where λ is the operating wavelength, G is the spacing between the signal and ground electrodes, and Γ is the electro-optic overlap integral factor, i.e., the normalized overlap integral of the optical field and the microwave electric field over the waveguide cross-section [7].

Equation (2) indicates that reducing the electrode gap G or increasing the overlap factor Γ can lower VπL. The TFLN platform, with its high refractive-index contrast, compresses the mode field area to the sub-micron scale, reducing G to 3–5 μm and significantly enhancing Γ, thereby overcoming the efficiency bottleneck of conventional bulk-material modulators [2,9].

2.3 Factors Limiting Electro-Optic Bandwidth

The 3 dB bandwidth of an electro-optic modulator is collectively governed by impedance matching, velocity matching, and microwave propagation loss [8,10]. In the TFLN platform, the extremely small electrode-to-waveguide spacing (sub-micron to several microns), large differences in dielectric constant among substrate materials (silicon, quartz, etc.), and the introduction of microstructured electrodes (periodic capacitive loading, slow-wave structures, etc.) render the high-frequency microwave loss and dispersion mechanisms more complex and platform-specific than those in conventional bulk devices [11].

The microwave propagation loss α_m is primarily composed of conductor loss and dielectric loss [12]. Due to the skin effect, at high frequencies (>40 GHz) the microwave current concentrates at the electrode surface, with the skin depth ($\delta=\sqrt{\frac{2}{\omega\mu\sigma}}$) inversely proportional to the square root of frequency; current crowding at sharp corners in periodically microstructured electrodes further exacerbates the loss [11]. In terms of dielectric loss, the loss tangent tan δ of the SiO_2 buried layer is on the order of 10^{-4}, but the dielectric relaxation behavior of high-k materials such as $BaTiO_3$ can elevate tan δ to the order of 0.1 in the tens-of-GHz regime, necessitating a trade-off between modulation efficiency enhancement and increased dielectric loss [13]. Regarding radiation loss, a high-permittivity silicon substrate ($\varepsilon_r \approx 11.9$) enhances radiation leakage, which can be effectively suppressed by employing a quartz substrate or substrate undercut [3].

The velocity matching condition—that the microwave phase velocity $v_m = \frac{c}{n_m}$ equals the optical group velocity $v_g = \frac{c}{n_g}$ —is central to broadband performance [11]. In conventional coplanar waveguides, n_m exhibits weak dispersion with increasing frequency. However, upon introducing microstructures such as periodically capacitively loaded T-electrodes and slow-wave electrodes, the transmission line displays strong dispersion characteristics: n_m increases sharply near the cutoff frequency, and velocity matching holds only within a narrow band; outside this band, $|n_m - n_g|$ rapidly increases, leading to bandwidth collapse [9]. Concurrently, the optical field energy in TFLN ridge waveguides is distributed among the lithium niobate core, the low-index buried layer (SiO_2), and the upper cladding, such that the optical group index n_g (typically 2.2–3.0) varies with wavelength, exhibiting waveguide dispersion that indirectly affects pulse broadening in ultra-broadband (>100 GHz) modulators [11].

The frequency response function can describe the combined influence of the aforementioned factors on electro-optic bandwidth [8,10]:

$$H(\omega) = 20\log\left|\frac{2Z_{in}}{Z_0+Z_{in}}\right| \cdot e^{-\alpha_m L/2} \cdot \sqrt{\frac{\sinh^2(\alpha_m L/2)+\sin^2(bL/2)}{(\alpha_m L/2)^2+(bL/2)^2}} \quad (3)$$

where Z_{in} is the input impedance, Z_0 is the characteristic impedance of the transmission line, α_m is the microwave propagation loss, L is the modulation region length, and $b = \frac{2\pi f}{c}\left(n_m - n_g\right)$ is the velocity mismatch term. Equation (4) reveals that when α_m or b increases, the high-frequency response degrades rapidly. To achieve a 3 dB electro-optic bandwidth exceeding 100 GHz, stringent conditions of α_m < 0.5 dB/(cm·GHz$^{1/2}$) and $|n_m - n_g|$ < 0.1 must be satisfied [11].

