

Supplementary Information for

Ultra-broadband near- to mid-infrared electro-optic modulator on thin-film lithium niobate

Qiyuan Li^{1,†}, Qiyuan Yi^{1,†}, Aolong Sun^{2,†}, Chenglin Shang¹, Yiqi Dai¹, Sizhe Xing², Jinlai Cui³, Yupeng Zhu³, Jiayi Li³, Jun Zheng³✉, Junwen Zhang²✉, Nan Chi², An Pan^{1,4,†}, Cheng Zeng¹✉, Jinsong Xia¹, Shuang Zheng^{1,5}, Li Shen^{1,5,6}✉, and Minming Zhang^{1,5}

¹Wuhan National Laboratory for Optoelectronics and School of Optical and Electronic Information, Huazhong University of Science and Technology, Wuhan, China

²Key Laboratory for Information Science of Electromagnetic Waves, Department of Communication Science and Engineering, Fudan University, Shanghai, China

³Key Laboratory of Optoelectronic Materials and Devices, Institute of Semiconductors, Chinese Academy of Sciences, Beijing, China

⁴Wuhan ANPI Optoelectronics Company, Ltd, Wuhan, China

⁵Optics Valley Laboratory, Wuhan, China

⁶Hubei Optical Fundamental Research Center, Wuhan, China

[†]These authors contributed equally: Qiyuan Li, Qiyuan Yi, Aolong Sun, An Pan.

✉e-mail: zhengjun@semi.ac.cn; junwenzhang@fudan.edu.cn; zengchengwuli@hust.edu.cn; lishen@hust.edu.cn

Supplementary Note 1: Design of the broadband edge coupler

A. Cross section views of the spot-size converters (SSC) and corresponding optical field distribution

To achieve broadband high-efficiency light coupling into and out of the modulator, its edge couplers are based on two spot-size converters (SSCs) consisting of thin-film lithium niobate (TFLN) bi-layer tapers and a silicon oxynitride (SiON) ridge waveguide. Fig. S1 illustrates the cross-sectional structure and corresponding TE mode field distributions at various wavelengths across different sections. The light from the incident fiber first enters into the SiON rib waveguide (Part I). Then in LN bi-layer tapers region, the fundamental transverse electric (TE) mode transitions from the SiON waveguide to the LN lower slab waveguide via the lower inverted taper formed by the lower slab width increases (Part II). Then, the width of the LN ridge increases linearly while keeping the LN lower slab width unchanged to form the upper inverted taper (Part III). Then, LN slab region enlarges linearly while keeping the LN ridge width unchanged (Part IV). After these parts, the light from the coupled fiber finally converts to the LN ridge waveguide with a width of $0.8\ \mu\text{m}$ and a height of $0.18\ \mu\text{m}$ on a $0.12\text{-}\mu\text{m}$ -thick slab to operate in single-mode-condition in 1260-2060 nm (Part V). The proposed dual-layer taper and SiON cladding waveguide architecture exhibits superior broadband operational characteristics and enhanced packaging compatibility, compared to prior multilayer SSC designs [1-2].

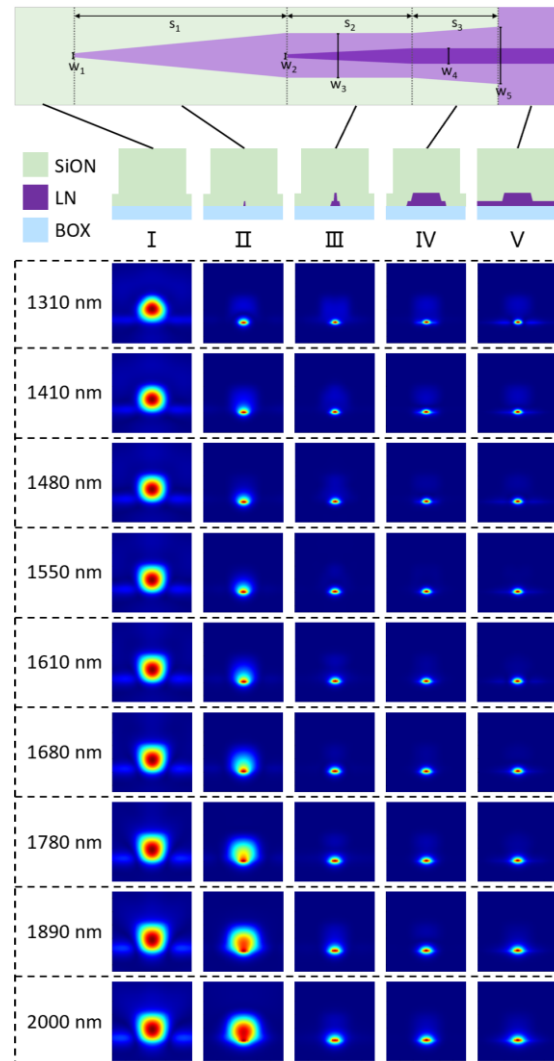


Fig. S1: Cross-section of the SSC and corresponding TE mode field distributions at various wavelengths from 1310 to 2000 nm.

B. The influence of tip widths to the coupling loss

After light enters the SiON rib waveguide, the conversion loss primarily arises from reflections at the abrupt height transitions within the LN waveguide. Specifically, these transitions occur at the interfaces between the SiON rib waveguide and the LN lower slab waveguide (denoted as w_1) and between the LN lower slab waveguide and the LN ridge waveguide (denoted as w_2). The conversion losses for Part I to Part V, evaluated across varying w_1 and w_2 , are illustrated in Fig. S2a and S2b, respectively. The LN ridge waveguide consists of a 0.18- μm -high rib on a 0.12- μm -high slab, resulting in a larger height discontinuity at w_2 . Consequently, this abrupt transition (w_2) has a more pronounced effect on the conversion loss compared to w_1 . Additionally, the reflection intensity at these height changes increases more drastically with increasing tip width, particularly at shorter wavelengths, which explains the observed loss fluctuations. To balance fabrication feasibility with minimal tip widths, we selected $w_1=w_2=200$ nm.

