

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

Corresponding Author: Dr Li Shen

This file contains all reviewer reports in order by version, followed by all author rebuttals in order by version.

Attachments originally included by the reviewers as part of their assessment can be found at the end of this file.

Version 0:

Reviewer comments:

Reviewer #1

(Remarks to the Author)

In this work, the authors demonstrate a broadband thin-film lithium niobate (TFLN) modulator capable of operating across the O-, C-, and 2- μm wavelength bands. Large 3-dB bandwidths are achieved in all three bands. The manuscript appears to lack novel insights, and the reviewer interprets this work as an engineering advancement rather than a conceptual breakthrough. However, the results are attractive, and the reviewer feels it would be unfair to reject this work, given that this is also true of many papers published in high-impact journals. Before I can recommend its publication in Nature Communications, the authors should address the following concerns.

Major concerns:

1. This manuscript does not provide new insights or methods for the field. The broadband operation is achieved by optimizing each optical component, including the spot-size converter (SSC), optical splitter, passive waveguide, and active modulation region. However, the broadband optical splitter was already proposed and demonstrated in their previous work (Ref. 32). The broadband SSC is realized by engineering the lengths/widths of multilayer waveguide tapers, but the concept of multilayer SSCs for broadband operation is described in several previous works, such as:

[1] X. Liu et al., "Ultra-broadband and low-loss edge coupler for highly efficient second harmonic generation in thin-film lithium niobate," *Advanced Photonics Nexus*, 1(1), 016001-016001, 2022. DOI: 10.1117/1.APN.1.1.016001.

[2] H. Chen et al., "An Ultrabroadband and Cost-Effective Edge Coupler for Efficient Thin Film Lithium Niobate Photonics," *Photonics*, 10(7), 760, 2023. DOI: 10.3390/photonics10070760.

While the design of passive waveguide and modulation region may have some novelty, it is not surprisingly new. The authors should highlight the novelty in the structure or design method, if there is any.

2. Another main concern is the claim of an operational wavelength range exceeding 800 nm. While the simulation results may indicate such a range, the experimental results—specifically the 3-dB bandwidths and eye patterns—were only measured only at 3 wavelengths (1310, 1550, and 2000 nm). Although the transmission spectra of the SSC over these 3 bands are shown (Fig. 3a), the transmission spectra of the modulator itself are not provided. There are several wavelength bands between 1310 nm and 1550 nm, and between 1550 nm and 2000 nm. It is risky to claim an 800-nm operational range without more comprehensive experimental data.

3. More details on the thermo-optic phase shifter should be provided. For example, information on its length and width, resistance, modulation efficiency, and wavelength dependency is lacking.

4. More details and supporting information on the bandwidth measurements should be provided, possibly in the form of supplementary material. For example, what is the bias voltage applied to the GeSn photodetector (PD)? What is the frequency response of the GeSn PD at this bias? Since the measured 3-dB bandwidth (48 GHz) is close to the PD's limit, the frequency response curve of the PD itself is necessary to verify the reliability of the measurement.

5. The theoretical 3-dB bandwidth is predicted to be 80 GHz (Line 154), but the measured value is 48 GHz. Please add some discussion (or quantitative analysis, if necessary) to explain this discrepancy.

6. Lines 170-173: The insertion loss at 1970 nm (5.8 dB) is significantly higher than that at 1310 nm (1.2 dB). The authors attribute this to "absorption by the metal electrodes". However, given the increased sensitivity of longer wavelengths to scattering loss caused by surface roughness and interface defects, please provide the results of passive loss measurements for comparison.

Minor issues:

7. Line 74: "TNLN" should be "TFLN".

8. Lines 50-53: The authors first mention issues associated with previous platforms, including the TFLN platform. Then, in line 54, they claim that "TFLN has emerged as a uniquely promising platform to overcome these barriers." I am confused by the logic here. How can the same platform be both the source of the problem and the solution? I suggest the authors reorganize this part for clarity.

9. Line 138: "The electrode gap (G) is defined as the vertical separation between..." However, from Fig. 1(a), it appears that the authors are referring the horizontal separation, not the vertical. Please double-check.

Reviewer #2

(Remarks to the Author)

The manuscript entitled "Ultra-broadband near- to mid-infrared electro-optic modulator on thin-film lithium niobate" by Qiyuan Li et al. reports a TFLN based MZ modulator with adiabatic power splitters and tapered fiber edge coupler for broadband operation, and single-lane transmission results exceeding 100 Gbaud for OOK and 65 Gbaud for PAM4 over O, C, and 2- μ m bands. The reviewer found the contents are technically sound, however doubts if it is worth for publication in Nature Communications in terms of the timeliness and impact. Specifically, while it is true that multi-band optical transmission is recently attracting much attention, the full spectrum is normally targeted to O to U band in the research field, which is then still not yet well developed. A wider bandwidth is in general always welcomed, but the 2- μ m band is not really a focus of recent researches. In addition, Ref. [30] already reported a even higher 3-dB bandwidth EO modulator operating over O to U band, where the 2- μ m performance was not tested. However, the point to fit the 2- μ m operation is just relatively conventional broadband designs of 3-dB couplers and edge couplers, which is not really a big leap for high impact. Therefore, the manuscript will be worth for publication in some technical journals but not so in high impact journals like Nature Communications.

Some minor comments are listed below for future drafting.

- In Fig.1, the shape of the electrodes on the device in (a) does not match that of the fabricated device in (b).
- In line 103, it says "The simulations reveal an optimal rib width of 4.4 μ m..." However, the reviewer did not understand why it is optimum from this explanation.
- In line 129 to 137, the waveguide width outside the modulation region is explained. However, the design mentioned here "the waveguide is engineered to support single mode operation at 1310 nm, but tapered to 3.5 μ m." is confusing.
- In line 138, "vertical" should be "horizontal."

Reviewer #3

(Remarks to the Author)

I co-reviewed this manuscript with one of the reviewers who provided the listed reports. This is part of the Nature Communications initiative to facilitate training in peer review and to provide appropriate recognition for Early Career Researchers who co-review manuscripts.

Version 1:

Reviewer comments:

Reviewer #1

(Remarks to the Author)

Please see the attached document.

Reviewer #2

(Remarks to the Author)

The authors' effort for responding to the detailed comments is commended, but the rebuttal did not answer the main concern on the timeliness and impact. Therefore, the reviewer suggests the same conclusion that the manuscript will be worth for publication in some technical journals but not so in high impact journals like Nature Communications.

- It says, "Our work, however, identifies a critical co-development opportunity: while advancing existing O-to-U band technologies by improving the full spectrum broadband optical modulator, we advocate for simultaneous exploration of emerging spectral windows such as the 2- μ m band." The reviewer agreed that 2- μ m band is an emerging spectral window and worth to investigate, but again a wider bandwidth is in general always welcomed, but the 2- μ m band is not really a focus of recent research. More specifically, for the low-loss hollow-core fibres (HCFs) the authors raised, the very latest impactful result presented in the post-deadline session of ECOC 2025, one of the most prestigious conferences in this field, showed an ultra-low loss of 0.052 dB/km centered at 1550nm in the range of 1450nm to 1650nm.

- It also says, "We respectfully disagree with the Reviewer's assertion that accommodating 2- μ m operation merely requires conventional broadband designs of 3-dB couplers and edge couplers. Our work envisions an ambitious goal: leveraging the vast bandwidth resources spanning from the O-band to the 2- μ m band to enable future ubiquitous optical communications with sustainable scalability. This ambition is supported by recent technological advancements, such as photodetectors inherently capable of operating across the O-band to 2- μ m range [12]. A compelling example is a recent Nature Photonics

study demonstrating that broadband HCFs exhibit <0.1 dB/km attenuation between 1,481 nm and 1,625 nm and can theoretically support low-loss transmission windows (≤ 0.2 dB/km) spanning from 700 nm to $\sim 2,400$ nm [R6]. These findings further underscore the technical viability of our proposed extended full spectrum optical communications." However, here the reviewer pointed out that the progress of the paper over the already published device was just conventional broadband designs of 3-dB couplers and edge couplers. This is not at all related the other technologies such as photodetectors inherently capable of operating across the O-band to 2- μ m range and broad band HCFs.

Reviewer #3

(Remarks to the Author)

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Version 2:

Reviewer comments:

Reviewer #1

(Remarks to the Author)

The authors have addressed my concerns. I recommend its publication.

Reviewer #3

(Remarks to the Author)

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Reviewer #1 (Remarks to the Author):

In this work, the authors demonstrate a broadband thin-film lithium niobate (TFLN) modulator capable of operating across the O-, C-, and 2- μm wavelength bands. Large 3-dB bandwidths are achieved in all three bands. The manuscript appears to lack novel insights, and the reviewer interprets this work as an engineering advancement rather than a conceptual breakthrough. However, the results are attractive, and the reviewer feels it would be unfair to reject this work, given that this is also true of many papers published in high-impact journals. Before I can recommend its publication in Nature Communications, the authors should address the following concerns.

We sincerely thank the Reviewer for their careful and positive review of our paper. Those comments are helpful for us to revise and improve our paper, as well as to clearly clarify the significance of our work to readers. Below, we first outline the key innovations of this study, followed by detailed responses to each of the Reviewer's technical inquiries (highlighted in blue). All revisions in the main manuscript are marked in red for clarity.

In this work, we design and demonstrate a high-performance TFLN modulator with an unprecedented 800-nm operational bandwidth spanning 1260–2060 nm. To specifically address the Reviewer's inquiry regarding bandwidth characterization (Comment 2), we tried our best to conduct comprehensive re-characterization across the entire accessible wavelength range including the full O-U bands (1260–1680 nm) and 2- μm band (1920–2060 nm), using all our available laser sources. The experimental results are detailed in Reply 2.

In summary, the measured electro-optic (EO) bandwidths of the modulator reach ~ 100 GHz at critical communication wavelengths of 1310 nm (O-band), 1485 nm (S-band), 1550 nm (C-band), and 1590 nm (L-band) using a 110-GHz lightwave component analyzer (LCA, Ceyear 6433P). These values align with state-of-the-art performance of single-waveband-optimized integrated modulators reported in literature [21, 30–31, 39–40]. Due to the limited wavelength module of the LCA, a 67-GHz vector network analyzer (Keysight N5247B) is used to measure the rest wavebands. The modulator exhibits > 67 GHz 3-dB EO bandwidths for all conventional optical communication bands (O–U bands) and > 50 GHz in the 2- μm waveband. Furthermore, we demonstrated single-lane data transmission exceeding 240 Gbps across the entire O–U bands for the first time using a single broadband modulator. Notably, in the 2- μm waveband, we achieved a record 170 Gbps—the highest ever reported to date in this wavelength regime.

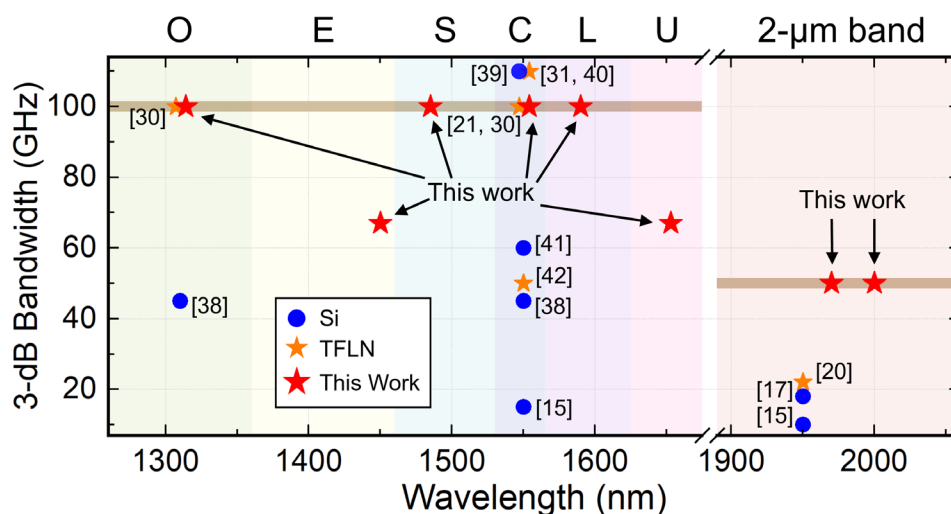


Fig. 5/R1 | Comparison of 3-dB bandwidth of short-wave infrared high-speed EO modulators.

Therefore, we updated the Fig.5 in the revised manuscript on page 10 to highlight the superior performance of our modulator. We have also added these updated results into Table 2 for comparisons with the existing 2- μ m band EO modulators.