3. Synergistic Optimization of Modulation Efficiency and Electro-Optic Bandwidth

3.1 Microstructured Electrode Design

3.1.1 Periodically Capacitively Loaded T-Microstructured Electrodes

Periodically arranging T-shaped microstructured elements on both sides of the signal electrode in a conventional coplanar waveguide is equivalent to introducing shunt capacitance on the transmission line [3,11]. Each T-shaped element can be treated as a lumped capacitor; their periodic arrangement produces a self-compensation effect whereby the reflected signal of one capacitive unit is canceled by the subsequent unit, thereby significantly reducing microwave transmission loss. By adjusting the geometric parameters of the T-shaped elements, the microwave effective index can be independently tuned to match the optical waveguide group index without altering the electrode gap.

Under capacitive loading, the microwave characteristic impedance and effective refractive index can be expressed as [8]:

$$Z_0 = \sqrt{\frac{L_0}{C_0 + C_T}} \tag{4}$$

$$n_m = c\sqrt{L_0(C_0 + C_T)} \tag{5}$$

where L_0 and C_0 are the per-unit-length inductance and capacitance of the unloaded transmission line, and C_T is the per-unit-length parasitic capacitance introduced by the T-shaped elements.

In 2021, Kharel et al. employed a segmented T-electrode structure on a quartz substrate, achieving VπL = 2.6 V·cm with a 3 dB bandwidth exceeding 100 GHz [11]. In 2022, Chen et al. combined localized isotropic etching of the silicon substrate to reduce the microwave effective index from approximately 2.8 to 2.25, realizing VπL = 2.5 V·cm and a 3 dB electro-optic bandwidth >70 GHz [3]. This approach is compatible with standard CMOS processes but requires a substrate undercut or a low-permittivity substrate to lower the microwave phase velocity, entailing relatively high fabrication complexity.

3.1.2 Slow-Wave Electrodes and Spoof Surface Plasmon Polaritons

Slow-wave electrodes exploit the slow-light effect of spoof surface plasmon polaritons near the band edge of metallic photonic crystals to achieve localized electric field enhancement [14]. Xu Guangyao et al. constructed a one-dimensional equivalent photonic crystal along the propagation direction by patterning periodic zigzag metallic photonic crystal structures on coplanar transmission line electrodes. Near the band edge, the group velocity of the microwave mode decreases substantially, the electro-optic overlap integral factor increases significantly, and the propagation length required to achieve a π phase shift is shortened [14]. This scheme enhances electric field strength while avoiding the optical absorption loss associated with merely reducing the electrode gap. However, it currently remains primarily at the simulation stage, and dispersion engineering demands high geometric precision in the periodic structures.

3.1.3 Buried Dual-Capacitor and Interdigitated T-Electrodes

The buried dual-capacitor electrode embeds a bilayer capacitive electrode within the lithium niobate thin film, positioning it vertically closer to the waveguide core region [15]. Song et al. embedded the lower electrode into the lithium niobate film; at an embedding depth of 300 nm, the average internal electric field was approximately 40% higher than in a conventional non-embedded structure. By selectively etching the lithium niobate in non-modulation regions, unnecessary contact between the metal and the waveguide was eliminated. The fabricated 10-mm-long modulator achieved a measured VπL = 1.45 V·cm and an electro-optic bandwidth exceeding 40 GHz [15]. The key fabrication challenge lies in precisely controlling the embedding depth: the total thickness of the lithium niobate film typically ranges from 300 to 600 nm, and etching to 300 nm requires a high-selectivity etch-stop layer; otherwise, the underlying buried layer may be damaged, or electrode short circuits may occur.

Building on this concept, Li Haisheng et al. combined the buried dual-capacitor structure with a $BaTiO_3$ high-k cladding, utilizing dielectric boundary conditions to enhance the electric field within the lithium niobate. Simulations yielded VπL = 1.42 V·cm, optical loss <0.2 dB/cm, and bandwidth >60 GHz [8]. Zhong Chuangyang et al. further integrated a slot waveguide with interdigitated T-electrodes, achieving a simulated VπL = 0.59 V·cm and a bandwidth of approximately 60 GHz. The interdigitated electrodes mitigate fluctuations in electric-field modulation efficiency caused by periodic variations in conductor spacing in symmetric T-electrodes, yielding a smoother electro-optic modulation response [7].