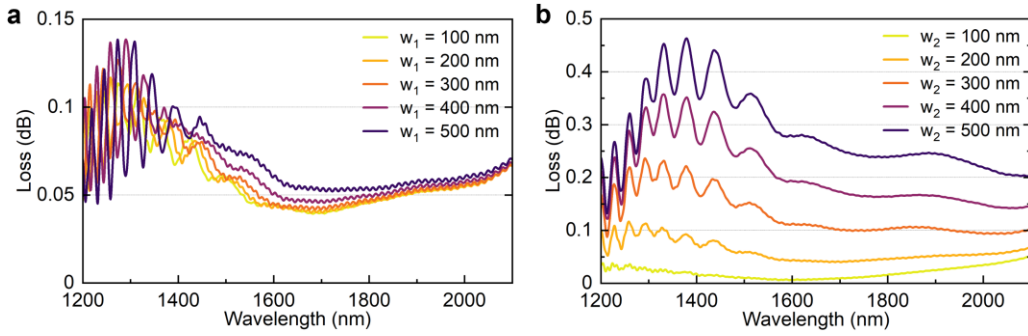


Fig. S2: Simulated conversion loss for different tip widths w_1 and w_2 .

Supplementary Note 2: Waveguide width optimization

Figure S3 illustrates the variations in LN waveguide widths across different sections. A narrower width of $W=0.8$ μm is maintained specifically in the regions of the SSC, power splitters, and bend waveguides. In contrast, a wider width of $W=3.5$ μm is adopted for the high-speed modulation region, thermo-optic phase shifter regions, connections between components, and waveguide propagation paths. The modulation efficiency is primarily determined by the confinement of the optical field within the electro-optic region, while metal-induced absorption loss depends on the optical field overlap with the electrodes. Taking $\lambda=1550$ nm as an example (Fig. S3b), we calculated the half-wave voltage-length product ($V_\pi L$) and metal-induced absorption loss at 1550 nm. Both parameters were parameterized as functions of the LN waveguide width. Simulated optical and electrical field distributions at 1550 nm for waveguide widths of 0.8 μm and 3.5 μm are shown in Fig. S3c for comparison.

Increasing the waveguide width enhances the overlap between the optical field and the electrical field, as the optical field becomes more concentrated within the LN core (rather than the cladding), thereby improving the electro-optic overlap. However, excessively wide waveguides cause the optical field edges to approach the metal electrodes, exacerbating metal-induced absorption. To balance these effects, we selected a waveguide width of $W=3.5$ μm to optimize modulation efficiency across a broad bandwidth. At this width, the optical field is sufficiently confined within the LN core to maximize the electro-optic

overlap factor while minimizing metal absorption loss.

On the other hand, narrower waveguide widths reduce optical mode confinement, leading to increased propagation losses due to stronger mode overlap with the waveguide sidewalls and cladding. To balance performance across device integration and signal propagation requirements, we maintained the waveguide width at $W = 3.5 \mu\text{m}$ for component connections and overall waveguide operation. The rationale for selecting $W = 3.5 \mu\text{m}$ in the thermo-optic phase shifter region is detailed in Supplementary Note 4. Except for the regions of SSC and power splitter, the waveguide width of $W = 0.8 \mu\text{m}$ is only set in the bend waveguide region to form the asymmetric interference arm. The bend waveguides are designed with single mode condition across the entire operating range, reducing the bending radius.

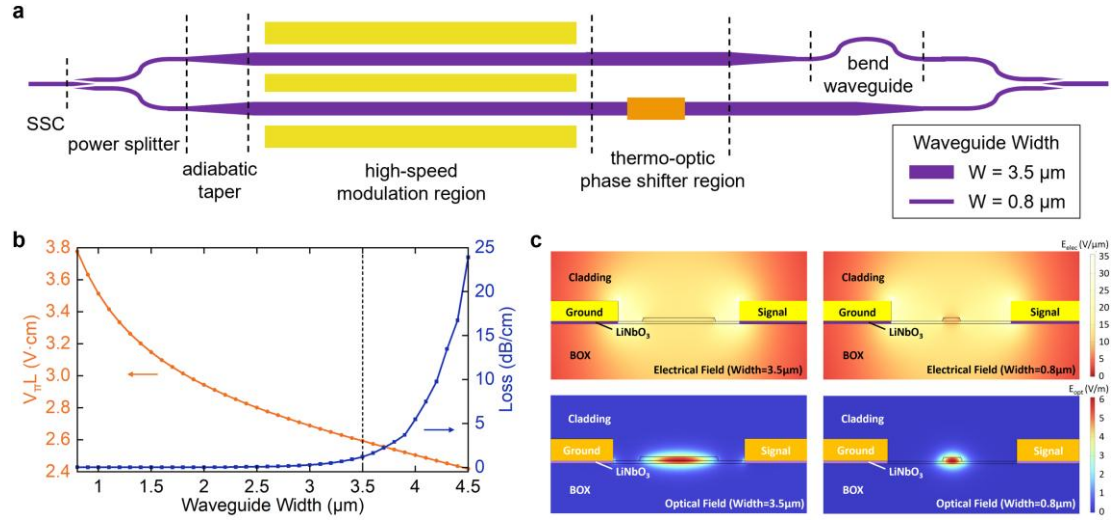


Fig. S3: (a) Schematic illustration of LN waveguide widths in different parts. (b) Simulated $V_{\pi} \cdot L$ and loss as a function of waveguide width. (c) Simulated optical and electrical field distributions with waveguide width $W = 0.8$ and $3.5 \mu\text{m}$ at $\lambda = 1550 \text{ nm}$.

Supplementary Note 3: Design of the traveling-wave electrode

A. Design details of the impedance of the traveling-wave electrodes

Based on the transmission line theory, the EO frequency response $m[\omega]$ of a TFLN Mach-Zehnder modulator can be expressed as [3]:

$$m[\omega] = 20 \log_{10} \left[\frac{Z_L + Z_S}{Z_L} \cdot \left| \frac{Z_{in}}{Z_{in} + Z_S} \right| \cdot \frac{(Z_L + Z_0) \cdot F_+ + (Z_L - Z_0) \cdot F_-}{(Z_L + Z_0) \cdot e^{\gamma_m L} + (Z_L - Z_0) \cdot e^{-\gamma_m L}} \right]$$

where ω is the angular frequency of the RF signal, Z_L and Z_S are the load and source impedance, respectively. Among them, Z_{in} is the RF line input impedance:

$$Z_{in} = Z_0 \cdot \frac{Z_L + Z_0 \cdot \tanh(\gamma_m L)}{Z_0 + Z_L \cdot \tanh(\gamma_m L)}$$

where L is the length of the traveling-wave electrode, and Z_0 is the line characteristic impedance. And γ_m is the RF complex propagation constant:

$$\gamma_m = \alpha_m + j \frac{\omega}{c_0} n_m$$

where n_m is the RF effective index, α_m is the RF attenuation, and c_o is the velocity of light. Besides, $F_{\pm}$ is given by:

$$F_{\pm} = \frac{1 - e^{\pm \gamma_m L - j \frac{\omega}{c_o} n_g L}}{\pm \gamma_m L - j \frac{\omega}{c_o} n_g L}$$

where n_g is the group index of the optical mode.