Table 2. Performance comparison of on-chip integrated EO modulators operating at 2- μ m band

Ref.	Platform	Structure	Extinction Ratio (dB)	3-dB Bandwidth (GHz)	Max. Baud Rate and Signal Format	Other wavebands capable
[15]	SOI	MZI	-	10	20 Gbaud OOK	C-band
[16]	SOI	Michelson	15	-	20 Gbaud OOK 15 Gbaud PAM-4	No
[20]	LNOI	MZI	20	22	32 Gbaud OOK	No
[17]	SOI	MZI	22	18	30 Gbaud OOK 40 Gbaud PAM-4	No
[18]	SOI	MRM	19	18	50 Gbaud OOK	No
[19]	SOI	Racetrack Ring	21	26	34 Gbaud OOK	No
This work	LNOI	MZI	18	>50	150 Gbaud OOK 85 Gbaud PAM-4	O-U bands

- [15] W. Cao, D. Hagan, D. J. Thomson, M. Nedeljkovic, C. G. Littlejohns, A. Knights, S. Alam, J. Wang, F. Gardes, W. Zhang, S. Liu, K. Li, M. S. Rouified, G. Xin, W. Wang, H. Wang, G. T. Reed, and G. Z. Mashanovich, "High-speed silicon modulators for the 2 μ m wavelength band," *Optica* 5(9), 1055-1062 (2018).
- [16] W. Cao, S. Liu, C. G. Littlejohns, D. J. Thomson, M. Nedeljković, W. Zhang, K. Li, M. Banakar, Y. Tran, X. Yan, H. Du, Z. Ren, F. Gardes, G. T. Reed, and G. Z. Mashanovich, "High-speed silicon Michelson interferometer modulator and streamlined IMDD PAM-4 transmission of Mach-Zehnder modulators for the 2 μ m wavelength band," *Opt. Express* 29(10), 14438-14451 (2021).
- [17] X. Wang, W. Shen, W. Li, Y. Liu, Y. Yao, J. Du, Q. Song, and K. Xu, "High-speed silicon photonic Mach-Zehnder modulator at 2 μ m," *Photon. Res.* 9, 535-540 (2021).
- [18] W. Shen, G. Zhou, J. Du, L. Zhou, K. Xu, and Z. He, "High-speed silicon microring modulator at the 2 μ m waveband with analysis and observation of optical bistability," *Photon. Res.* 10(3), A35 (2022).
- [19] X. Wang, J. Wang, Y. Yao, S. Xiao, Q. Song, and K. Xu, "Efficient and high-speed coupling modulation of silicon racetrack ring resonators at 2 μ m waveband," *Opt. Lett.* 49(8), 2157-2160 (2024).
- [20] B. Pan, J. Hu, Y. Huang, L. Song, J. Wang, P. Chen, Z. Yu, L. Liu, and D. Dai, "Demonstration of high-speed thin-film lithium-niobate-on-insulator optical modulators at the 2- μ m wavelength," *Opt. Express* 29(12), 17710-17717 (2021).
- [21] C. Wang, M. Zhang, X. Chen, M. Bertrand, A. Shams-Ansari, S. Chandrasekhar, P. Winzer, and M. Loncar, "Integrated lithium niobate electro-optic modulators operating at CMOS-compatible voltages," *Nature* 562, 101 (2018).
- [30] F. Valdez, V. Mere, X. Wang, and S. Mookherjee, "Integrated O- and C-band silicon-lithium niobate Mach-Zehnder modulators with 100 GHz bandwidth, low voltage, and low loss," *Opt. Express* 31(4), 5273-5289 (2023).
- [31] X. Fang, F. Yang, X. Chen, Y. Li, and F. Zhang, "Ultrahigh-Speed Optical Interconnects With Thin Film Lithium Niobate Modulator," *J. Lightwave Technol.* 41(4), 1207-1215 (2023).
- [39] C. Han, Z. Zheng, H. Shu, M. Jin, J. Qin, R. Chen, Y. Tao, B. Shen, B. Bai, F. Yang, Y. Wang, H. Wang, Z. Zhang, S. Yu, C. Peng and X. Wang, "Slow-light silicon modulator with 110-GHz bandwidth," *Sci. Adv.* 9, eadi5339 (2023).
- [40] J. Shen, Y. Zhang, L. Zhang, J. Li, C. Feng, Y. Jiang, H. Wang, X. Li, Y. He, X. Ji, G. Yin, Y. Tian, X. Xiao, and Y. Su, "Highly Efficient Slow-Light Mach-Zehnder Modulator Achieving 0.21 V $\cdot$ cm Efficiency with Bandwidth Surpassing 110 GHz," *Laser Photonics Rev.* 18(1), 2200192 (2024)

Major concerns:

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While the design of passive waveguide and modulation region may have some novelty, it is not surprisingly new. The authors should highlight the novelty in the structure or design method, if there is any.

Reply 1: We greatly appreciate the reviewer's thoughtful feedback and concerns regarding the novelty of our modulator structure and design methodology. While we acknowledge that the fundamental components of TFLN modulators have been extensively explored in prior studies, most existing work has focused on improving the radio-frequency (RF) modulation bandwidth or efficiency. In contrast, the primary motivation of our work is to develop a high-performance integrated modulator that combines ultrabroad EO and optical bandwidths, thereby enabling high-speed optical communications that fully exploit the broadband bandwidth resources spanning from the O-band to the 2- μm spectral region. To address the critical challenge of simultaneously achieving such ultrabroad EO and optical bandwidths in integrated modulators, we propose a novel architectural framework. Specifically, we employ adiabatic mode evolution engineering in the passive optical components of the modulator including optical splitters, the spot-size converters (SSCs) and optimized waveguide widths to support the record operational bandwidth. Concurrently, the traveling-wave electrodes in the active modulation region were engineered to align the RF effective index with the optical group indices, ensuring consistent large EO bandwidth performance across the entire spectrum.

For the 3-dB power splitter used in MZI-based modulators, conventional multimode interference (MMI) couplers exhibit limited operational wavelength ranges due to significant variations in effective refractive indices of higher-order modes with wavelength changes. In contrast, adiabatic coupling structures enable optical mode field evolution through tapered waveguide sections over ultrawide wavelength range, as long as the adiabatic condition is maintained. Building upon our prior demonstration of an ultra-wideband beam splitter [32], this work innovatively integrates this beam splitter into active broadband TFLN modulators. Specifically, this work presents novel findings and extends the analysis and discussions of extended full spectrum optical communications, far beyond our earlier investigation of the passive beam splitter, which focused solely on its standalone performance [32].

To emphasize the novelty of the adiabatic coupling employed in the passive optical components of our modulator design, we have enhanced the description in the last paragraph of the "Main" section on page 2:

"Here, we demonstrate a high-speed TFLN electro-optic modulator with a record-breaking continuous operational range of 1260–2060 nm, seamlessly bridging the O-U bands and the 2- μm band. **This broadband capability is enabled by leveraging adiabatic mode evolution engineering in critical passive optical components—such as optimized optical splitters and spot-size converters (SSCs).** By integrating adiabatic mode evolution engineering with the TFLN platform, our device

achieves a 3-dB EO bandwidth exceeding 67 GHz across the O-U bands and 50 GHz in the 2- μ m band—the highest reported for this spectral region.”

Secondly, in the section of “Design of the broadband TNLN modulator” on page 5:

“The full spectrum 3-dB power splitter is based on TFLN adiabatic waveguide, with light is adiabatically coupled from the input waveguide to two symmetric output waveguides through three tapers. This design leverages adiabatic coupling principles, enabling uniform 3-dB power splitting over an ultrawide wavelength range provided that adiabatic conditions are satisfied. We employ this broadband power-splitting scheme into the TFLN modulator to construct the light interference structure. Further design details of the 3-dB power splitter are provided in Ref. [32].”

Regarding the broadband SSC, our proposed dual-layer taper and SiON cladding waveguide architecture exhibits superior broadband operational characteristics and enhanced packaging compatibility. While prior multilayer SSC designs (e.g., Ref [1] provided by the Reviewer) have demonstrated wavelength operation at dual bands (775 nm and 1550 nm) with 100 nm tip width, our bilateral two-layer design utilizes a 200 nm tip width. This critical dimension adjustment significantly improves fabrication tolerance while maintaining operational bandwidth. Although the spectral ranges of Ref. [1] and our work differ, our structure achieves a wider spectral coverage (1260-2060 nm) with lower insertion loss over the working wavelength range, as shown in fig 3(a). Ref [2] only presented simulation study on ultra-broadband edge couplers, proposed a six-layer structure with SU-8 polymer cladding. However, the six layers and excessive length of this design would introduce substantial alignment errors and impose prohibitively high fabrication complexity. We question the practical feasibility of such a structure in manufacturing.

We have also revised the manuscript to add discussions on the design and experimental results of our SSCs on page 3-4.

“To achieve ultra-broadband operating bandwidth for practical optical packaging, the edge coupler was designed based on broadband SSC, which is illustrated in Fig. 2(a) and (b). The structure comprises LN bi-layer tapers and a silicon oxynitride (SiON) ridge waveguide.”

“Achieving low coupling loss (<1 dB) across the 1260-2060 nm spectral range requires precise matching between the mode field diameter (MFD) of the SiON waveguide and the coupled fibre. The MFD of the UHNA4 fibre increases with wavelength, for example, it is 3.3 μ m at 1310 nm, 4.0 μ m at 1550 nm, and 5.3 μ m at 2000 nm. For a SiON rib waveguide with a rib height of 3.2 μ m and slab height of 1 μ m, the wavelength-dependent coupling loss with varying the width of the SiON rib waveguide are presented in Fig. 2c. Narrower rib widths minimize coupling loss at shorter wavelengths (e.g., 1310 to 1480 nm), while broader widths improve performance at longer wavelengths (e.g., 1680 to 2000 nm). However, an anomalous variation in coupling loss occurs at 1310, 1410, and 1480 nm when the rib width exceeds 4.8 μ m, caused by resonant fluctuations from higher-order mode excitation. Specifically, increased rib width enhances susceptibility to higher-order modes at shorter wavelengths, inducing resonances that disrupt coupling efficiency. Notably, at 1550 nm, the SSC exhibits consistent low coupling loss across different rib widths. Below 1550 nm, coupling loss increases with rib width, while the opposite trend is observed above 1550 nm. To balance high coupling efficiency across O- to U-bands (with prioritized performance in the C-band) and maintain acceptable loss at longer wavelengths, the SiON rib width was optimized to 4.4 μ m. This design also demonstrates robust tolerance to dimensional variations in the SiON waveguide cross-section.

“The SSC parameters were optimized through a dual focus: maximizing the taper length to ensure adiabatic mode evolution and minimizing the tip width to enhance coupling efficiency, while maintaining fabrication feasibility. The design details of the SSC including the influence of tip widths to the coupling loss are discussed in Supplementary Note 1. The finalized SSC parameters are summarized in Table 1.”

Detailed design of our broadband SSC coupler can be found in Supplementary Note 1 of the revised manuscript.

Supplementary Note 1: Design of the broadband edge coupler

A. Cross section views of the 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 [S1-S2].

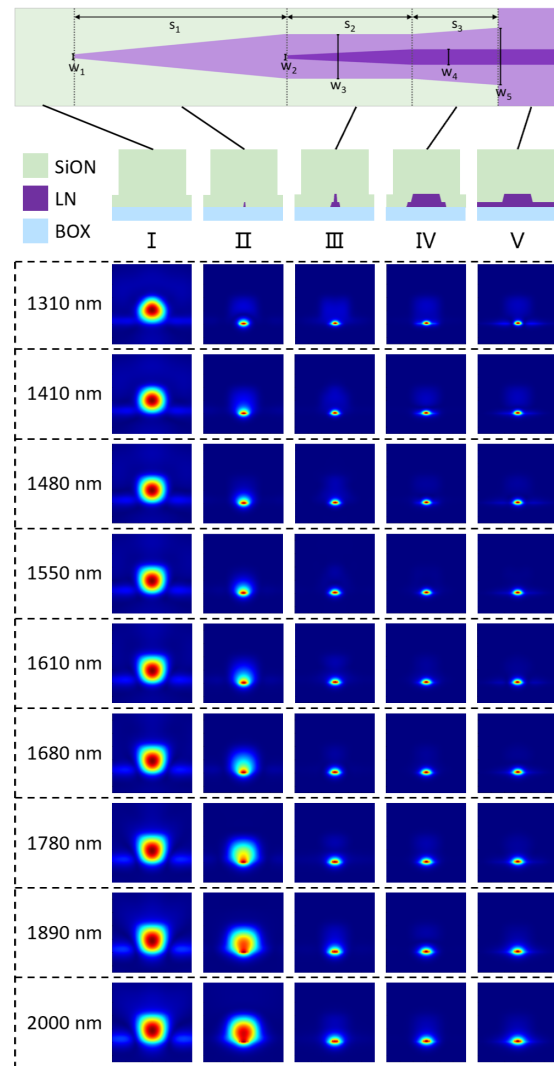


Fig. S1: Cross-section of the SSC and corresponding TE mode field distributions at various wavelengths from 1310 to 2000 nm.

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.

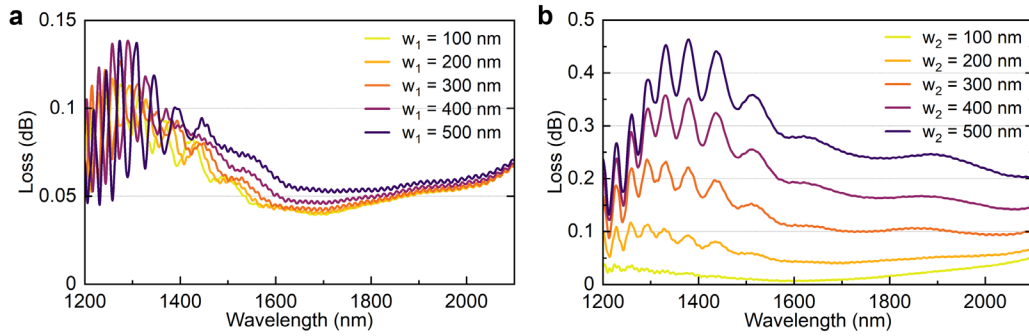


Fig. S2: Simulated conversion loss for different tip widths w_1 and w_2 .

To optimize the waveguide width and traveling-wave electrode, we systematically balanced modulation efficiency and broadband metal-induced absorption loss, achieving a high-performance modulator design. This optimization process is thoroughly documented in Supplementary Note 2 and 3, where detailed analyses of the trade-offs between EO performance and materials-related loss mechanisms are provided.

We have revised the manuscript to include the optimization process of the waveguide width and design of the traveling-wave electrode in the second paragraph on page 4 and first paragraph on page 5:

“To balance these trade-offs, we implement an adiabatic taper proximal to the 3-dB power splitter, expanding the waveguide width to $W = 3.5 \mu\text{m}$ within the modulation region. The details of the waveguide width optimization are discussed in Supplementary Note 2. A FDE solver was employed to numerically analyze the coupled electrical-optical modal properties of the device architecture. The electrode gap (G) is defined as the horizontal separation between the ground plane and the signal electrode. As shown in Fig. 2(f), we calculated the half-wave voltage-length product ($V_\pi \cdot L$) and quantified the metal-induced absorption loss, both parameterized as functions of G at wavelengths of 1310, 1550, and 2000 nm.”