3.2 Optical Mode Engineering

Waveguide mode engineering enhances the effective electric field within the lithium niobate by tailoring the waveguide geometry and dielectric distribution. The principles underlying both slot waveguides and high-permittivity cladding derive from the boundary conditions of the electric displacement vector at dielectric interfaces—the electric field intensity in low-refractive-index regions exceeds that in high-index regions, thereby strengthening the electric field in the lithium niobate region [7,8].

A slot waveguide consists of two high-index silicon nanowires separated by a low-index lithium niobate slot [7,16]. Its optical group index of approximately 2.82 matches the elevated microwave effective index induced by T-electrodes, thereby circumventing the need for substrate undercut [10]. Under simulation, the structure integrating a slot waveguide with interdigitated T-electrodes achieves $V\pi L$ = 0.59 V·cm and a 3 dB bandwidth of approximately 60 GHz. However, this scheme faces significant fabrication challenges: both the silicon nanowire width and the lithium niobate slot width must be rigorously controlled to below 200 nm, which can be achieved only with high-resolution electron-beam lithography, thereby limiting mass-production compatibility. The sub-wavelength small mode field area increases coupling loss to standard single-mode fiber, and the silicon–lithium niobate heterogeneous interface is prone to scattering loss. To date, experimental validation with low-loss devices remains lacking [7,16].

The high-permittivity cladding approach introduces a high-k material between the lithium niobate waveguide and the metal electrode. Chen et al. employed liquid glycerol as the cladding, experimentally achieving $V\pi L$ = 1.4 V·cm and an electro-optic bandwidth >67 GHz [13]. Li Haisheng et al. replaced the conventional SiO_2 cladding with a thin solid $BaTiO_3$ film, yielding a simulated $V\pi L$ of 1.42 V·cm and a bandwidth >60 GHz; the electric-field enhancement effect was found to saturate when the cladding permittivity exceeded 40 [8]. This scheme entails relatively lower fabrication complexity; however, the lattice mismatch between $BaTiO_3$ and lithium niobate is approximately 7%, leading to high dislocation and crack densities during heteroepitaxial growth. The difference in thermal expansion coefficients introduces interfacial thermal stress during annealing and subsequent processing, potentially causing film delamination or defect proliferation.

3.3 Velocity Matching and Bandwidth Extension

Velocity matching is a prerequisite for achieving ultra-high electro-optic bandwidth. In the TFLN platform, the low-permittivity SiO_2 buried layer and silicon substrate account for most of the device thickness, so the microwave effective index is typically lower than the optical waveguide group index [3].

Substrate undercut is one effective approach to resolving velocity mismatch. Chen et al. performed approximately 28-μm-deep undercut etching of the bottom silicon substrate in a Si/TFLN modulator, reducing the microwave effective index from 2.8 to 2.25 to match the optical group index of 2.28 [3]. Substituting a quartz substrate is another effective strategy: since the relative permittivity of quartz is lower than that of silicon, a lower microwave effective index can be achieved without undercut [2,11]. However, quartz exhibits poor compatibility with CMOS processes and lower thermal conductivity than silicon, compromising heat dissipation under high-power operating conditions. Certain schemes actively raise the microwave effective index using T-type capacitively loaded electrodes to match the optical group index, or exploit the naturally elevated optical group index in slot waveguides to achieve matching, thereby circumventing the need for substrate undercut [7,14].

Microwave propagation loss is another critical factor limiting the electro-optic bandwidth of long modulation regions. Means of reducing loss include increasing the electrode metal thickness, optimizing the signal electrode dimensions to achieve 50 Ω impedance matching, and employing low-dielectric-loss upper cladding materials [1,12]. Folded and crossed waveguide structures utilize RF phase delay to equivalently increase the modulation length within a limited chip area, potentially halving the half-wave voltage relative to a single-section structure; however, these are narrowband modulation schemes whose bandwidth is constrained by the delay line length [17].