Consequently, the theoretical EO frequency response of the TFLN Mach-Zehnder modulator is mainly dominated by the following factors. One is the effective index mismatch between the RF n_m and optical waves n_g , which has an influence on $F_{\pm}$. And the other is the impedance relationship between the source impedance Z_s , load impedance Z_L , and transmission line characteristic impedance Z_0 . In our EO frequency response simulations, the source impedance Z_s is set as 50 Ω . The transmission line characteristic impedance Z_0 is $\sim 42 \Omega$. And the load resistance Z_L is designed as 38 Ω . To more intuitively demonstrate the impact brought by the relationship between Z_0 and Z_L , we calculate the EO response of our TFLN modulator at $\lambda=1550$ nm for the load resistance $Z_L = 34 \Omega$, 38 Ω , 42 Ω and 46 Ω , as shown in Fig. S4. It can be found that the load resistance Z_L slightly lower than the characteristic impedance Z_0 will cause an elevated response in the low-frequency region of the EO S_{21} responses and has a slight improvement on the 3-dB bandwidth, while cause some ripples in the response [4]. Therefore, we selected $Z_L = 38 \Omega$ because a further reduction would cause excessive signal reflection, leading to large ripples and an unacceptable frequency response flatness for practical communication systems.

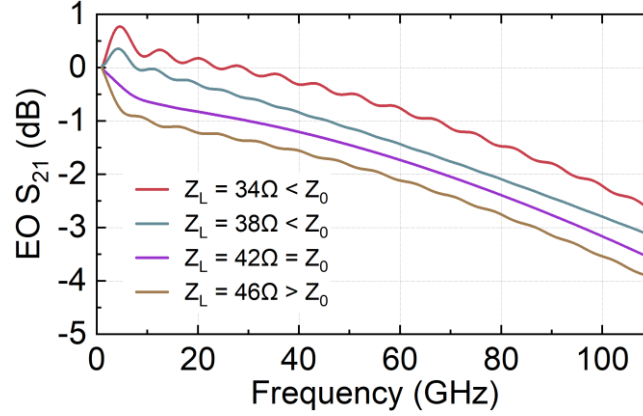


Fig. S4: Simulated EO frequency response of the TFLN modulator at $\lambda=1550$ nm with the cases for $Z_L < Z_0$, $Z_L = Z_0$, and $Z_L > Z_0$.

B. Design details of effective index matching of the traveling-wave electrode

For the traveling-wave electrode, high-speed transmission requires effective index matching between the RF n_m and optical waves n_g . A significant mismatch between these indices can lead to reduced electro-optic (EO) 3-dB bandwidth. Ideally, this index matching should be achieved across all RF driving frequencies and optical operating wavelengths. However, the optical group index decreases as the wavelength increases, while RF n_m remains constant for different wavelengths. This inherent wavelength-dependent disparity makes simultaneous index matching for multi-wavelength communication on a single modulator inherently challenging. Nevertheless, the index mismatch can be effectively minimized across the 0- to 2- μm wavelength band, this optimization ensures that the RF and optical phase velocities

remain sufficiently aligned to maintain high EO bandwidth performance across the targeted wavebands.

For the electrode parameters that affect RF n_m , the signal and ground electrode widths are designed as $W_S = 25 \mu\text{m}$ and $W_G = 150 \mu\text{m}$, respectively, with gold (Au) electrodes of height $H = 1 \mu\text{m}$. The electrode gap was set as $G = 6 \mu\text{m}$ through a trade-off analysis between modulation efficiency and metal-induced absorption loss. Our investigation focused on the LN waveguide width (W) and SiO₂ cladding thickness as critical parameters affecting both the optical group index n_g and RF n_m . As shown in Fig. S5a and Fig. S5b, n_g exhibits minor variations across typical communication wavelengths (e.g. S+C+L bands) when altering the LN waveguide width. Meanwhile, the RF n_m demonstrates relatively weak dependence on waveguide width. Considering the balanced requirements of modulation efficiency and waveguide propagation characteristics from prior analyses, a standard waveguide width of $W = 3.5 \mu\text{m}$ was retained.

As for SiO₂ cladding thickness, optical n_g shows almost no change with the cladding thickness $> 1 \mu\text{m}$ for a particular wavelength. In contrast, n_m exhibits pronounced sensitivity to cladding thickness variations. This parameter's tunability enables prioritization of specific optical wavelength regions. To accommodate high-speed communication applications spanning near-infrared to mid-infrared regimes, a cladding thickness of $2 \mu\text{m}$ was selected. This configuration minimizes n_g/n_m mismatch across O-U bands, ensuring negligible 3-dB bandwidth degradation. In the $2 \mu\text{m}$ waveband, theoretical simulations indicate a 3-dB bandwidth of $\sim 80 \text{ GHz}$ at $\lambda = 2000 \text{ nm}$ for a 9-mm-long, impedance-matched, lossless modulator. This performance remains fully adequate for emerging $2\text{-}\mu\text{m}$ band communication systems, even accounting for residual index mismatch effects.

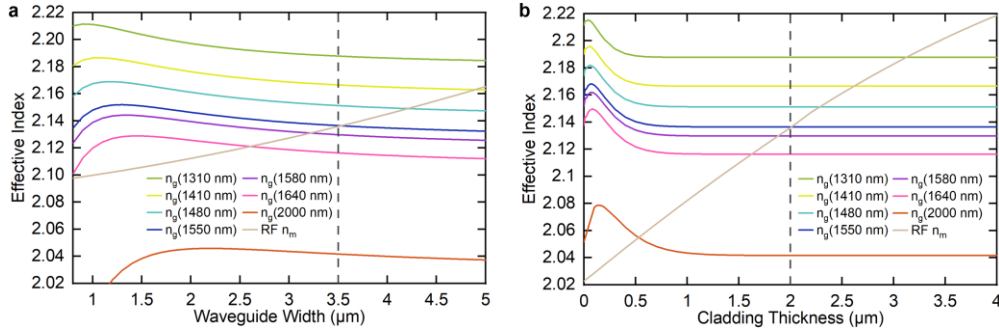


Fig. S5: The effective index factor with (a) LN waveguide width and (b) SiO₂ cladding thickness.