“For $\lambda = 2000$ nm, the residual index mismatch leads to a theoretical 3-dB bandwidth of approximately 80 GHz for a 9-mm-long, impedance-matched, lossless modulator. Design details of the broad bandwidth traveling-wave electrodes can be found in Supplementary Note 3.”

Supplementary Note 2: Waveguide width optimization

Figure S3 illustrates the variations in LN waveguide widths across different sections. A narrower width of $W = 0.8 \mu\text{m}$ is maintained specifically in the regions of the SSC, power splitters, and bend waveguides. In contrast, a wider width of $W = 3.5 \mu\text{m}$ 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 ($V_\pi \cdot L$) and metal-induced absorption loss at 1550 nm. Both parameters were parameterized as functions of the lithium niobate (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 $W = 3.5$ μm for component connections and overall waveguide operation. The rationale for selecting $W = 3.5$ μm 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 $W = 0.8$ μm 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.

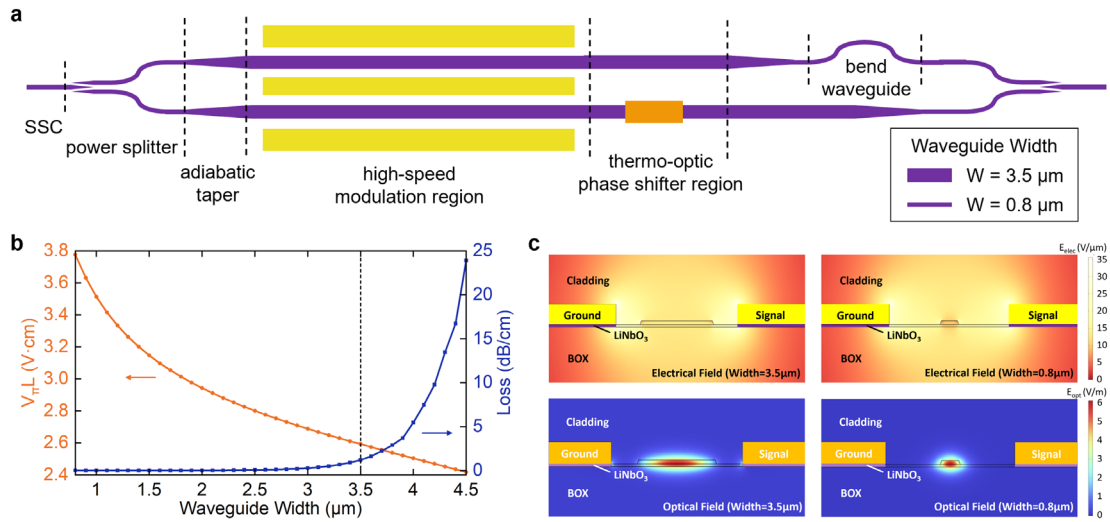


Fig. S3: (a) Schematic illustration of LN waveguide widths in different parts. (b) Simulated $V_\pi \cdot L$ and loss as a function of waveguide width. (c) Simulated optical and electrical field distributions with waveguide width $W = 0.8$ and 3.5 μm at $\lambda = 1550$ nm.

Supplementary Note 3: Design 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 O- 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 SiO_2 cladding thickness as critical parameters affecting both the optical group index n_g and RF n_m . As shown in Fig. S4(a) and (b), 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 SiO_2 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- μm band communication systems, even accounting for residual index mismatch effects.

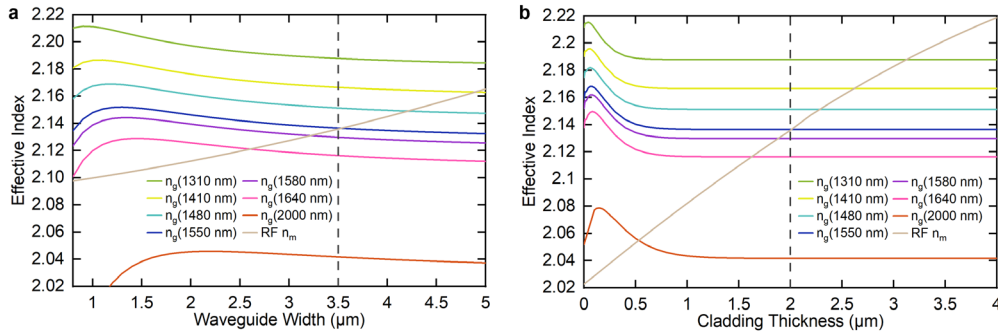


Fig. S4: The effective index factor with (a) LN waveguide width and (b) SiO_2 cladding thickness.

2: Another main concern is the claim of an operational wavelength range exceeding 800 nm. While the simulation results may indicate such a range, the experimental results—specifically the 3-dB bandwidths and eye patterns—were only measured only at 3 wavelengths (1310, 1550, and 2000 nm). Although the transmission spectra of the SSC over these 3 bands are shown (Fig. 3a), the transmission spectra of the modulator itself are not provided. There are several wavelength bands between 1310 nm and 1550 nm, and between 1550 nm and 2000 nm. It is risky to claim an 800-nm operational range without more comprehensive experimental data.

Reply 2: The authors sincerely thank the Reviewer for their constructive suggestions. Following the reviewer's recommendation, we have performed comprehensive characterizations of the modulator across the entire accessible wavelength range including the full O-U bands (1260–1680 nm) and the 2- μm band (1920–2060 nm), according to our available laser sources. The revisions aim to rigorously address the Reviewer's concerns and provide confirmed validation of the 800-nm operational wavelength range. The uncharacterized wavelength interval between 1680 nm and 1890 nm corresponds to a region rarely utilized in optical communication systems, and suitable laser sources for this range were not accessible in our lab.

The measured TE mode coupling losses are 0.78 dB/facet at 1310 nm, 1.18 dB/facet at 1450 nm, 1.73 dB/facet at 1485 nm, 0.69 dB/facet at 1550 nm, 0.56 dB/facet at 1590 nm, 0.69 dB/facet at 1653 nm, 0.82 dB/facet at 1970 nm, and 2.21 dB/facet at 2000 nm, as shown in Fig. 3(a). Regarding the 3-dB bandwidth and data transmission performance, in addition to the three wavelengths (1310, 1550, and 2000 nm, corresponding to the O-, C-, and 2 μ m bands) previously measured in the original manuscript, we have added five additional wavelengths: 1450 nm (E-band), 1485 nm (S-band), 1590 nm (L-band), 1653 nm (U-band), and 1970 nm (2- μ m band). The 3-dB bandwidths of these wavelengths have been added into Fig. R3(b).

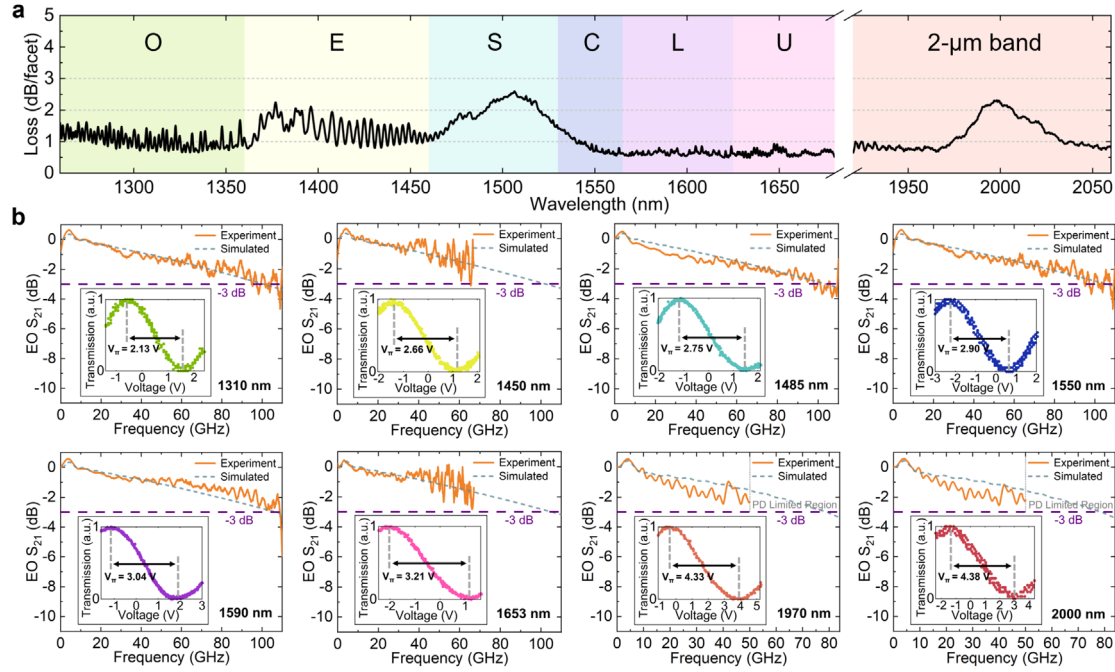


Fig. 3/R2 | Measured performance of the TFLN modulator. a Measured coupling loss of the SSC for the 1260-1680 nm and 1920-2060 nm range. **b** Measured EO S_{21} responses of the TFLN modulator. The dash lines indicate the simulated bandwidths. The insets show normalized optical transmissions with measured half-wave voltage V_{π} .

We would like to thank the Reviewer again for giving us an opportunity to thoroughly evaluate the performance of our TFLN modulator across an 800 nm operational wavelength range, spanning from the O-band to the 2- μ m spectral region. For the communication bands at 1310 nm (O), 1485 nm (S), 1550 nm (C), and 1590 nm (L), we employed a 110-GHz lightwave component analyzer (Ceyear 6433P) to characterize the EO responses. For the extended wavelengths (1450 nm/S-band, 1653 nm/U-band, 1970 nm, and 2000 nm/2- μ m band), measurements were conducted using a 67-GHz vector network analyzer (Keysight N5247B) to obtain the EO S_{21} responses. As shown in Fig. R3(b), the results reveals that the TFLN modulator exhibits >67 GHz 3-dB EO bandwidths across all conventional full spectrum optical communication bands (O–U bands). Notably, the modulator exhibits exceptionally broad bandwidths of ~100 GHz at critical telecommunication wavelengths: 1310 nm (O-band), 1485 nm (S-band), 1550 nm (C-band), and 1590 nm (L-band). These performance metrics are comparable to state-of-the-art single-waveband-optimized integrated modulators reported in literature [21, 30-31, 39-40], while maintaining this high performance across an extended multi-wavebands.

After characterizing the EO bandwidth of the TFLN modulator chip, we identified that the previously used butterfly-packaged configuration with a 1.8 mm RF coaxial connector inherently constrained the maximum achievable data rate. Specifically, this configuration exhibited a 3-dB EO bandwidth of ~43 GHz, which limited the data rate to only 115 Gbps at 1550 nm due to its restricted RF bandwidth. For reference, the measured S_{21} frequency response curve and pictures of this earlier butterfly-packaged modulator are illustrated in Fig. R3(a). To accurately evaluate the high-speed

transmission potential of the chip, we implemented an optical interface directly coupling the modulator chip to UHNA4 fibres, as illustrated in the inset of Fig. R3(b). This configuration bypassed the RF bandwidth constraints of the butterfly package while maintaining optical compatibility for precise performance evaluation.

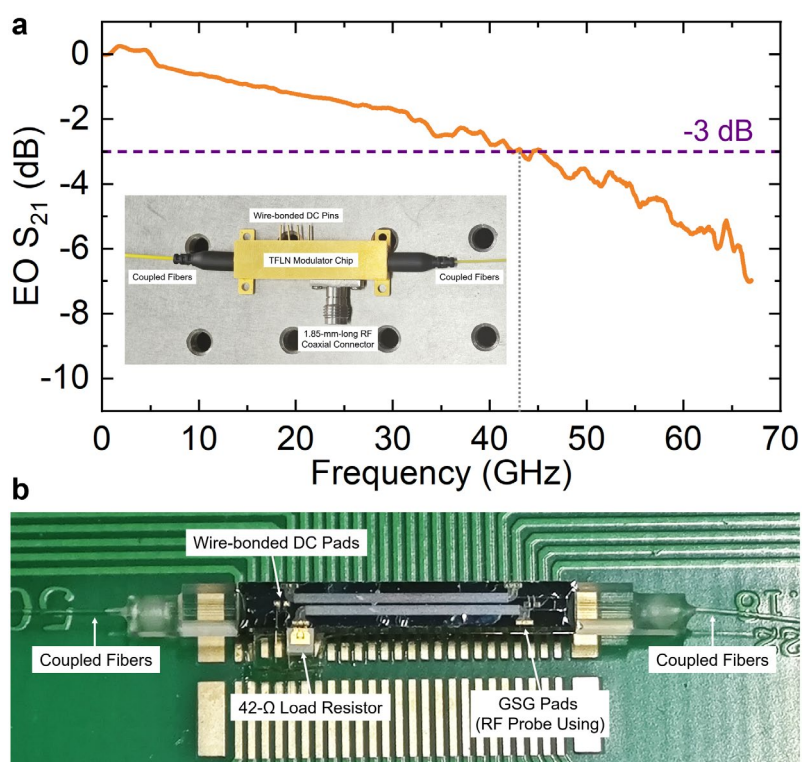


Fig. R3: (a) Measured EO S_{21} responses of the butterfly-packaged TFLN modulator. Inset: pictures of the butterfly-packaged TFLN modulator. (b) optical packaged TFLN modulator chip.