4. Functional Expansion and Heterogeneous Integration Technologies

4.1 Polarization-Independent Modulation

After transmission through standard single-mode fiber, the state of polarization of an optical wave varies randomly due to birefringence and environmental perturbations. If directly coupled into a polarization-sensitive lithium niobate modulator without polarization control, polarization-dependent loss will ensue. Therefore, realizing polarization-independent electro-optic modulation is of considerable importance [18].

Wang Zong et al. proposed a polarization-independent modulation scheme based on polarization diversity, mode conversion, and unified modulation. First, a trident-shaped polarization-independent optical power splitter splits the TE_0 and TM_0 modes at 3 dB; then, an adiabatic tapered mode converter efficiently converts the TM_0 mode to the TE_1 mode (conversion efficiency of 99.7%), while the TE_0 mode remains unchanged. In the modulation region, the waveguide width is optimized (to approximately 2.84 μm) such that the VπL of the two modes are equal at approximately 2.5 V·cm, enabling unified modulation. Combined with periodically capacitively loaded traveling-wave electrodes and localized substrate undercut, simulation results indicate that both modes achieve an electro-optic bandwidth exceeding 100 GHz [18].

4.2 Heterogeneous Material Integration

4.2.1 Si/TFLN and SiN/TFLN Heterogeneous Integration

Si/TFLN and SiN/TFLN heterogeneous integration currently represents the most CMOS-compatible approach. The common design philosophy is to combine silicon or silicon nitride waveguides with TFLN to form a hybrid waveguide structure, where the optical field is primarily confined in the silicon or silicon nitride layer, and the electro-optic effect in the proximal lithium niobate region is harnessed for modulation, thereby avoiding direct etching of the lithium niobate thin film [2,19]. Weigel et al. bonded a TFLN to an SOI wafer and used a silicon-ridge waveguide to guide the optical field, achieving an electro-optic bandwidth exceeding 100 GHz [20].

In the SiN/TFLN approach, Shen Xiangguo et al. proposed an MZI modulator incorporating a BCB adhesive layer. The modulation region adopts a vertical structure (silicon nitride waveguide as the bottom layer, lithium niobate thin film as the top layer). The BCB filling layer reduces VπL from 2.75 V·cm to 1.76 V·cm, while an inverted-step lithium niobate thin-film coupling structure lowers the single-end coupling loss from 1.23 dB to 0.73 dB. Simulation results yield VπL = 1.76 V·cm and a 3 dB electro-optic bandwidth of up to 140 GHz [19]. Silicon nitride waveguides offer low propagation loss, tunable refractive index over a range, and full CMOS process compatibility, making them an important direction for heterogeneous integration.

4.2.2 Chalcogenide Glass/TFLN Mid-Infrared Heterogeneous Integration

The SiO_2 buried layer in commercial TFLN wafers exhibits significant lattice vibrational absorption in the 3–5 μm mid-infrared (MIR) band. Mode overlap between the optical field and this absorptive layer induces severe propagation loss, limiting the extension of the TFLN platform to the MIR regime. Pan Kaiyan et al. proposed a heterogeneous integration scheme for chalcogenide glass (ChG) and TFLN. A ChG strip waveguide with tunable refractive index is deposited atop the lithium niobate thin film, drawing the majority of the optical field energy upward into the ChG layer and reducing its proportion in the SiO_2 buried layer, while retaining a 54.1% optical confinement factor in the lithium niobate layer to exploit the Pockels effect [21] fully.

Multi-physics simulation optimization of this device at a wavelength of 4.1 μm yields a propagation loss of 0.67 dB/cm, VπL = 14.7 V·cm, and a 3 dB electro-optic bandwidth exceeding 110 GHz. However, this scheme still faces critical bottlenecks: the ChG thin-film process window is narrow, heterogeneous interfaces are prone to introducing scattering loss, the intrinsic reduction of the lithium niobate electro-optic coefficient in the MIR band results in relatively low modulation efficiency, and the fabrication of MIR-specific TFLN wafers and low-loss coupling techniques are still immature, constraining experimental validation and engineering application [21].