Supplementary Note 4: The details of the thermo-optic phase shifter

Figure S6a displays the cross-sectional view of the TO phase shifter region, in which titanium (Ti) heater is placed right above the LN waveguide. To ensure a compact size, the length of Ti heater is set to $L_h = 200 \mu\text{m}$, while the width and thickness of Ti heating resistor are set to $W_h = 4 \mu\text{m}$ and $H_h = 200 \text{ nm}$, respectively.

The two key performance metrics of TO phase shifters are phase-shift efficiency and absorption loss. The phase shift of the light caused by the heater can be expressed as

$$\Delta\varphi = \frac{2\pi L}{\lambda_0} \frac{dn}{dT} \Delta T$$

where L is the length of the heater, λ_0 is the operating wavelength, $\frac{dn}{dT}$ is the effective TO coefficient of the waveguide material, and ΔT is the change of temperature. P_π is the DC power required to achieve a π -phase shift, used to describe phase-shift efficiency. To balance the heating efficiency and metal

absorption losses, the vertical height from the waveguide to the heater H_c was set as $1.3\ \mu\text{m}$, and a $2\text{-}\mu\text{m}$ -thick SiO_2 was used as a cladding layer above the heater.

The waveguide width was kept as $W = 3.5\ \mu\text{m}$ in the thermo-optic phase shifter region after the modulation region, and then narrow to $W = 0.8\ \mu\text{m}$ for single-mode operation through an adiabatic taper before entering bend waveguide which is used to create the asymmetric interference arm. The design of widening the waveguide width in the thermo-optic phase shifter region concentrate more thermal energy in the optical mode region to lower heat loss. And it can reduce the overlap of the evanescent field between the optical mode field and the Ti heating resistor, decreasing the metal absorption loss.

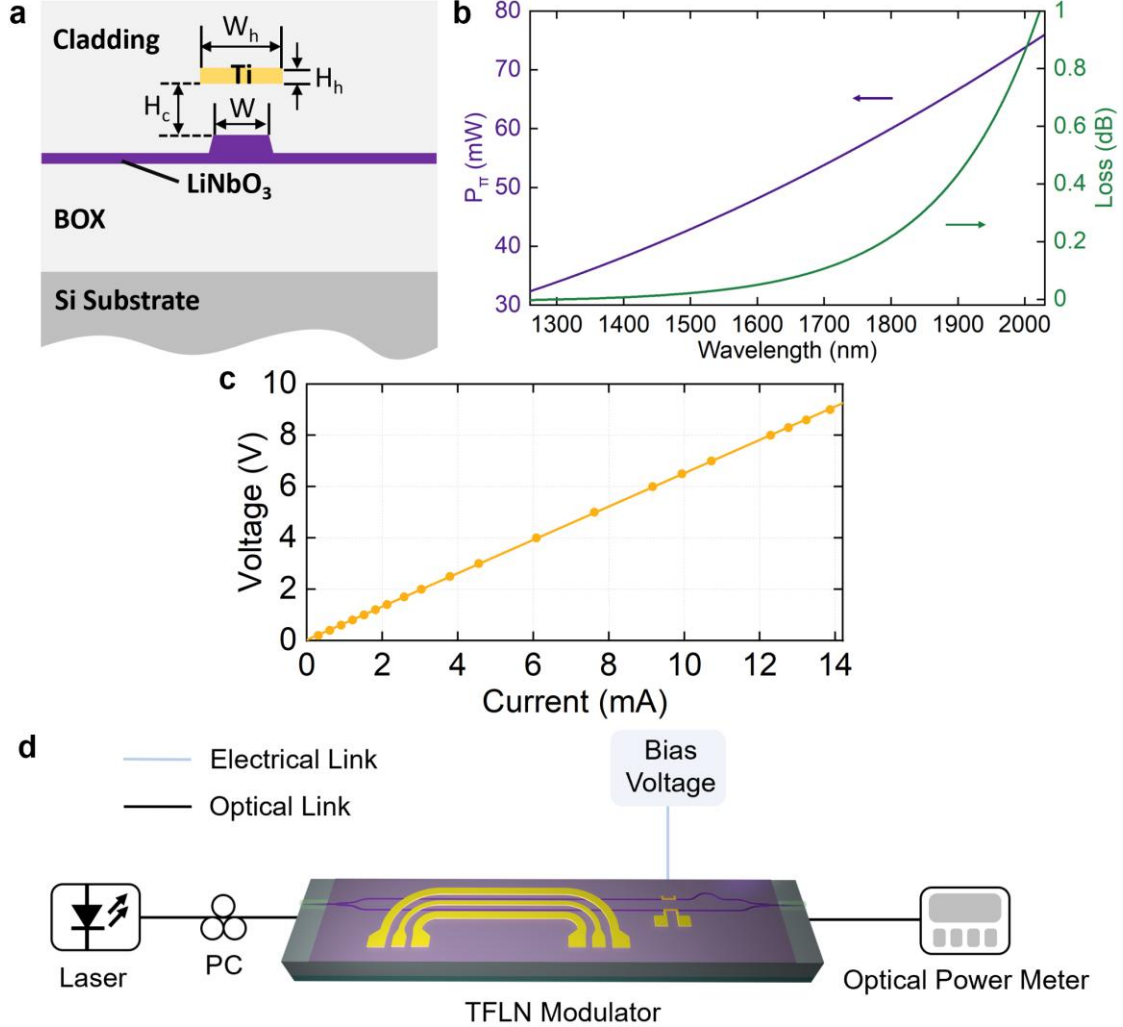


Fig. S6: (a) Cross-sectional view of the thermo-optic phase shifter region. (b) Simulated P_π and loss as a function of wavelength. (c) Experimental setup for the thermo-optic phase shifter characterization. (d) I-V curves of the Ti heater.

After the modulation region, both arms of the Mach-Zehnder interferometer are placed with the same Ti heater, as illustrated in Fig. 1b. One heater is connected to DC pads as a true TO phase shifter, while the other is not. This symmetric thermal compensation architecture ensures simultaneous heating of both arms, mitigating phase drift induced by ambient temperature fluctuations and thereby enhancing signal transmission stability.