Figure 4/R4 presents eye diagrams, bit error rates (BERs) curves of PAM-4 signals as functions of received optical power, alongside comprehensive BER measurements for both OOK and PAM-4 modulations across eight wavelengths spanning the O-band to the 2- μ m band. The maximum achievable data rates for each wavelength are summarized in Fig. 4/R5(d). Experimental results demonstrate high-speed data transmissions exceeding 170 Gbps for OOK and 240 Gbps for PAM-4 signals at all six selected wavelengths across the entire O- to U-bands. Notably, in the 2- μ m band (1970 nm and 2000 nm), the modulator supports 150 Gbps for OOK and 170 Gbps for PAM-4 transmissions, with all BER maintained below the hard-decision forward error correction (HD-FEC) threshold of 3.8×10^{-3} . This represents the first experimental validation of full-spectrum optical communications (O to U bands) with single-lane data rates exceeding 240 Gbps, enabled by the modulator's ultra-wide wavelength operability. Furthermore, the achieved single-lane 170 Gbps transmission in the 2- μ m band significantly surpasses the previously reported record for this spectral region.

We have also updated Fig.5 (Comparison of 3-dB bandwidth) and Table 2 (Performance comparison of on-chip integrated EO modulators operating at 2- μ m band) in the revised manuscript, also provided at the beginning of this response. In terms of the transmission spectra of the TFLN modulator, we added measured transmission spectra of 1260-1680 nm and 1920-2060 nm range in Fig R5/S7. The details can be found in Supplementary Note 5. Additionally, we present updated results for both simulated and measured V_{π} ·L parameters across all eight wavelengths in Supplementary Note 7, ensuring consistency between theoretical predictions and experimental observations. Furthermore, Supplementary Notes 9 and 10 now include expanded discussions on the methodology of the data transmission measurements, alongside detailed listings of all experimental components, including laser sources, optical amplifiers, and detectors employed in the experiments.

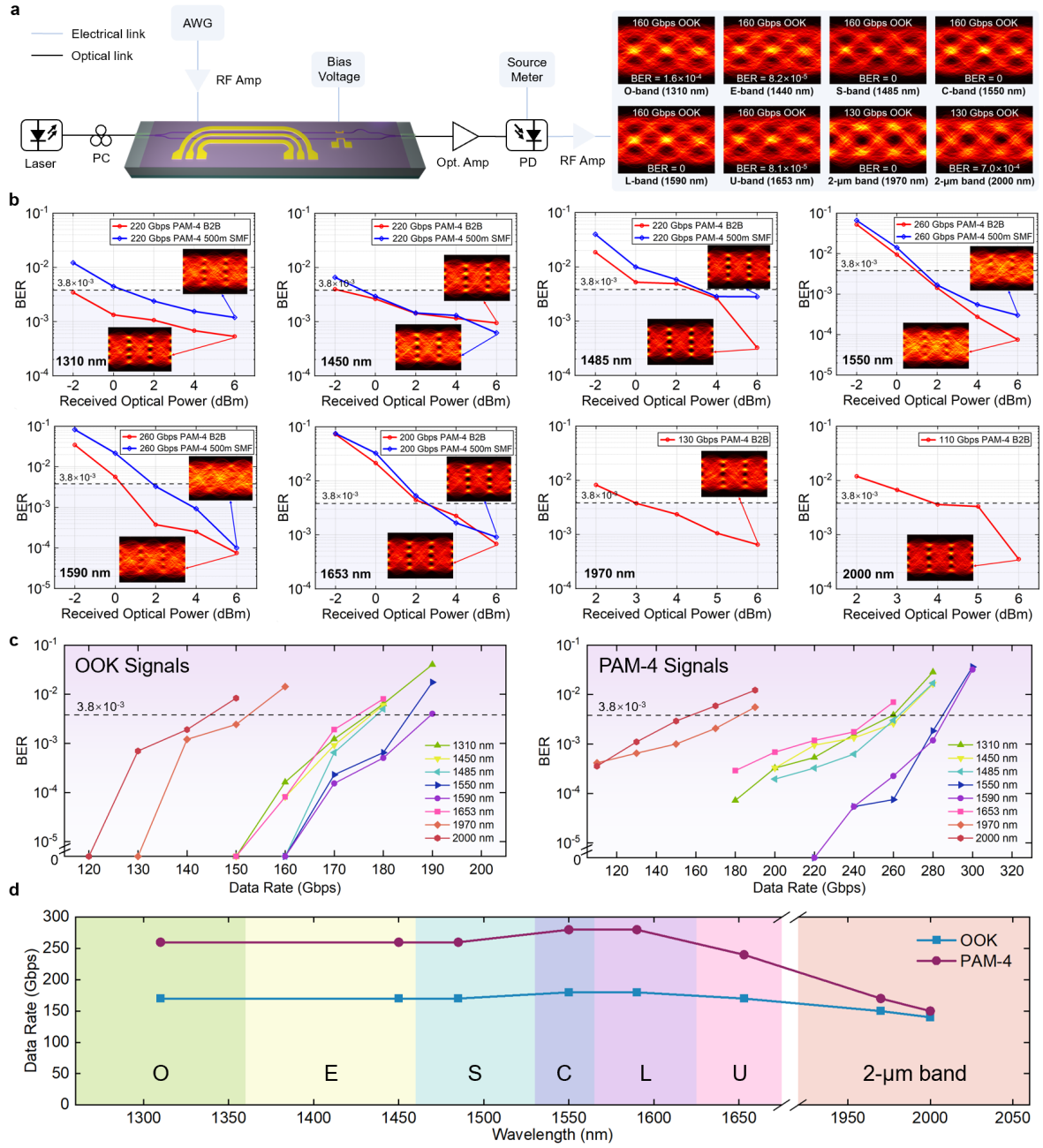


Fig. 4/R4 | Data transmission results. a Experimental setup for measuring the eye diagrams and the calculated eye diagrams for OOK signals. **b** Measured BER curves versus the received optical power of PAM-4 signals for $\lambda = 1310/1450/1485/1550/1590/1653/ 1970/2000$ nm. The insets show the calculated eye diagrams. **c** The BER curves with increasing data rates of different wavelengths with OOK and PAM-4 signals. **d** The maximum data rates of OOK/PAM-4 signals with BERs under the HD-FEC threshold operated in the ultra-wide wavebands.

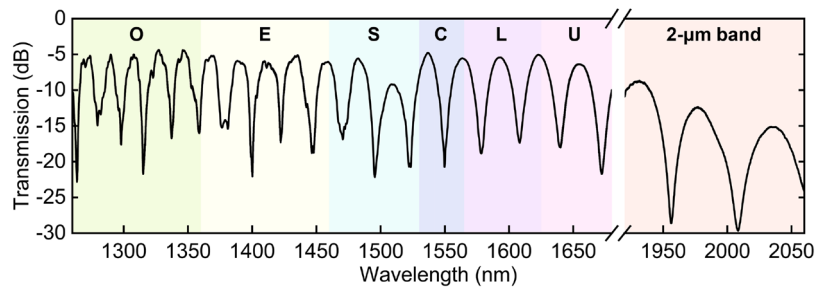


Fig. S7/R5: Transmission spectra of the TFLN modulator.

We have listed all the revisions in the manuscript associated with updated electro-optic (EO) bandwidths and data transmission measurements below.

Firstly, in the abstract on page 1:

“The fabricated modulator demonstrates >67 GHz EO bandwidth in both O-U bands and > 50 GHz (detector-limited) in the 2- μ m band. Specifically, the modulator achieves a 3-dB EO bandwidth of ~100 GHz at 1310 nm (O-band), 1485 nm (S-band), 1550 nm (C-band), and 1590 nm (L-band). This device enables single-lane transmission exceeding 240 Gbps (PAM-4 modulation) across all O–U bands. Notably, we achieve 150 Gbps OOK and 170 Gbps PAM-4 transmission in the 2- μ m band - the highest rates reported for this spectral region. This breakthrough establishes TFLN as a compelling platform for multispectral photonics, bridging conventional telecom infrastructure with emerging 2- μ m technologies for next-generation full-spectrum optical communications.”

Secondly, in the last paragraph in the “Main” section on page 2:

“Here, we demonstrate a high-speed TFLN electro-optic modulator with a record-breaking continuous operational range of 1260–2060 nm, seamlessly bridging the O-U bands and the 2- μ m band. This broadband capability is enabled by leveraging adiabatic mode evolution engineering in critical passive optical components—such as optimized optical splitters and spot-size converters (SSCs). By integrating adiabatic mode evolution engineering with the TFLN platform, our device achieves a 3-dB EO bandwidth exceeding 67 GHz across the O-U bands and 50 GHz in the 2- μ m band—the highest reported for this spectral region. Furthermore, the modulator achieves a 3-dB EO bandwidth of ~100 GHz in the O-, S-, C-, and L-bands (1310 nm, 1485 nm, 1550 nm, 1590 nm). The modulator exhibits exceptional efficiency, with $V_{\pi} \cdot L$ values of 1.92, 2.48, 2.61, 2.74, and 3.94 V·cm at 1310, 1485, 1550, 1590, and 2000 nm, respectively. Experimental validation using an optical packaged device demonstrates transmission of 170/170/170/180/180/170 Gbps On-Off Keying (OOK) and 260/260/260/280/280/240 Gbps 4-level Pulse Amplitude Modulation (PAM-4) signals for the corresponding O-, E, S-, C-, L-, and U- bands. Notably, the modulator also enabled 150 Gbps OOK and 170 Gbps PAM-4 transmissions in the 2- μ m band, with BER all below the hard-decision forward error correction (HD-FEC) threshold (3.8×10^{-3}). This breakthrough paves the way for universal optical transmitters capable of unifying fragmented spectral resources into a single ultra-broadband communication infrastructure, with transformative potential for next-generation optical networks, quantum systems, and sensing technologies.”

Thirdly, in the first and second paragraphs in the “Measurement and analysis” section on page 6:

“Coupling losses were measured using tunable lasers for the 1260–1680 nm bands, and a custom-built 2- μ m amplified spontaneous emission (ASE) source paired with an optical spectrum analyzer (Yokogawa AQ6375B) for the 1920–2060 nm range. Using a polarization controller (PC), the measured TE mode coupling losses are 0.78 dB/facet at 1310 nm, 1.18 dB/facet at 1450 nm, 1.73 dB/facet at 1485 nm, 0.69 dB/facet at 1550 nm, 0.56 dB/facet at 1590 nm, 0.69 dB/facet at 1653 nm, 0.82 dB/facet at 1970 nm, and 2.21 dB/facet at 2000 nm, as shown in Fig. 3(a). The slightly higher losses at shorter and longer wavelengths are attributed to minor mode mismatch between the UHNA4 fibre and the SiON waveguide.”

“Notably, three pronounced loss peaks near 1510 nm and 2000 nm correlate with intrinsic N–H infrared absorption bands in the plasma-deposited SiON layer, consistent with prior reports of N–H bond absorption [33–36]. The slight loss rise of 1370–1410 nm can be attributed to the O–H bond during the plasma deposition of SiON layer [37]. The normalized transmission spectra of the TFLN modulator for the 1260–1680 nm and 1920–2060 nm spectral region can be found in Supplementary Note 5. Following characterization of the modulator’s total optical losses, the on-chip insertion losses (ILs) were deduced as 1.2 dB, 2.8 dB, and 5.8 dB at wavelengths of 1310 nm, 1550 nm, and 1970 nm, respectively. Following characterization of the modulator’s total optical losses, the on-chip insertion losses (ILs) were deduced as 1.2 dB, 2.8 dB, and 5.8 dB at wavelengths of 1310 nm, 1550 nm, and 1970 nm, respectively.”

“Fig. 3(b) illustrates the half-wave voltage V_{π} measurements with a 100 kHz triangular voltage sweep. With a modulator length of 9 mm, the $V_{\pi} \cdot L$ values are calculated to be 1.92/2.39/2.48/2.61/2.74/2.89/3.90/3.94 V·cm for $\lambda = 1310/1450/1485/1550/1590/1653/1970/2000$ nm, respectively. The simulated and measured $V_{\pi} \cdot L$ parameters across these eight wavelengths can be found in Supplementary Note 7.”

Fourthly, in the EO response measurements of the “Measurement and analysis” section on page 7:

“The EO responses of the fabricated TFLN modulator were characterized using an 110-GHz lightwave component analyzer (LCA, Ceyear 6433P) in conjunction with a tunable laser (Santec TSL-570). A 110-GHz high-speed RF probe was employed to deliver RF signals from the LCA, while a 42- Ω load resistor was attached at the end of the traveling-wave electrode to achieve impedance matching. As shown in Fig. 3b, the 3-dB bandwidths of ~100 GHz were observed at wavelengths of 1310 nm (O-band), 1485 nm (S-band), 1550 nm (C-band), and 1590 nm (L-band). Due to the lack of relevant wavebands detection modules in the LCA, we utilized a 67-GHz vector network analyzer (VNA, Keysight N5247B) to measure the EO S_{21} response. The EO response was captured by feeding electrical signals from the PDs into the VNA. The measured EO response curves for the E- (1450 nm) and U-bands (1653 nm) using the commercial PD revealed that the modulator’s 3-dB bandwidth exceeded 67 GHz, limited by the VNA’s bandwidth. For the 2- μ m band, where commercial PDs lack sufficient bandwidth, we employed a recently demonstrated high-speed GeSn PD (bandwidth >40 GHz, Ref. [12]) to measure the bandwidth. The details of GeSn PD and the EO frequency responses for the 2- μ m band measurement are shown in Supplementary Note 8. After system calibration and PD-response de-embedding, characterization of the frequency response and high-speed data transmission capabilities was achieved. The measured EO S_{21} response at $\lambda = 2$ μ m (Fig. 3c) reveals a 3-dB bandwidth of >50 GHz, the highest reported to date for optical modulators operating in the 2- μ m band.”