4.3 Application-Specific Customized Designs

In ultrashort pulse generation, Liu Jiaxu et al. designed a cascaded TFLN electro-optic modulator time-lens system based on slow-wave electrodes [10]. The intensity modulator employs T-type slow-wave electrodes to achieve VπL = 2.46 V·cm and a bandwidth exceeding 100 GHz, without requiring complex processes such as substrate removal or heterogeneous bonding. System simulations demonstrate that under RF drives at 10 GHz, 30 GHz, and 45 GHz, 21, 17, and 17 comb lines are generated, respectively, with flatness below 3 dB; after compression by single-mode fiber, the pulse widths are 3.45 ps, 1.5 ps, and 1 ps, respectively. Compared with conventional traveling-wave electrode systems, the pulse width reduction at 60 GHz reaches 52.9% [10].

In laser ranging, phase-based systems employ electro-optic modulators to modulate an optical carrier with an RF signal. Because TFLN modulators utilize a thermo-optic phase-shifting mechanism to control the bias operating point, conventional sinusoidal pilot-tone bias control schemes cannot operate stably [22]. Hu Yubin et al. proposed a bias control scheme based on a square-root circuit, rendering the drive voltage delivered to the thermal tuning electrode linearly proportional to the output optical power. Experimental results show that the maximum drift of the optical power at the Quad point over a 30 min observation period does not exceed 0.03 dB. The ranging system equipped with this module maintains a ±0.22 mm accuracy after 10 h of continuous operation. In contrast, the cumulative error of a control system without the module increases by 3.11 mm [22].

In fully packaged devices, Shang Chenglin et al. proposed a complete packaging solution for TFLN electro-optic modulators. The optical packaging employs horizontal end-face coupling: a double-layered inverse-taper spot-size converter expands the output spot diameter to approximately 3.5 μm; combined with high-numerical-aperture single-mode fiber and a custom fiber array for coupling, the maximum TE optical coupling efficiency degradation during thermal cycling tests is merely 0.01 dB. The electrical packaging employs a 1.85 mm coaxial connector that transitions through an RF pin and an alumina ceramic board transmission line to the chip electrode, achieving S21 < 0.6 dB and S11 < −13 dB up to 50 GHz. The packaged device exhibits an optical insertion loss of ≤5 dB, a 3 dB bandwidth of ≥40 GHz, a VπL of ≤ 3 V·cm at 1 GHz, and a compact device footprint of only 30 mm × 20 mm × 5 mm [23].

5. Discussion

Table 1 summarizes the performance of representative TFLN electro-optic modulators, clearly reflecting the current technological development trajectory and revealing the intrinsic trade-offs among efficiency, bandwidth, and loss.

Table 1: Performance comparison of typical thin-film lithium niobate electro-optic modulators

Technical Approach	VπL (V·cm)	3 dB BW (GHz)	Optical Loss (dB/cm)	Status	Ref.
Conventional CPW electrode	2.2	100	~0.1	Exp.	[1]
Periodically capacitively loaded T-electrode	2.5	>100	~0.1	Exp.	[3]
Microstructured segmented TW electrode	2.6	>100	—	Exp.	[11]
Buried dual-capacitor + embedding	1.45	>40	0.5	Exp.	[15]
Dual-capacitor + $BaTiO_3$ cladding	1.42	>60	<0.2	Sim.	[8]
Slot waveguide + interdigitated T-electrode + $BaTiO_3$	0.59	~60	<0.07	Sim.	[7]
SiN/TFLN heterogeneous integration	1.76	140	0.195	Sim.	[19]
Polarization-independent scheme	2.5	>100	—	Sim.	[18]
ChG/TFLN mid-infrared	14.7	>110	0.67	Sim.	[21]