Then, we conduct TO simulations for P_π and loss as a function of the wavelength, as shown in Fig. S6b. In our simulation, thermal conductivities of the LN, SiO_2 and Ti heater are chosen as 5.234, 1.38 and 18

W/(m·K), respectively. The optical loss remains negligible across the O- to U-bands, though a slight increase is observed in the 2- μ m wavelength region—a trade-off necessitated by maintaining moderate DC power consumption across all operational bands. Figure S6c displays the measured I-V curve and the fitted result of the Ti heater, revealing the resistance of the heater $\sim 650\ \Omega$. Considering the length and width of the heater, the sheet resistance $R_{\square}$ of the 200nm-thick-Ti deposited by EBE is $\sim 13\ \Omega$.

To characterize the wavelength-dependent TO modulation efficiency, P_{π} was measured at representative wavelengths spanning the O to 2- μ m wavebands. The experimental setup, illustrated in Fig. S6d, involved a tunable laser source (TLS, Santec TSL-570) covering 1260–1680 nm and a 2000-nm laser as optical inputs. The input light adjusted by a polarization controller (PC) were launched into the TFLN modulator through a polarization-maintaining (PM) fiber. A DC bias voltage was applied to the modulator through electrical probes, while an optical power meter continuously monitored the output power variations.

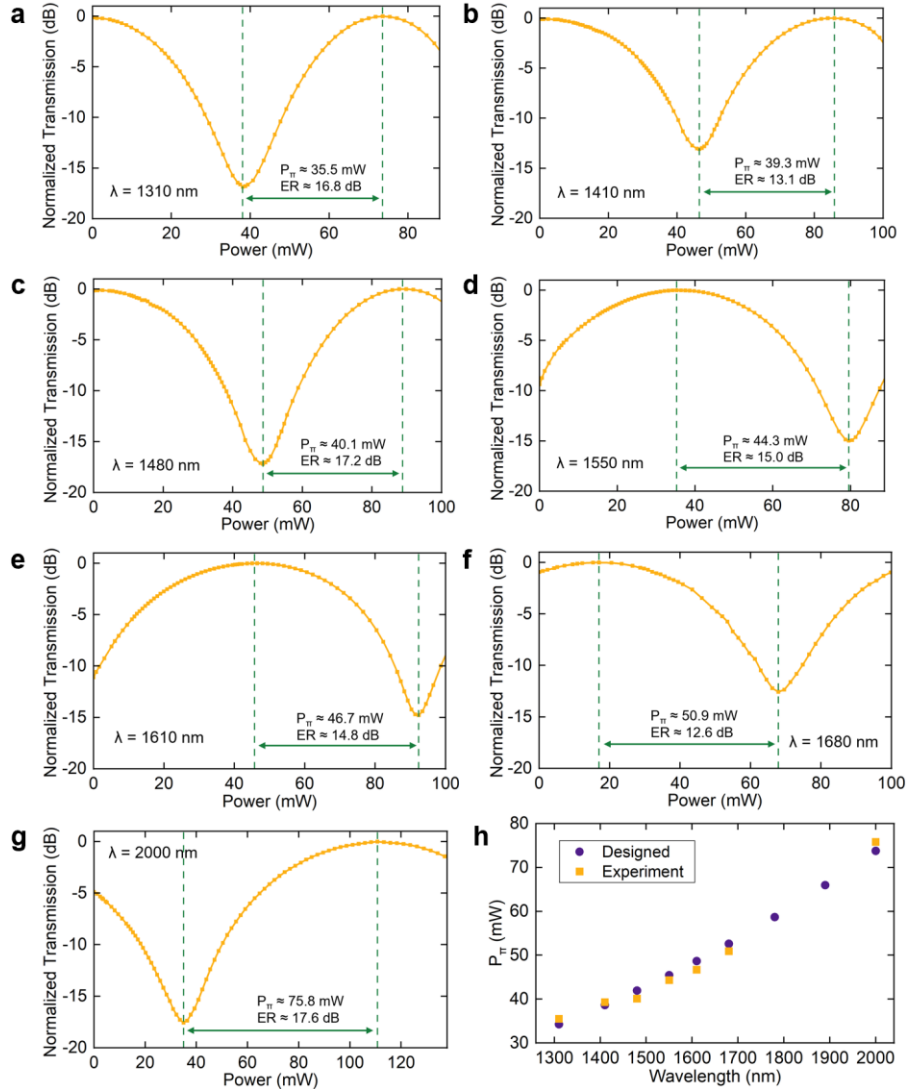


Fig. S7: The dependence of the normalized transmission as a function of heat power at wavelength (a) $\lambda = 1310\text{ nm}$ (b) 1410 nm (c) 1480 nm (d) 1550 nm (e) 1610 nm (f) 1680 nm (g) 2000 nm . (h) Designed and experiment P_{π} at several typical wavelengths.

We measured the P_{π} values by monitoring the modulator's output optical power as we varied the heat

power at a selected wavelength. The normalized transmission dependence on heat power for wavelengths $\lambda = 1310, 1410, 1480, 1550, 1610, 1680$, and 2000 nm (corresponding to the O, E, S, C, L, U, and 2- μ m wavebands, respectively) is presented in Fig. S7a–Fig. S7g. By comparing the heat power levels at maximum and minimum transmission, we obtained P_π values of 35.5, 39.3, 40.1, 44.3, 46.7, 50.9, and 75.8 mW for these wavelengths. The static extinction ratios (ERs) were also derived from these results. The observed wavelength-dependent ER variations can primarily be attributed to power imbalances between the output ports of the 3-dB splitter, which stem from fabrication tolerances.

The simulated and experimental P_π values for selected operating wavelengths are summarized in Fig. S7h, illustrating the wavelength dependence of the thermo-optic phase shifter's modulation efficiency. The experimental P_π values for these wavelengths generally align with the theoretical predictions. Discrepancies between the two may arise from uncertainties in the thermal conductivity of the deposited titanium layer and variations in the wavelength-dependent thermo-optical coefficient of LN.

Supplementary Note 5: Transmission spectra of the TFLN modulator

Figure S8 presents the normalized transmission spectra of the TFLN modulator. The loss of the TFLN modulator contains the loss of the fused fiber splice since the SSCs are fixed by UV-curable glue. The spectra in the 1260–1680 nm wavelength range were measured using a Santec TSL-570 tunable laser source with polarization control achieved through a PC. For the 1920–2060 nm spectral region, measurements were conducted using a custom-built 2- μ m amplified spontaneous emission (ASE) source coupled with a Yokogawa AQ6375B optical spectrum analyzer (OSA).