Fifthly, in the high-speed data transmission measurements of the “Measurement and analysis” section on page 7-9:

“To evaluate the high-speed data transmission performance of the TFLN modulator, the device was optically packaged to UHNA4 fibers and characterized across all operational wavelength regions: the O-band (1310 nm), E-band (1450 nm), S-band (1485 nm), C-band (1550 nm), L-band (1590 nm), U-band (1653 nm), and 2- μ m band (1970/2000 nm). The selected wavelengths in each band were chosen to align with current and potential communication applications, as well as the available laser sources and amplifiers. Fig. 4(a) illustrates the experimental setup for measuring eye diagrams and bit error rate (BER). Optical signals were generated using various laser sources at 1310 nm, 1450 nm, 1485 nm, 1550 nm, 1590 nm, 1653 nm, 1970 nm, and 2000 nm. High-frequency RF signals, synthesized by a 256 GSa/s arbitrary waveform generator (AWG, Keysight M8199B), were amplified to ~2.4 Vpp using an RF amplifier and applied to the modulator. A pre-equalizer was implemented to preprocess signals prior to loading them into the AWG, thereby compensating for bandwidth limitations of the system. The bias point of the modulator was stabilized via an integrated heater. The modulated light was amplified using wavelength-specific amplifiers: semiconductor optical amplifiers (SOAs) for the O-, E-, S-, and U-bands; two erbium-doped fibre amplifiers (EDFAs) for the C- and L-bands; and a thulium-doped fibre amplifier (TDFA) for the 2- μ m band. The amplified light was then coupled into a 100-GHz-bandwidth photodetector (PD, Finisar XPDV4121R) for wavelengths up to the U-band, and a GeSn PD (previously characterized in prior work) for the 2- μ m band. Received signals were captured by a high-speed real-time oscilloscope (Keysight UXR0594BP), featuring a 59-GHz bandwidth and 256 GSa/s sampling rate. The BER can be calculated after a series of offline digital signal processing (DSP). A Volterra nonlinear equalizer (VNLE) and maximum likelihood sequence equalization (MLSE) algorithm was jointly employed to mitigate both linear and nonlinear signal impairments. Detailed specifications of the equipment used in high-speed data transmission measurements are provided in Supplementary Note 9.”

“The inset of Fig. 4(a) displays measured eye diagrams and corresponding BERs for 160 Gbps OOK signals across the O-, E-, S-, C-, L-, and U-bands, as well as 130 Gbps OOK signals in the 2- μ m band. Clear eye openings were observed for all

the wavelengths, respectively. To our knowledge, this represents the highest OOK transmission rate in the 2- μ m band and the first TFLN modulator capable of exceeding 170 Gbps OOK operation across all O-U bands. We further evaluated PAM-4 performance by measuring BER curves as a function of received optical power (ROP), defined as the optical power incident on the PD. A variable optical attenuator (VOA) was inserted after the optical amplifiers to adjust ROP. Fig. 4(b) shows back-to-back (B2B) BER curves for the TFLN modulator. For O-U bands, transmission results through a 500-m standard SMF were also included and exhibit negligible power penalties compared to the B2B case. To further explain the data rates of single-lane transmission, we analyze the BER performance of OOK and PAM-4 signals for all eight wavelengths ranging from 120 to 300 Gbps (see Fig. 4c). Under the same HD-FEC threshold (3.8×10^{-3}), we successfully realize the transmission of 260/260/260/280/280/240/170/150 Gbps PAM-4 signals were obtained at 1310/1450/1484/1550/1590/1653/1970/2000 nm. Figure 4(d) shows the maximum data rates achieved using OOK/PAM-4 signals while maintaining a BER below the HD-FEC threshold for all eight wavelengths. This represents the first experimental validation of full-spectrum optical communications (O to U bands) with single-lane data rates exceeding 240 Gbps (PAM-4), enabled by the modulator's ultra-wide wavelength operability. Furthermore, the achieved single-lane 170 Gbps transmission in the 2- μ m band significantly surpasses the previously reported record for this spectral region [18]. Further discussions on data transmission measurements for various wavebands can be found in Supplementary Note 10.”

Finally, in the “Discussion and conclusion” section on page 9-10:

“Fig. 5 compares the 3-dB EO bandwidths of integrated modulators in the short-wave infrared spectrum regime from 1.2–2.2 μ m. Our TFLN modulator operates across an unprecedented 800-nm optical bandwidth, spanning the O-U bands (1260–1680 nm), and extending into the 2- μ m regime (1920–2060 nm). This broad operational range enables multi-band compatibility within a single device, a critical advantage for versatile photonic systems. The TFLN modulator maintains a flat frequency response across its operational range. The measured EO bandwidths of the modulator reach ~ 100 GHz at critical communication wavelengths of 1310 nm (O-band), 1485 nm (S-band), 1550 nm (C-band), and 1590 nm (L-band), which are comparable with state-of-the-art performance of single-waveband-optimized integrated modulators reported in literature [21, 30–31, 38–39]. The 50-GHz bandwidth at 2000 nm enables, to our knowledge, demonstration of the highest single-lane 170 Gbps transmission data transmission in this band. This represents a 2.3-fold improvement in bandwidth over existing 2- μ m modulators, directly enhancing data capacity and underscoring the potential for next-generation high-speed communication systems. The detailed comparisons of the state of art integrated EO modulators operating in the 2- μ m spectral band are given in the ‘Methods’.”

“In conclusion, we demonstrate a TFLN modulator featuring high EO bandwidth and a record-breaking operational range spanning over 800 nm, from the O-band to the 2- μ m spectral region. The device achieves 3-dB EO bandwidths of over 67 GHz in both the O- and C-bands and >50 GHz in the 2- μ m band. Specifically, the modulator achieves a 3-dB EO bandwidth of ~ 100 GHz at 1310 nm (O-band), 1485 nm (S-band), 1550 nm (C-band), and 1590 nm (L-band). High speed data transmissions of >160 Gbps and 150 Gbps OOK signals and 240 Gbps and 170 Gbps PAM-4 signals were experimentally validated at all O-U bands and the 2- μ m band, with BERs below the HD-FEC threshold of 3.8×10^{-3} . These results underscore the transformative potential of TFLN modulators in enabling ultrabroadband optical communication systems that seamlessly bridge conventional telecom bands with the emerging 2- μ m window. This advancement directly addresses the escalating bandwidth demands of next-generation data centers and high-performance computing infrastructures.”

“Table 2 summarizes the performance metrics of integrated electro-optic modulators operating in the 2- μ m spectral band. Our TFLN modulator achieves a >50 GHz EO 3-dB bandwidth—the highest reported value in this spectral region—enabling a baud rate of 85 Gbaud (170 Gbps for PAM-4) and surpassing prior state-of-the-art devices. This advancement establishes a new benchmark for high-speed data transmission in the 2- μ m band.”

Detailed experimental results and analyses are provided in Supplementary Notes 5, 7 and 9-10 for reference.

Supplementary Note 5: Transmission spectra of the TFLN modulator

Figure S7 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- μm 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- μm band correlates with the enhanced metal absorption coefficient at longer wavelengths.

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

Figure S9 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 $V_\pi \cdot L$ is listed in Supplementary Table 1. The relatively consistent results validate the accuracy between the numerical model and the fabrication.

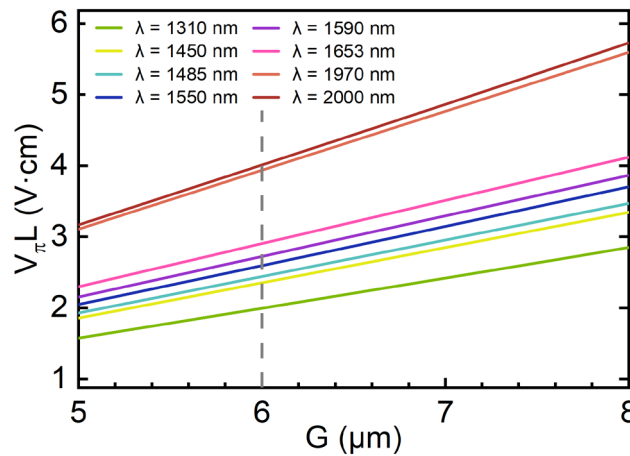


Fig. S9. Simulated $V_\pi \cdot L$ as a function of G .

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

Wavelength (nm)	Simulated $V_\pi \cdot L$ (V·cm)	Experiment $V_\pi \cdot L$ (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 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.

3: More details on the thermo-optic phase shifter should be provided. For example, information on its length and width, resistance, modulation efficiency, and wavelength dependency is lacking.

Reply 3: We thank the reviewer for raising this good point. We added the parameters of the thermo-optic phase shifter used in the modulator in the “Design of the broadband TNLN modulator” section on page 6:

“For $\lambda = 2000$ nm, the residual index mismatch leads to a theoretical 3-dB bandwidth of approximately 80 GHz for a 9-mm-long, impedance-matched, lossless modulator. The thermo-optic phase shifter is employed to establish the optimal operating bias point. By adopting thermal-optic (TO) tuning instead of EO tuning via bias tees on the traveling-wave electrodes, this approach not only simplifies packaging and testing procedures but also significantly improves the stability of the bias point by avoiding the LN DC bias drift problem caused by the DC bias voltage under EO bias conditions. Detailed design parameters and experimental results of the thermo-optic phase shifter used in our modulator can be found in supplementary Note 4.”

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

Figure S5a 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 $L_h = 200$ μ m, while the width and thickness of Ti heating resistor are set to $W_h = 4$ μ m and $H_h = 200$ 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

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

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.

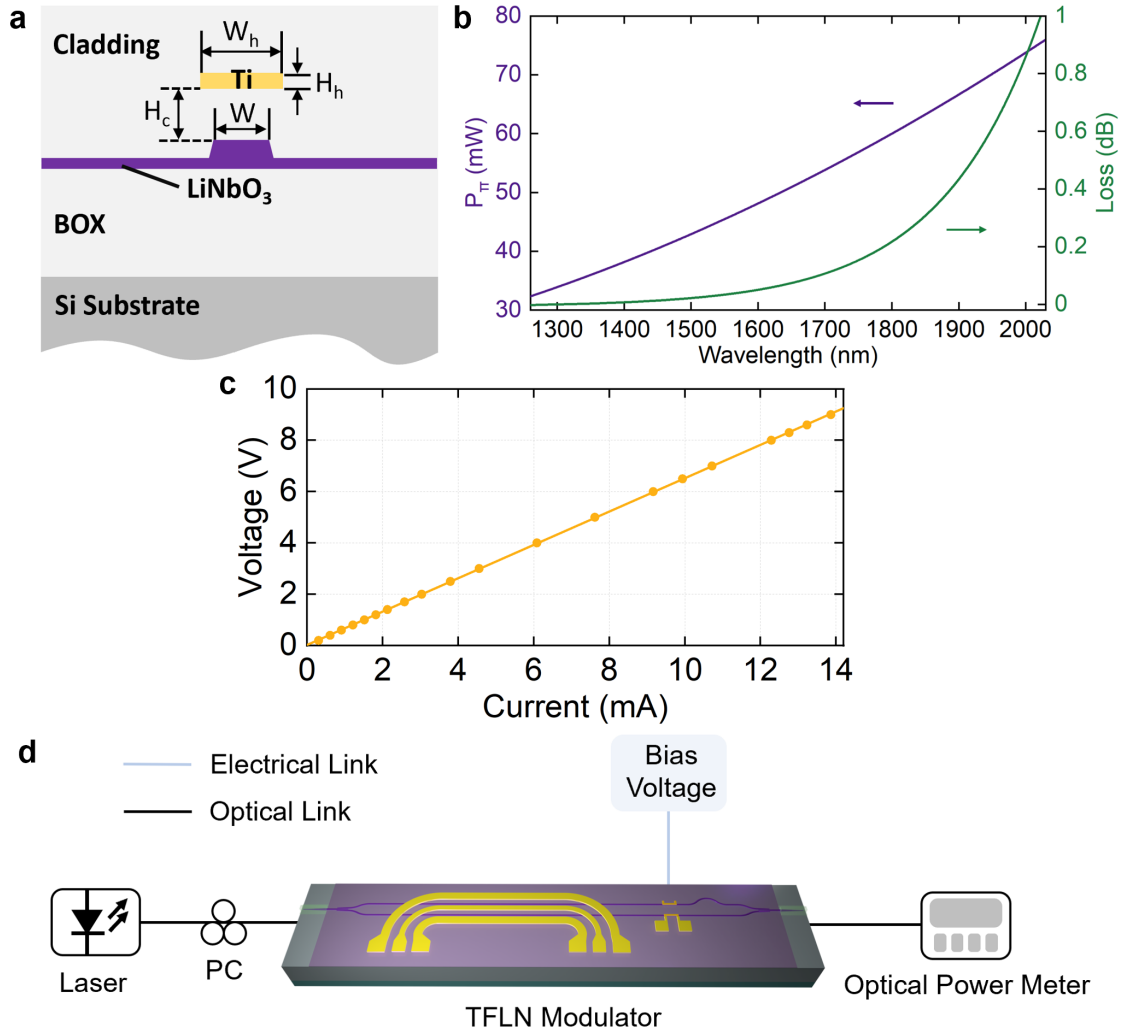


Fig. S5: (a) Cross-sectional view of the thermo-optic phase shifter region. (b) Simulated P_π and loss as a function of wavelength. (c) Experimental setup for the thermo-optic phase shifter characterization. (d) I-V curves of the Ti heater.

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. S5b. In our simulation, thermal conductivities of the LN, SiO₂ 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 S5c 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. S5d, 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.