5.1 Analysis of the Cost of Efficiency Enhancement

Regarding modulation efficiency, VπL has been reduced from 2.2 V·cm in conventional designs to 1.42 V·cm (experimentally 1.45 V·cm) using buried dual-capacitor structures, and schemes based on slot waveguides can theoretically reach as low as 0.59 V·cm. However, these performance improvements come at significant technical costs. First, fabrication complexity has increased substantially: capacitively loaded T-electrodes rely on sub-micron-precision electron-beam lithography and multi-step metal lift-off processes [3,11]; buried electrodes require precise control of a 300 nm embedding depth [15]; slot waveguide linewidths must be maintained below 200 nm [7]. At present, most schemes with VπL below 1.5 V·cm remain at the simulation stage, and practical device fabrication faces multiple challenges in etching precision, material quality, and interfacial defects.

Second, the efficiency–bandwidth–loss trade-off triangle persists. High-permittivity cladding introduces additional dielectric loss that limits bandwidth [8]; the small mode field area of slot waveguides increases coupling loss [7]; and reducing the electrode-to-waveguide distance in buried electrode designs increases metal-induced optical absorption loss [15]. Furthermore, bandwidth evaluation criteria have yet to be standardized: simulated bandwidths are often based on idealized assumptions, while measured values are affected by impedance mismatch and packaging parasitics and tend to fall below theoretical predictions [23].

5.2 Future Research Directions

In device design, fundamentally breaking the efficiency–bandwidth–loss trade-off will require multi-objective optimization and inverse design methodologies. Conventional parametric sweeps cannot readily meet the simultaneous requirements of impedance and velocity matching, as well as low microwave loss. In contrast, electromagnetic–optical co-design based on adjoint sensitivity analysis or machine-learning-assisted optimization can explore novel electrode topologies and waveguide mode distributions across a much larger parameter space. Segmented coaxial transmission line electrodes have demonstrated terahertz-bandwidth potential in simulations [6]; their experimental realization will depend on high-precision three-dimensional micro- and nano-fabrication techniques.

At the integration and application level, co-design of thermal management and bias control will become critical for high-power, high-stability systems. Thermo-optic phase shifting is widely employed for bias-point adjustment in TFLN modulators, yet its thermal response is relatively slow and susceptible to ambient temperature fluctuations. Future approaches may integrate on-chip micro-heaters with active temperature feedback circuits, combined with low-thermal-resistance substrate engineering, to achieve fast and stable operating-point locking. Concurrently, optoelectronic co-packaging technology will deeply integrate the modulator with CMOS driver chips within a single package, significantly shortening RF interconnect lengths, reducing parasitic parameters, and propelling modulators toward higher bandwidth and lower power consumption.

In terms of functionality, the TFLN platform is evolving from single-function intensity modulation to reconfigurable photonic circuits. Functions such as polarization-independent modulation, tunable filters, and nonlinear frequency conversion are expected to be integrated on a single chip, forming multifunctional optoelectronic chips for optical communication, microwave photonics, and quantum information processing.

6. Conclusions

This paper has systematically reviewed the technical progress of thin-film lithium niobate high-speed electro-optic modulators in two respects: synergistic optimization of modulation efficiency and electro-optic bandwidth, and functional expansion and heterogeneous integration. Through synergistic innovation in microstructured electrode design, optical mode engineering, and velocity-matching strategies, $V\pi L$ has been reduced from >10 V·cm in conventional bulk-material devices to 1–2.5 V·cm. At the same time, the 3 dB electro-optic bandwidth has exceeded 140 GHz. Schemes such as polarization-independent modulation and heterogeneous integration of Si/SiN and chalcogenide glass have expanded device functionality and spectral coverage. The principal challenges in current technological development include: the efficiency–bandwidth–loss trade-off triangle has yet to be fundamentally overcome; certain high-performance schemes remain at the simulation stage; and thermal management and coupling loss control in heterogeneous integration remain unresolved. Looking ahead, with the introduction of multi-objective optimization design methodologies and the deep integration of modulators with CMOS driver circuits, TFLN electro-optic modulators are poised to become a key enabling technology for next-generation high-speed photonic integrated chips.

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Conflicts of Interest

The authors declare no conflict of interest.

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