The transmission spectrum of the TFLN modulator exhibits irregular features in the short-wavelength regime (O- and E-bands), which is attributed to optical power fluctuations originating from the SSC as detailed in Supplementary Note 1. These fluctuations introduced a minor detrimental effect on the ER and insertion loss within the affected bands. The localized loss depressions near 1510 nm and 2000 nm arise from N–H bond absorption within the plasma-deposited SiON layer of the SSC. Additionally, the significant loss increase observed in the 2- μ m band correlates with the enhanced metal absorption coefficient at longer wavelengths.

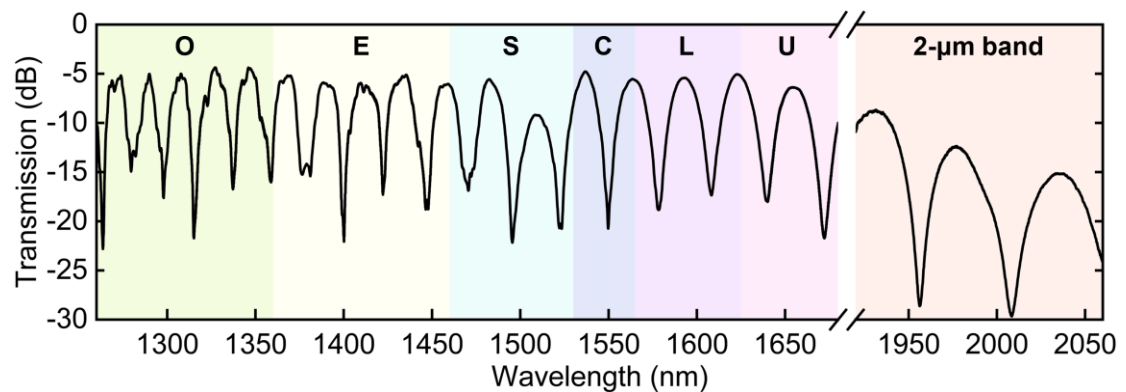


Fig. S8: Transmission spectra of the TFLN modulator.

Supplementary Note 6: Loss analysis

A. Passive waveguide propagation loss measurement

The propagation loss of the passive straight waveguide (width $W = 3.5 \mu\text{m}$) was determined using a reference waveguide (Fig. S9a) and a spiraled waveguide (Fig. S9b) with a 27-mm length difference. The reference waveguide was carefully designed to ensure geometric consistency between the $0.8\text{-}\mu\text{m}$ -wide bend segments and the adiabatic tapers with gradually varying widths. Three grating couplers were employed for light coupling: one operating in the O-band (1310 nm), another in the C-band (1550 nm), and a third at near $2 \mu\text{m}$ (1970 nm). This method yielded measured propagation losses of 0.21 dB/cm, 0.19 dB/cm, and 0.22 dB/cm at the respective wavelengths. The wavelength-dependent loss behavior demonstrates that the reduction in Rayleigh scattering at longer wavelengths offsets the rise in surface scattering contributions, resulting in comparable total losses across the O, C, and $2\text{-}\mu\text{m}$ bands. This balance ensures consistent performance of the passive waveguide across the studied spectral range.

B. Bend waveguide loss measurement

The bending radius was set to $240 \mu\text{m}$ to minimize bending losses. A test structure consisting of six cascaded bent waveguides (Fig. S9c) was employed, where each cascaded unit was derived from the bent waveguides in one arm of a Mach-Zehnder interferometer (MZI) to form asymmetric interference arms. For a unit bent waveguide with a width of $W = 0.8 \mu\text{m}$, the measured bending losses were 0.13, 0.14, and 0.28 dB/cm at wavelengths of 1310, 1550, and 1970 nm, respectively.

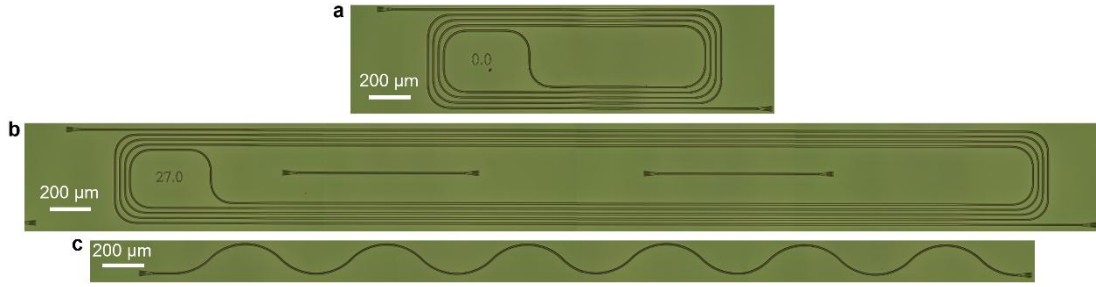


Fig. S9: Microscopy images of the passive waveguide for measuring propagation loss (stitching image). (a) reference waveguide. (b) tested spiraled waveguide. (c) six cascaded bend waveguides.

C. On-chip loss source analysis

To comprehensively characterize the on-chip losses across a broad operating wavelength range ($\lambda = 1310, 1550, \text{ and } 1970 \text{ nm}$), we performed a detailed loss analysis summarized in Supplementary Table S1. The passive waveguide propagation loss was calculated using a $\sim 1.3\text{-cm}$ -long straight waveguide encompassing the 9-mm -long modulation region (with a fixed width $W = 3.5 \mu\text{m}$) and a $0.8\text{-}\mu\text{m}$ -wide bend waveguide (radius of $240 \mu\text{m}$). Adiabatic tapers used to change the waveguide widths were integrated between these segments to ensure gradual dimension transitions, enabling stable mode profile adaptation without inducing modal conversion or radiation losses. The power splitter loss was experimentally measured using reference devices identical to those in the modulator fabrication process. Metal absorption losses from the traveling-wave electrode and thermo-optic phase shifter were derived from simulation results. The relatively higher experimental on-chip insertion loss (IL) can be attributed to fabrication overlay inaccuracies in the traveling-wave electrode and limitations in the metal absorption loss model.