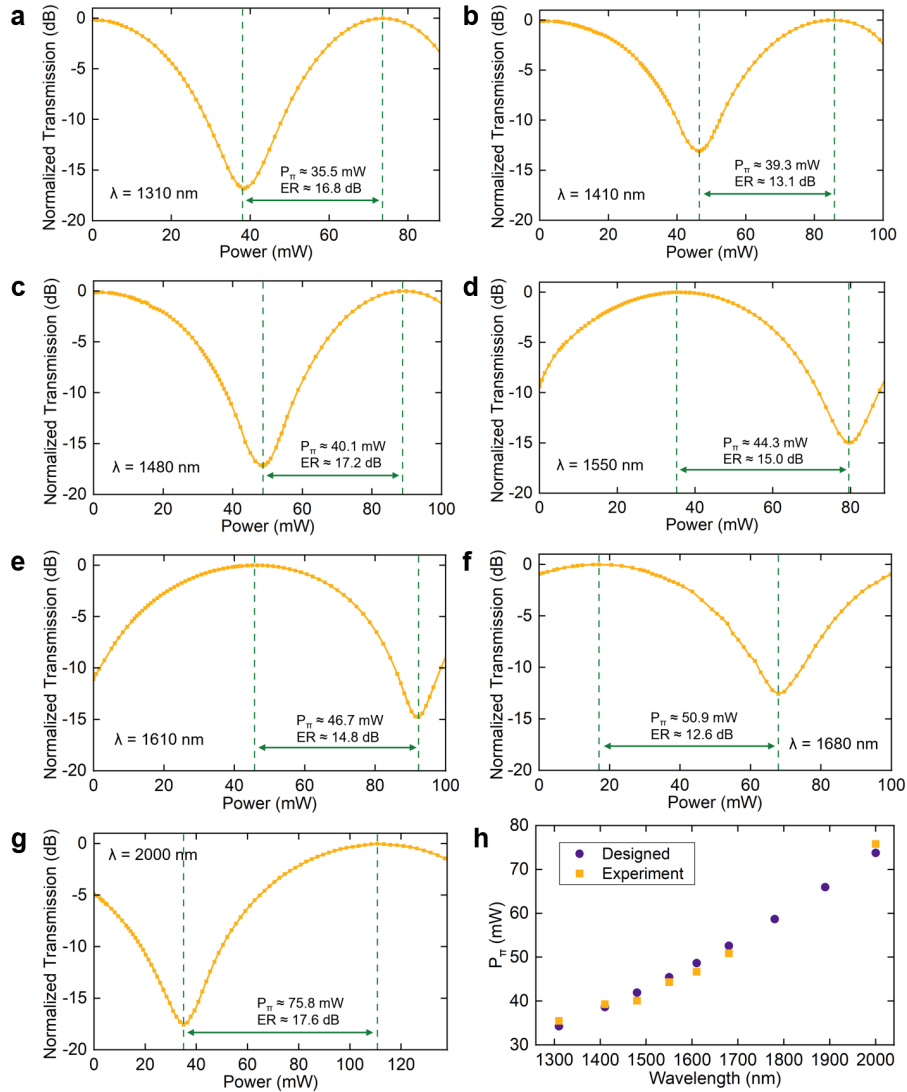


Fig. S6: The dependence of the normalized transmission as a function of heat power at wavelength (a) $\lambda = 1310\text{ nm}$ (b) 1410 nm (c) 1480 nm (d) 1550 nm (e) 1610 nm (f) 1680 nm (g) 2000 nm . (h) Designed and experiment P_π at several typical wavelengths.

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- μm wavebands, respectively) is presented in Fig. S6a–Fig. S6g. 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. S6h, 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.

4: More details and supporting information on the bandwidth measurements should be provided, possibly in the form of supplementary material. For example, what is the bias voltage applied to the GeSn photodetector (PD)? What is the frequency response of the GeSn PD at this bias? Since the measured 3-dB bandwidth (48 GHz) is close to the PD's limit, the frequency response curve of the PD itself is necessary to verify the reliability of the measurement.

Reply 4: This is a good and important point, which we are happy to address as below. For the experimental details, the bias voltage applied during frequency response measurements was maintained at -3 V. The EO frequency response characteristics of the GeSn PD at a wavelength of 2000 nm are now explicitly detailed, as shown in Fig. R6/S10. According to the test results, the 3-dB bandwidth of the GeSn PD exceeds 45 GHz, and the response curves exhibit stable behavior with smooth transitions up to 50 GHz under the -3 V bias condition. To ensure transparency, we have thoroughly documented these experimental conditions and additional response data in Supplementary Note 8, which we believe strengthens the validity of our measurements and interpretations.

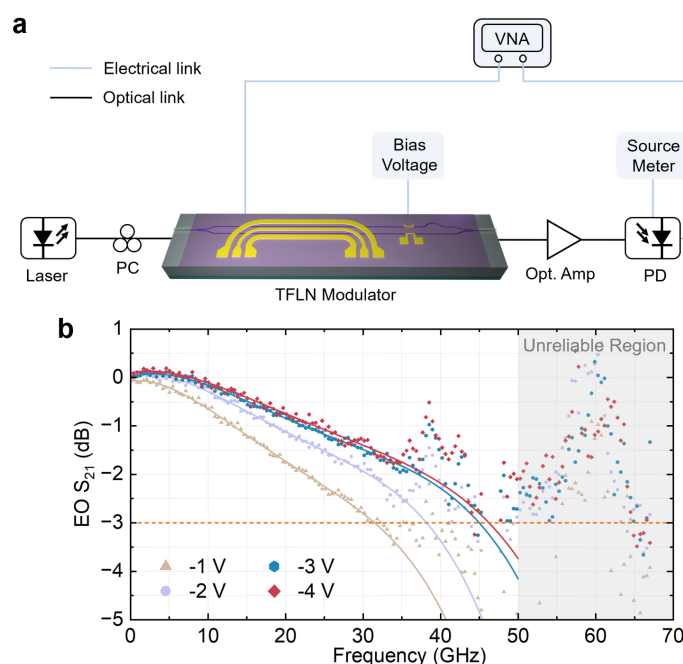


Fig. S10/R6: (a) Experimental setup for modulation bandwidth characterization. (b) EO frequency response of the used GeSn PD at $\lambda = 2000$ nm.

The electro-optic (EO) frequency responses for the 2- μm band measurements are detailed in Supplementary Note 8, which is referenced on page 7 of the revised manuscript.

“For the 2- μm band, where commercial PDs lack sufficient bandwidth, we employed a recently demonstrated high-speed GeSn PD (bandwidth >40 GHz, Ref. [12]) to measure the bandwidth. The details of GeSn PD and the EO frequency responses for the 2- μm band measurement are shown in Supplementary Note 8.”

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

For the measurement of frequency responses and high-speed data transmission in the 2 μm band, we utilized a recently demonstrated high-speed germanium tin (GeSn) photodetector (PD) [S3]. 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 μm and possess a cutoff wavelength of approximately 2750 nm.

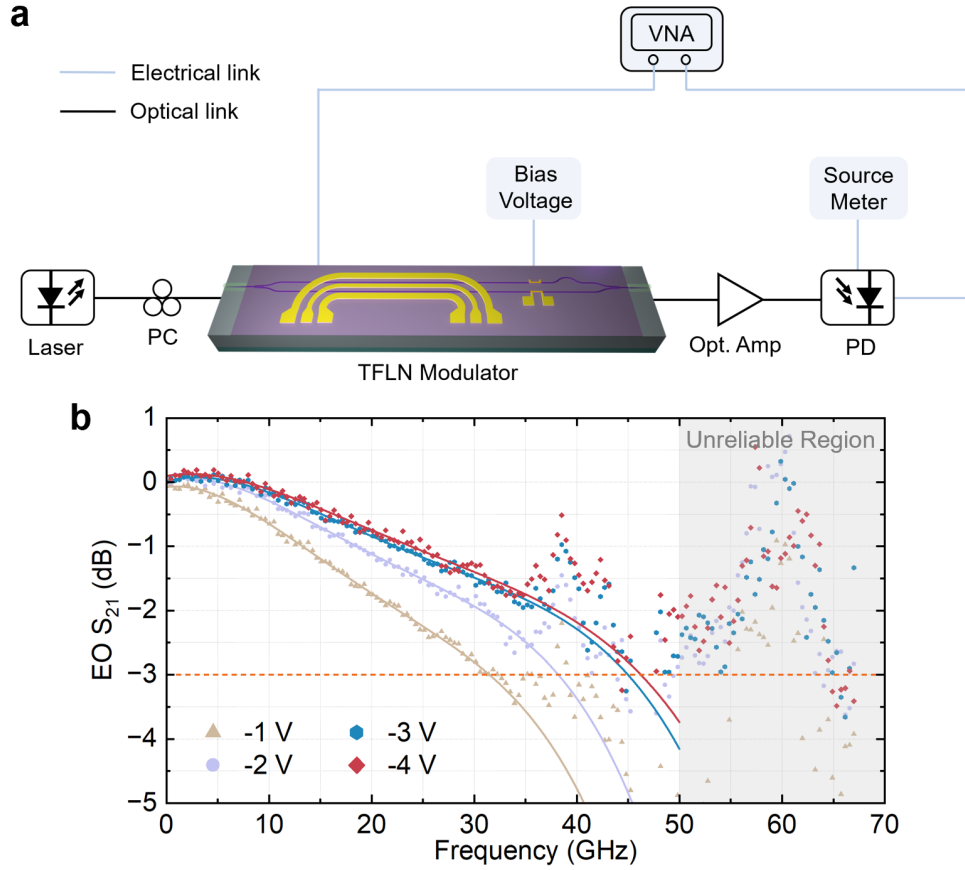


Fig. S10: (a) Experimental setup for modulation bandwidth characterization. (b) EO frequency response of the used GeSn PD at $\lambda = 2000$ nm.

Figure S10(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 fibre amplifier (TDFA), then coupled into the GeSn PD using a tapered lensed fibre with a mode field diameter (MFD) < 8 μm 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.

Figure S10(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. The responses remain stable with smooth curves up to 50 GHz, confirming the reliability of EO response measurements for the TFLN modulator in the 2- μm band within the 0–50 GHz frequency range. Above 50 GHz, the GeSn PD's EO response becomes unstable, rendering the response data unreliable.

[S3/12] Cui J et al, High-speed GeSn resonance cavity enhanced photodetectors for a 50 Gbps Si-based 2 μm band communication system, *Photonics Research*, 12(4), 767-773, (2024).

5: The theoretical 3-dB bandwidth is predicted to be 80 GHz (Line 154), but the measured value is 48 GHz. Please add some discussion (or quantitative analysis, if necessary) to explain this discrepancy.

Reply 5: We thank the reviewer for pointing out this good point. Regarding the discrepancy between the theoretically predicted and experimentally measured bandwidths, we attribute this deviation primarily to the limitations of the employed 2- μm germanium tin (GeSn) photodetector (PD). As previously discussed in our response to PD characterization concerns, the detector exhibits unstable frequency response beyond 50 GHz. Although measurement system response curves can technically be obtained above this threshold, the TFLN modulator's high-frequency response cannot be reliably characterized due to the PD's instability in this regime. The electro-optic S_{21} parameter of the TFLN modulator measures approximately -2.2 dB at 50 GHz, indicating a broader 3-dB bandwidth as evidenced by the S_{21} traces for 1970 and 2000 nm in Fig. R7.

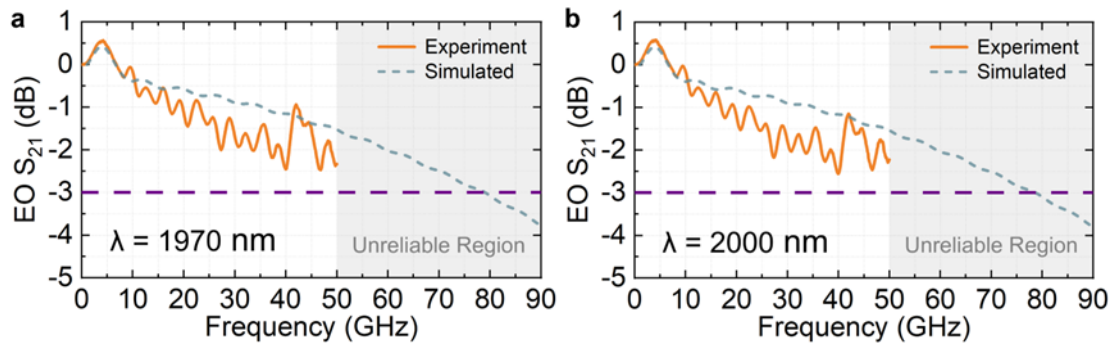


Fig. R7: Simulated and measured EO S_{21} responses of the TFLN modulator for (a) $\lambda = 1970$ nm and (b) $\lambda = 2000$ nm.

Regarding other factors contributing to the measured bandwidth being lower than the simulated value, we consider three primary considerations: First, the actual electrical conductivity of the gold (Au) electrode may deviate below the theoretical value used in simulations, leading to increased radio-frequency (RF) losses. Second, the deposition quality of the SiO_2 cladding layer may exhibit inferior uniformity compared to simulations, potentially including localized cracks. Such imperfections could enhance RF absorption within the SiO_2 , thereby increasing overall RF losses. Third, the mismatch between the RF effective index (n_m) and optical group index (n_g) may exceed the simulated scenario. While n_g is generally assumed to align closely with theoretical predictions, the actual n_m may deviate due to manufacturing inaccuracies in electrode topography, spacing, or overlay alignment. The combined effects of elevated RF losses and worsened mismatch between n_m and n_g collectively contribute to the observed discrepancy. However, we posit that these effects are minor, as the measured bandwidth values align closely with simulated results within the O- and U-bands, as demonstrated in Fig. 3(b).

6: Lines 170-173: The insertion loss at 1970 nm (5.8 dB) is significantly higher than that at 1310 nm (1.2 dB). The authors attribute this to “absorption by the metal electrodes”. However, given the increased sensitivity of longer wavelengths to scattering loss caused by surface roughness and interface defects, please provide the results of passive loss measurements for comparison.

Reply 6: We thank the reviewer for highlighting this important consideration. To address the concern regarding waveguide propagation loss characterization, we have employed three grating couplers operating at the O-, C-, and 2- μm bands within the layout’s allowable area. This configuration minimizes coupling efficiency inconsistencies by enabling consistent light coupling into the passive waveguide. 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 observed minimal wavelength dependence of the loss, as noted by the reviewer, arises from the trade-off between reduced Rayleigh scattering at longer wavelengths and increased surface scattering. This balance results in consistent total propagation losses across the O-, C-, and 2- μm bands.

Supplementary Table S1. On-chip loss source analysis

Wavelength	Measured on-chip IL	Simulated Au electrodes absorption loss	Simulated Ti heater absorption loss	Experiment average IL of 16-cascaded power splitter	3.5- μm -width 1.3-cm length waveguide propagation loss	0.8- μm -width bend waveguide 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

To further address the reviewer’s query about loss origins, we have included an on-chip loss component analysis in Supplementary Note 7. By comparing the measured passive losses with simulated metal absorption values in table S2, we confirm that the dominant source of enhanced loss at longer wavelengths stems from metal absorption losses, which is 2.9 dB at 1970 nm. This conclusion is supported by the correlation between wavelength-dependent metal absorption and the observed attenuation trends.

We have also revised the manuscript to reference the Supplementary Note 6 of loss analysis on page 6.

“Following characterization of the modulator’s total optical losses, the on-chip insertion losses (ILs) were deduced as 1.2 dB, 2.8 dB, and 5.8 dB at wavelengths of 1310 nm, 1550 nm, and 1970 nm, respectively. A test structure comprising 16 cascaded 3-dB power splitters was used to measure the ILs of individual splitters, yielding values of 0.23 dB, 0.11 dB, and 0.42 dB at 1310 nm, 1550 nm, and 1970 nm, closely matching simulations. After accounting for contributions from the power splitters and waveguide propagation losses, the primary source of on-chip loss was identified as absorption by the metal electrodes, which becomes more pronounced at longer wavelengths (e.g., 1970 nm). Detailed loss analysis of the fabricated modulator can be found in Supplementary Note 6.”

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. S8a) and a spiral waveguide (Fig. S8b) with a 27-mm length difference. The reference waveguide was carefully designed to ensure geometric consistency between the 0.8- μm -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 μm (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- μ 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 μ m to minimize bending losses. A test structure consisting of six cascaded bent waveguides (Fig. S8c) 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 $W = 0.8$ μ m, the measured bending losses were 0.13, 0.14, and 0.28 dB/cm at wavelengths of 1310, 1550, and 1970 nm, respectively.

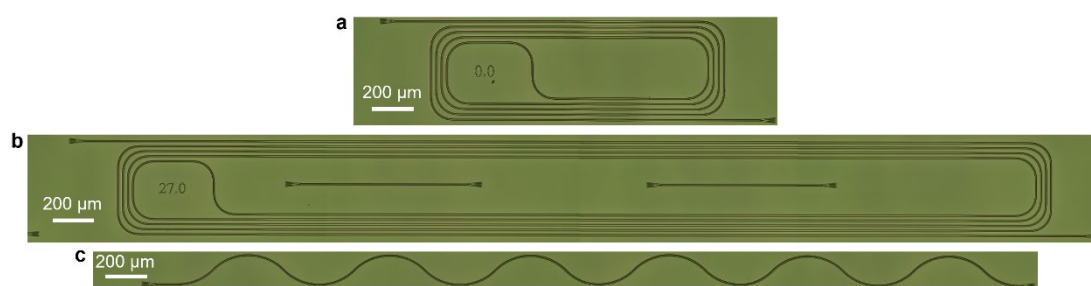


Fig. S8: Microscopy images of the passive waveguide for measuring propagation loss (stitching image). (a) reference waveguide. (b) tested spiraled waveguide. (c) six cascaded bend waveguides.

C. On-chip loss source analysis

To comprehensively characterize the on-chip losses across a broad operating wavelength range ($\lambda = 1310, 1550$, and 1970 nm), we performed a detailed loss analysis summarized in Supplementary Table S1. The passive waveguide propagation loss was calculated using a ~ 1.3 -cm-long straight waveguide encompassing the 9-mm-long modulation region (with a fixed width $W = 3.5$ μ m) and a 0.8 - μ m-wide bend waveguide (radius of 240 μ 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.

Minor issues:

7: Line 74: “TNLN” should be “TFLN”.

Reply 7: We are grateful to the reviewers for pointing out this. we have corrected the abbreviation from 'TNLN' to 'TFLN' and conducted a thorough review of the manuscript to ensure consistent and accurate usage of all abbreviations.

8: Lines 50-53: The authors first mention issues associated with previous platforms, including the TFLN platform. Then, in line 54, they claim that “TFLN has emerged as a uniquely promising platform to overcome these barriers.” I am confused by the logic here. How can the same platform be both the source of the problem and the solution? I suggest the authors reorganize this part for clarity.

Reply 8: We thank the reviewer for pointing out this good point. We have revised the manuscript on page xx in the second paragraph of the “Main” section as follow:

“While integrated PDs leveraging germanium or germanium tin (GeSn) on silicon photonic platforms have achieved 40–50 GHz bandwidths up to the 2- μ m band [12–14], high-speed modulators—the core of optical transmitters—remain constrained by narrow optical bandwidths. Existing integrated modulation platforms, such as silicon and germanium modulators relying on free-carrier effects [15–19], face inherent challenges at longer wavelengths due to waveguide dispersion and carrier velocity mismatch. These limitations confine existing modulators to single-band operations, hindering their adaptation to emerging multi-band communication systems. Thin-film lithium niobate (TFLN) has emerged as a uniquely promising platform for optical modulation, combining advantages such as ultra-broad optical transparency (visible to mid-infrared spectrum), large EO coefficients enabled by the Pockels effect, low optical loss, and compatibility with CMOS voltages enables modulators with unmatched bandwidth and efficiency [20–25]. Recent milestones include TFLN-based coherent transmission at 1.96 Tb/s [26] and compact packaged modules [27], underscoring its potential for next-generation networks. Although previous TFLN modulators have operated across discrete wavelengths from visible to 2- μ m bands [20, 28–31], achieving seamless broadband operation—critical for emerging multi-band systems—remains an unresolved challenge. This requires overcoming the intrinsic optical bandwidth limitations of conventional device designs.”

9: Line 138: “The electrode gap (G) is defined as the vertical separation between...” However, from Fig. 1(a), it appears that the authors are referring the horizontal separation, not the vertical. Please double-check.

Reply 9: Thank you to the reviewers for pointing out our incorrect reference to the parameter definitions. We have revised it in the manuscript on page 5:

“The electrode gap (G) is defined as the **horizontal** separation between the ground plane and the signal electrode.”

Reviewer #2 (Remarks to the Author):

The manuscript entitled “Ultra-broadband near- to mid-infrared electro-optic modulator on thin-film lithium niobate” by Qiyuan Li et al. reports a TFLN based MZ modulator with adiabatic power splitters and tapered fibre edge coupler for broadband operation, and single-lane transmission results exceeding 100 Gbaud for OOK and 65 Gbaud for PAM4 over O, C, and 2- μ m bands. The reviewer found the contents are technically sound, however doubts if it is worth for publication in Nature Communications in terms of the timeliness and impact.

We sincerely thank the reviewer for their constructive feedback and for recognizing the technical soundness of our work. We have carefully considered each technical comment and provide point-by-point responses below to strengthen the manuscript. The revisions specifically address the raised concerns about temporal relevance and broader impact, while further aligning the presentation with Nature Communications' standards for interdisciplinary significance. We remain open to any additional modifications that could enhance the work's contribution to the field.

1: Specifically, while it is true that multi-band optical transmission is recently attracting much attention, the full spectrum is normally targeted to O to U band in the research field, which is then still not yet well developed. A wider bandwidth is in general always welcomed, but the 2- μ m band is not really a focus of recent researches. In addition, Ref. [30] already reported a even higher 3-dB bandwidth EO modulator operating over O to U band, where the 2- μ m performance was not tested. However, the point to fit the 2- μ m operation is just relatively conventional broadband designs of 3-dB couplers and edge couplers, which is not really a big leap for high impact. Therefore, the manuscript will be worth for publication in some technical journals but not so in high impact journals like Nature Communications.

Reply 1: We greatly appreciate the reviewer’s thoughtful feedback and concerns regarding the impact of our work. Firstly, we would like to emphasize the novelty and technical motivation of our work by addressing the Reviewer's insightful

observation regarding spectral allocation in full-spectrum optical communications (O-U bands: 1260-1675 nm), which align with silica fibres' optimal transmission characteristics. Currently, The O-band (1260–1360 nm) remains critical for access networks due to its inherent dispersion properties enabling uncomplicated extended reach deployment. Meanwhile, the C- and L- bands (1530–1565 nm and 1565–1625 nm) dominate long-haul DWDM systems owing to their synergy with erbium-doped fibre amplifiers (EDFAs) and silica fibres' minimal attenuation (~ 0.2 dB/km at 1550 nm). The remaining three wavebands: E- and S-bands play a complementary role while U-band is used for monitoring and testing fibre optic lines. The field now confronts a dual technical imperative: conventional C+L bands approach nonlinear Shannon limit of conventional single-mode fibre [R1-R3], while AI-driven infrastructure demands O-band data rates exceeding 200 Gb/s for high-speed datacentre interconnects. This necessitates simultaneous advancements in spectral efficiency maximization and new transmission window development.

We appreciate the Reviewer's observation regarding the incompleteness of conventional full-spectrum development (O-U bands) and acknowledge the inherent value of bandwidth expansion using multi-band optical transmission. Our work, however, identifies a critical co-development opportunity: while advancing existing O-to-U band technologies by improving the full spectrum broadband optical modulator, we advocate for simultaneous exploration of emerging spectral windows such as the 2- μ m band. Furthermore, we argue that opening new optical communication windows (e.g., the 2- μ m band) represents a promising complementary strategy. Recent research has indeed explored a broad range of optoelectronic devices for the 2- μ m band, encompassing active components (lasers, modulators, detectors) and passive devices [2, 6, 13-15]. This momentum is driven by two key advancements: the availability of Thulium-Doped Fibre Amplifiers (TDFAs) and the emergence of low-loss hollow-core fibres (HCFs), which exhibit a theoretically predicted minimum loss of ~ 0.2 dB/km at 2 μ m [R5].

We respectfully disagree with the Reviewer's assertion that accommodating 2- μ m operation merely requires conventional broadband designs of 3-dB couplers and edge couplers. Our work envisions an ambitious goal: leveraging the vast bandwidth resources spanning from the O-band to the 2- μ m band to enable future ubiquitous optical communications with sustainable scalability. This ambition is supported by recent technological advancements, such as photodetectors inherently capable of operating across the O-band to 2- μ m range [12]. A compelling example is a recent Nature Photonics study demonstrating that broadband HCFs exhibit < 0.1 dB/km attenuation between 1,481 nm and 1,625 nm and can theoretically support low-loss transmission windows (≤ 0.2 dB/km) spanning from 700 nm to $\sim 2,400$ nm [R6]. These findings further underscore the technical viability of our proposed extended full spectrum optical communications.

Additionally, to address Reviewer 1's comment regarding with ultrawide operational bandwidth, we have rigorously recharacterized our TFLN modulator across the entire accessible wavelength range (1260–1680 nm and 1920–2060 nm, according to our available laser sources). The experimental results are detailed in Reply 2 to Reviewer 1. The TFLN modulator exhibits > 67 GHz 3-dB electro-optic (EO) bandwidths for all conventional optical communication bands (O–U bands). Notably, the modulator achieves a 3-dB EO bandwidth of ~ 100 GHz at 1310 nm (O-band), 1485 nm (S-band), 1550 nm (C-band), and 1590 nm (L-band). These performance metrics are comparable to state-of-the-art TFLN modulators optimized for single-waveband operation, as shown in Fig 5. Furthermore, we present the first demonstration of single-lane data transmission exceeding 240 Gbps with PAM-4 modulation format across all O–U bands using a single broadband modulator. In the 2- μ m spectral region, we achieved a record 170 Gbps—the highest data rate reported to date in this wavelength regime.

Beyond its superior performance metrics, the novelty of this work lies in its innovative design architecture, which addresses a critical challenge in integrated modulators: simultaneously achieving ultrabroad EO and optical bandwidths. To realize this, we implemented adiabatic mode evolution engineering in the passive optical components—such as optical splitters and spot-size converters—to achieve the record operational bandwidth. Simultaneously, traveling-wave electrodes were optimized by aligning the radio-frequency (RF) effective index with optical group indices, ensuring consistent EO bandwidth performance across the entire spectrum.

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- [14] J. Wang, X. Zhang, Y. Li, X. Wang, S. Xiao, Q. Song, Z. He, J. Du, H. K. Tsang, and K. Xu, “112 Gb s⁻¹ Germanium Photodetector at 2 μm Enabled by a 3D Integrated Waveguide Loop,” *Adv. Mater. Technol.* 2401718 (2025).
- [15] W. Cao, D. Hagan, D. J. Thomson, M. Nedeljkovic, C. G. Littlejohns, A. Knights, S. Alam, J. Wang, F. Gardes, W. Zhang, S. Liu, K. Li, M. S. Rouified, G. Xin, W. Wang, H. Wang, G. T. Reed, and G. Z. Mashanovich, “High-speed silicon modulators for the 2 μm wavelength band,” *Optica* 5(9), 1055–1062 (2018).
- [R5] F. Poletti, N. V. Wheeler, M. N. Petrovich, N. Baddela, E. Numkam Fokoua, J. R. Hayes, D. R. Gray, Z. Li, R. Slavik, and D. J. Richardson, “Towards high-capacity fibre-optic communications at the speed of light in vacuum,” *Nat. Photonics* 7, 279–284 (2013).
- [12] J. Cui, J. Zheng, Y. Zhu, X. Liu, Y. Wu, Q. Huang, Y. Yang, Z. Liu, Z. Liu, Y. Zuo, and B. Cheng, “High-speed GeSn resonance cavity enhanced photodetectors for a 50 Gbps Si-based 2 μm band communication system,” *Photon. Res.* 12(4), 767–773 (2024).
- [R6]. Petrovich, M., Numkam Fokoua, E., Chen, Y. et al. Broadband optical fibre with an attenuation lower than 0.1 decibel per kilometre. *Nat. Photon.* (2025), <https://doi.org/10.1038/s41566-025-01747-5>

Finally, in terms of the comparison with the work in Ref. [30], it is important to note that this work demonstrated two independent TFLN modulators based on the same Si-LN hybrid platform, each targeting the O-band and C-band. As highlighted in their Discussion section, both O-band and C-band modulator designs share identical TFLN layer thickness, silicon layer thickness, and require only a single bonding step. The principal design differences between the two modulators lie in the silicon rib waveguide width, multimode interferometer (MMI) coupler length, and electrode configurations. However, the inherent bandwidth limitations of the MMI-based coupler used in their design restrict operation to a single wavelength band. Consequently, we speculate that extending their modulator to the 2- μm wavelength range would necessitate specialized optimization.