Supplementary Table S1. On-chip loss source analysis

Wavelength	Measured on-chip IL	Simulated Au electrodes	Simulated Ti heater	Experiment average IL of 16-	3.5- μm -width $\sim 1.3\text{-cm}$ length	0.8- μm -width bend waveguide
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		absorption loss	absorption loss	cascaded power splitter	waveguide propagation loss	propagation loss
1310 nm	1.2 dB	0.008 dB	0.001 dB	0.23 dB	~0.27 dB	0.13 dB
1550 nm	2.8 dB	1.2 dB	0.03 dB	0.11 dB	~0.25 dB	0.14 dB
1970 nm	5.8 dB	2.9 dB	0.74 dB	0.42 dB	~0.28 dB	0.28 dB

Supplementary Note 7: Comparison of simulated and experiment $V_{\pi} \cdot L$

Figure S10 show the simulated half-wave voltage-length product $V_{\pi} \cdot L$ as a function of electrode gap (G) at several measured wavelengths. The comparison of simulated and experiment modulation efficiency $V_{\pi} \cdot L$ is listed in Supplementary Table 1. The relatively consistent results validate the accuracy between the numerical model and the fabrication.

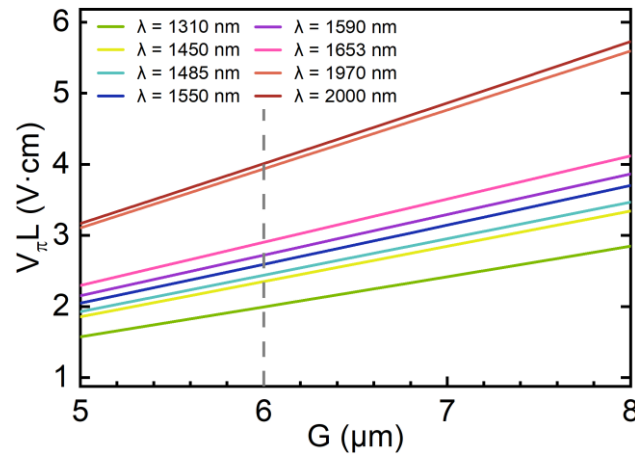


Fig. S10. Simulated $V_{\pi} \cdot L$ as a function of G .

Supplementary Table 2. Comparison of simulated and experiment $V_{\pi} \cdot L$

Wavelength (nm)	Simulated modulation efficiency (V·cm)	Experiment modulation efficiency (V·cm)
1310	1.99	1.92
1450	2.35	2.39
1485	2.44	2.48
1550	2.59	2.61
1590	2.72	2.74
1653	2.90	2.89
1970	3.93	3.90
2000	4.01	3.94

Supplementary Note 8: The details of the EO frequency responses for the 2- μ m band measurement

For the measurement of frequency responses and high-speed data transmission in the 2 μ m band, we utilized a recently demonstrated high-speed germanium tin (GeSn) photodetector (PD) [5]. The GeSn resonance-cavity-enhanced (RCE) PDs employed in this work feature an active layer with a tin (Sn) composition of 9–10.8%, fabricated on a silicon-on-insulator (SOI) substrate via a silicon-based CMOS process. The GeSn RCE PD exhibits a responsivity of 0.49 A/W at 2 μ m and possess a cutoff wavelength

of approximately 2750 nm.

Figure S11(a) illustrates the experimental setup for measuring the EO frequency response of the TFLN modulator in the 2- μm wavelength region. The output light of the TFLN modulator is first amplified by a thulium-doped fiber amplifier (TDFA), then coupled into the GeSn PD using a tapered lensed fiber with a mode field diameter (MFD) $< 8\ \mu\text{m}$ at the 2 μm wavelength to ensure efficient coupling into the PD. A bias voltage of -3 V was applied to the GeSn PD during the frequency response measurements. A 67-GHz RF probe was used to transmit the RF signals to the vector network analyzer (VNA), enabling the acquisition of the response curves.

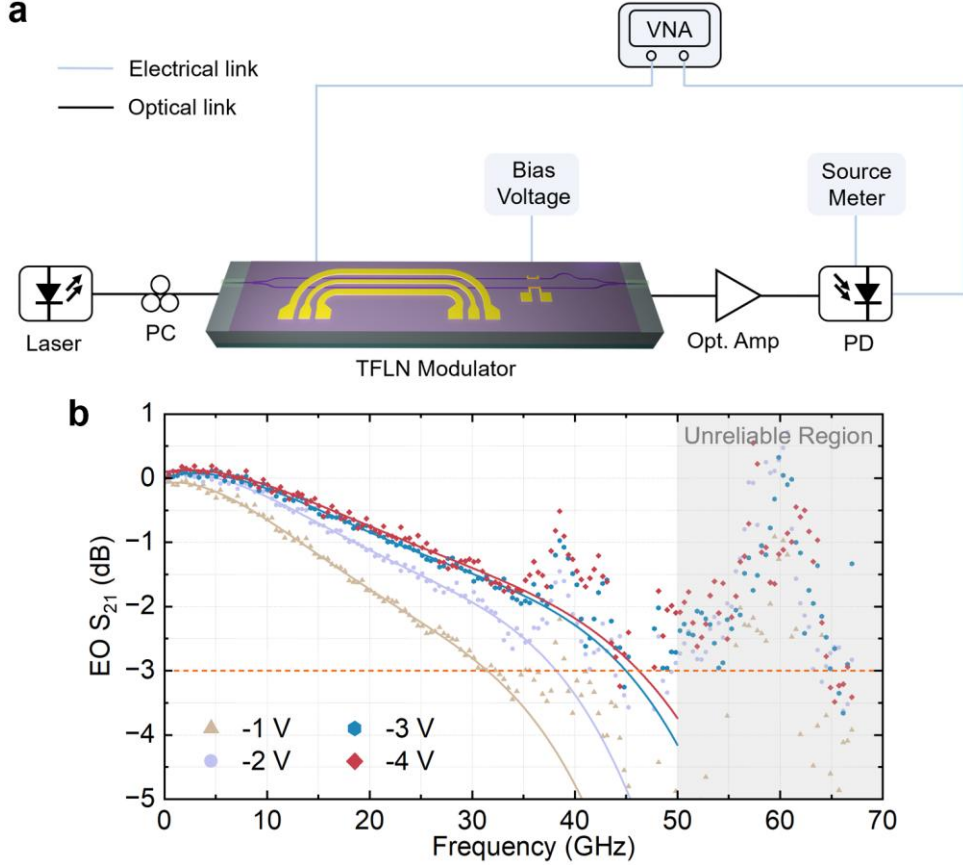


Fig. S11: (a) Experimental setup for modulation bandwidth characterization. (b) EO frequency response of the used GeSn PD at $\lambda = 2000\ \text{nm}$.

Figure S11(b) illustrates the EO frequency response of an 8- μm -diameter GeSn PD under different bias voltages at 2 μm . Experimental data are represented by dots, while solid lines indicate the fitting results from 0 to 50 GHz. The 3-dB bandwidth increases slightly with increasing bias voltage. However, the bandwidth at -4 V shows no significant improvement compared to that at -3 V, as carriers in the GeSn layer have reached the saturation drift velocity. The 3-dB bandwidth at both -3 V and -4 V exceeds 45 GHz. Owing to the limited and unstable high-frequency performance of the commercial reference modulator, the raw PD response shows fluctuations beyond $\sim 35\ \text{GHz}$. However, its magnitude remains bounded between -1 dB and -3.5 dB up to 50 GHz at a bias of -3 V, staying well above the noise floor. Above 50 GHz, the GeSn PD's EO response becomes unstable, rendering the response data unreliable. The response of our TFLN modulator was then extracted from the total system response by a de-embedding procedure using the characterized response of the GeSn PD (measured at a bias of -3 V) up

to 50 GHz.

Supplementary Note 9: Equipment models

The primary equipment employed in the high-speed data transmission system to characterize the TFLN modulator are listed in Supplementary Table 3.

Supplementary Table 3. List of instruments and components used in the data transmission measurement setups

Equipment	Model	Application Wavelength
Arbitrary Waveform Generator	Keysight M8199B	All
Real-time Oscilloscope	Keysight UXR0594BP	All
Photodiode	Finisar XPDV4121R	O-U bands
Laser	Keysight 8164B	$\lambda = 1310/1550/1590$ nm
	Santec TSL-570	$\lambda = 1450/1485$ nm
	Gysciencetech GST1653DFBBF1406	$\lambda = 1653$ nm
	Eblana photonics EP1970-0-DM-B06-FM	$\lambda = 1970$ nm
	Eblana photonics EP2000-0-DM-B06-FM	$\lambda = 2000$ nm
Semiconductor Optical Amplifier	Inphenix IPSAD1301C	$\lambda = 1310$ nm
	JHBF JSA-BT525G35-PM	$\lambda = 1450/1485$ nm
	Thorlabs BOA1084S	$\lambda = 1653$ nm
Erbium-Doped Fiber Amplifier	Amonics AEDFA-23-B-FA	$\lambda = 1550$ nm
	Ovlink EYDFA-L-HP-BA-30-SM-B	$\lambda = 1590$ nm
Thulium-doped fiber amplifier	Home-built	$\lambda = 1970/2000$ nm
RF amplifier	Jitai GT-LNA-67GHz	
RF probe	GGB 67A-GSG-150-DP	

Supplementary Note 10: Discussion on the data transmission measurement

A. Data transmission of O-U bands

Despite the modulator bandwidths showing minimal variation across O- to U-bands in our prior measurements, discrepancies in data transmission performance were observed across different wavelengths. Notably, the 100-GHz photodetector (PD) used for measurements maintained consistent bandwidth characteristics across all bands. Furthermore, the radio-frequency (RF) probes and cables in the transmission link remained unchanged throughout the experiments. Collectively, these factors indicate that the system bandwidth remained invariant across all tested wavelength bands (O- to U-bands).

However, the responsivity of PD varies at different wavebands. The responsivity of PD at different wavelengths can be known by observing the photocurrent of PD. The responsivity of PD is sufficient for data transmission at conventional wavelengths ($\lambda = 1310/1450/1485/1550/1590$ nm). However, at $\lambda = 1653$ nm—a wavelength near the PD's band edge—the responsivity diminishes notably compared to other bands. This reduction in responsivity directly weakens the received signal strength, leading to a pronounced decrease in achievable data rates, particularly for PAM-4 modulation formats. The PD's

diminished responsivity at 1653 nm is further evidenced by the bit-error-rate (BER)-received optical power (ROP) curves: even at lower selected data rates than those used for other wavelengths, the BER deteriorates rapidly as ROP decreases due to the weak photocurrent generated at this wavelength.

Conversely, distinct optical amplifiers are employed in the transmission links across different wavelength bands: erbium-doped fiber amplifiers (EDFAs) are utilized in C-/L-bands, whereas semiconductor optical amplifiers (SOAs) are deployed in O-/E-/S-/U-bands. EDFAs generate lower noise levels compared to SOAs, and the inferior signal-to-noise ratio (SNR) induced by SOAs results in performance degradation of PAM-4 signals across wavelength bands. For on-off keying (OOK) signals, data rates are primarily constrained by the real-time oscilloscope's bandwidth, yielding minimal variation across different bands. Thus, in the absence of bandwidth limitations, PAM-4 signals clearly exhibit wavelength-dependent performance variations attributable to amplifier noise characteristics. Consequently, the maximum achievable data rates under the hard-decision forward error correction (HD-FEC) threshold for C- and L-bands exceed those observed in other bands.

Therefore, the performance discrepancies of data transmission in different wavebands are caused by the influences of the external measurement equipment. It is expected that the high-speed performance of the TFLN modulator will be consistent across the entire O-U bands.

B. Data transmission of the 2- μ m band

For the 2- μ m wavelength band, a separate analysis is required due to the use of germanium tin photodetector (GeSn PD). Its higher dark current results in degraded signal-to-noise ratio (SNR), leading to a deterioration of the signals, especially for high-order signal formats such as PAM-4. Consequently, the achievable data rates for PAM-4 signals in the 2- μ m band remain comparable to those of OOK formats, unlike the pronounced performance gaps observed in the O-U bands.

Additionally, the higher insertion loss of the modulator in the 2- μ m band necessitates increased optical amplifier current, thereby introducing additional noise. Concurrently, commercial lasers operating at 2- μ m exhibit broader spectral linewidths and lower output optical power compared to other bands, further degrading data transmission performance. Collectively, these factors contribute to the reduced data rates in the 2- μ m band relative to other bands, independent of system bandwidth limitations. Within the 2- μ m band itself, the modulator demonstrates greater insertion loss at $\lambda = 2000$ nm compared to $\lambda = 1970$ nm. This is attributed to increased metal absorption and coupling losses at the longer wavelength. Consequently, higher amplifier currents are required, exacerbating noise contributions and further reducing achievable data rates at 2000 nm.

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