Ref. [30] similarly aims to enhance communication capacity through multiband operation, but have to rely on integrating several modulators with wavelength multiplexers on a single chip. Our work demonstrates a distinct advantage: a single modulator capable of ultrawide operational wavelength coverage spanning the O- to 2- μm bands. In terms of the EO bandwidth, experimental recharacterization demonstrates that our modulator achieves a 3-dB EO bandwidth of ~100 GHz across all conventional communication bands (O-, S-, C-, and L-bands). Notably, this EO bandwidth matches the values reported for specialized O- and C-band modulators in Ref. [30], despite the broader wavelength compatibility inherent in our design. Furthermore, we systematically performed high-speed data transmission characterizations across

the O- to U-bands and the 2- μ m band, thereby experimentally validating the operational reliability and performance consistency of our ultrabroadband TFLN modulator across the entire extended spectral range.

Some minor comments are listed below for future drafting:

2: In Fig.1, the shape of the electrodes on the device in (a) does not match that of the fabricated device in (b).

Reply 2: We thank the reviewer for pointing out this good point. We have updated Fig 1a and Fig 4a with the correct shape of the electrodes in the revised manuscript.

3: In line 103, it says “The simulations reveal an optimal rib width of 4.4 μ m...” However, the reviewer did not understand why it is optimum from this explanation.

Reply 3: To address the reviewer’s doubt about the optimal SiON rib width, combined with our full-spectrum demonstration, we added several wavelengths to the optimization. As it can be seen from Fig. R7, narrower rib widths generally reduce coupling loss at shorter wavelengths (e.g., 1310–1480 nm), whereas broader widths improve coupling efficiency at longer wavelengths (e.g., 1680–2000 nm). However, an anomalous increase in coupling loss occurs at specific wavelengths (1310, 1410, and 1480 nm) when the rib width exceeds 4.8 μ m, attributed to resonant interference caused by higher-order mode excitation. Specifically, widened rib structures enhance susceptibility to higher-order modes at shorter wavelengths, inducing resonant peaks that disrupt coupling stability. Notably, at 1550 nm, the SSC exhibits consistent low coupling loss across all rib widths, serving as a reference wavelength for design optimization. Below 1550 nm, coupling loss increases with rib width, while an inverse trend is observed above 1550 nm. To balance ultrabroadband performance (prioritizing C-band efficiency) and maintain acceptable loss margins across the O- to U-bands, the SiON rib width was optimized to 4.4 μ m.

We have also revised the manuscript to add discussions on the design and experimental results of our SSCs on page 3-4.

“To achieve ultra-broadband operating bandwidth for practical optical packaging, the edge coupler was designed based on broadband SSC, which is illustrated in Fig. 2(a) and (b). The structure comprises LN bi-layer tapers and a silicon oxynitride (SiON) ridge waveguide.”

“Achieving low coupling loss (<1 dB) across the 1260-2060 nm spectral range requires precise matching between the mode field diameter (MFD) of the SiON waveguide and the coupled fibre. The MFD of the UHNA4 fibre increases with wavelength, for example, it is 3.3 μ m at 1310 nm, 4.0 μ m at 1550 nm, and 5.3 μ m at 2000 nm. For a SiON rib waveguide with a rib height of 3.2 μ m and slab height of 1 μ m, the wavelength-dependent coupling loss with varying the width of the SiON rib waveguide are presented in Fig. 2c. Narrower rib widths minimize coupling loss at shorter wavelengths (e.g., 1310 to 1480 nm), while broader widths improve performance at longer wavelengths (e.g., 1680 to 2000 nm). However, an anomalous variation in coupling loss occurs at 1310, 1410, and 1480 nm when the rib width exceeds 4.8 μ m, caused by resonant fluctuations from higher-order mode excitation. Specifically, increased rib width enhances susceptibility to higher-order modes at shorter wavelengths, inducing resonances that disrupt coupling efficiency. Notably, at 1550 nm, the SSC exhibits consistent low coupling loss across different rib widths. Below 1550 nm, coupling loss increases with rib width, while the opposite trend is observed above 1550 nm. To balance high coupling efficiency across O- to U-bands (with prioritized performance in the C-band) and maintain acceptable loss at longer wavelengths, the SiON rib width was optimized to 4.4 μ m. This design also demonstrates robust tolerance to dimensional variations in the SiON waveguide cross-section.

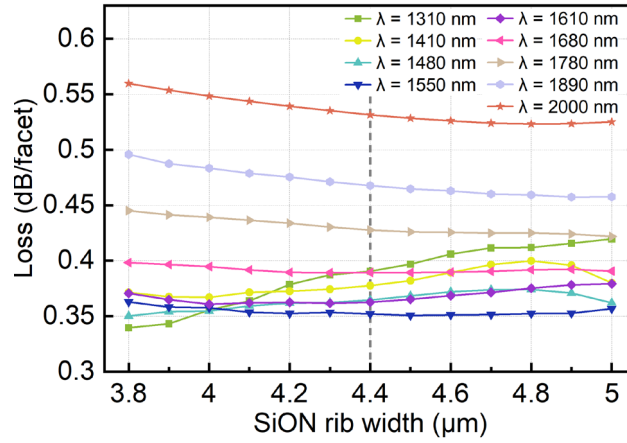


Fig. 2c/R8 | Design of the TFLN modulator. c Dependence of the coupling loss on SiON rib width.

4: In line 129 to 137, the waveguide width outside the modulation region is explained. However, the design mentioned here “the waveguide is engineered to support single mode operation at 1310 nm, but tapered to 3.5μm.” is confusing.

Reply 4: We sincerely appreciate the reviewer's insightful comment. The waveguide width $W = 0.8 \mu\text{m}$ is set for single mode operation in the range of 1260–2060 nm, but this narrow width will increase the propagation loss in the modulation region. Therefore, we set the waveguide width as $W = 3.5 \mu\text{m}$ in the modulation region for low-loss propagation. The change of the waveguide width from $W = 0.8 \mu\text{m}$ to $W = 3.5 \mu\text{m}$ is achieved through an adiabatic taper. The transition between these dimensions is achieved through an adiabatic taper design, which ensures smooth mode adaptation across the width variation. And the waveguide width was set as $W = 0.8 \mu\text{m}$ in the regions of SSC, power splitter, and bend waveguide.

We have added the explanation of LN waveguide widths in the Supplementary Note 2. We have also revised the description of waveguide widths in the main manuscript on page 5:

“Outside the modulation region, the waveguides are engineered to support single-mode operation at 1310 nm, ensuring broadband compatibility across the O-/C- and 2-μm bands. This design suppresses higher-order mode excitation over the 1260–2050 nm range, thereby preventing EO performance degradation in the modulation region. Finite-difference eigenmode (FDE) simulations indicate that single-mode operation requires a waveguide top width of $\sim 0.8 \mu\text{m}$ and therefore the waveguide width was set as $W = 0.8 \mu\text{m}$ in the regions of SSC, power splitter, and bend waveguide. However, this narrow width reduces optical mode confinement, increasing propagation losses due to stronger mode overlap with waveguide sidewalls and cladding, particularly at longer wavelengths. Additionally, the constrained geometry elevates the half-wave voltage requirement. To balance these trade-offs, we implement an adiabatic taper proximal to the 3-dB power splitter, expanding the waveguide width to $W = 3.5 \mu\text{m}$ within the modulation region. The details of the waveguide width optimization are discussed in Supplementary Note 2.”

5: In line 138, “vertical” should be “horizontal.”.

Reply 5: Thank you to the reviewers for pointing out our incorrect reference to the parameter definitions. We have revised it in the manuscript on page 5:

“The electrode gap (G) is defined as the horizontal separation between the ground plane and the signal electrode.”

Reviewer #3 (Remarks to the Author):

I co-reviewed this manuscript with one of the reviewers who provided the listed reports. This is part of the Nature Communications initiative to facilitate training in peer review and to provide appropriate recognition for Early Career Researchers who co-review manuscripts.

[We would like to thank the co-Reviewer for their careful and positive review of our paper.](#)

Reviewer #1 (Remarks to the Author):

The authors have significantly revised the manuscript. I am now convinced that this modulator indeed has an 800-nm operation bandwidth. However, the revised manuscript has raised new concerns, and I must recommend another round of revision.

We appreciate your positive assessment of our previous revisions, especially regarding the 800 nm operational bandwidth as you highlighted. Below we have addressed each of your following comments (in blue), with all corresponding changes in the manuscript and supplementary information marked in red.

Major concerns:

1: Figure 3(b): two curves (1310 nm & 1550 nm) are identical. The authors should double-check their raw data.

Reply 1: We sincerely appreciate your meticulous observation. The curves for 1310 nm and 1550 nm in the original Fig. 3(b) were inadvertently duplicated when adding the simulated curves into the measured EO response. We sincerely apologize for our mistake of the repetition of two curves and thank you for identifying this. We have corrected this by plotting the correct curve of the measured EO S_{21} response for 1550 nm in the revised Fig. 3(b)/R1 on page 7.

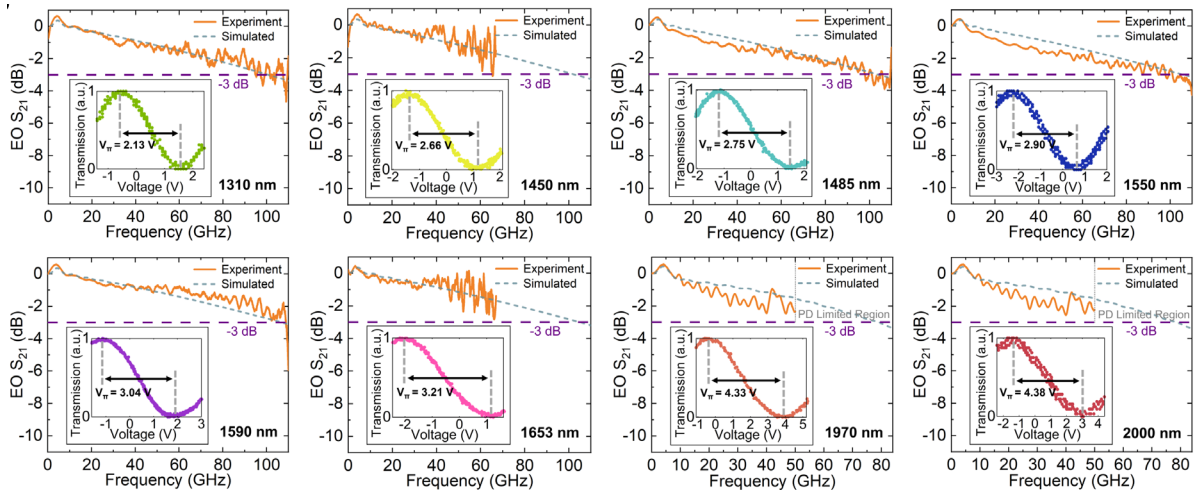


Fig. 3/R1 | Measured performance of the TFLN modulator. b Measured EO S_{21} responses of the TFLN modulator. The dash lines indicate the simulated bandwidths. The insets show normalized optical transmissions with measured half-wave voltage V_{π} .

We thank you for your suggestion, and have conducted a thorough re-examination of the raw data for all figures, with particular attention to the multi-wavelength measurements. To ensure transparency, the complete dataset has been deposited in the Figshare repository [<https://doi.org/10.6084/m9.figshare.30598463>].

2: Figure 3(b): Why is there a noticeable low-frequency peak in all EO simulated curves?

Reply 2: We thank you for this insightful question regarding the low-frequency peak in the simulated EO curves. This feature is an intentional aspect of our electrode design, which we implemented to marginally extend the 3-dB bandwidth. This effect was achieved by setting the load resistance ($Z_L = 38 \Omega$) slightly lower than the characteristic impedance of the transmission line ($Z_0 \approx 42 \Omega$), resulting in an initial rise in the EO response. As predicted by transmission line theory, this configuration elevates the low-frequency response, which slightly improves the 3-dB bandwidth at the cost of introducing minor ripples [R1/S3, R2/S4].

As shown in Fig. R2 below, the EO response curves at 1550 nm were simulated for different load resistances. It can be found that the load resistance Z_L slightly lower than the characteristic impedance Z_0 will produce the low-frequency peak and a desired bandwidth improvement, though causing some ripples in the response. 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.

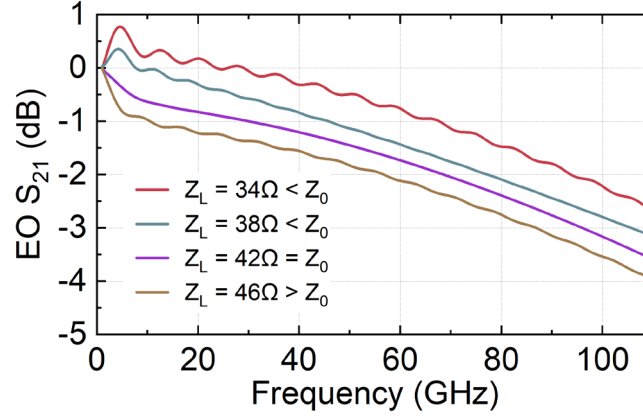


Fig. R2/S4: Simulated EO frequency response of the TFLN modulator at $\lambda=1550$ nm with the cases for $Z_L < Z_0$, $Z_L = Z_0$, and $Z_L > Z_0$.

Although the theoretical 3-dB bandwidth varies with wavelength due to effective index mismatch between the RF and optical waves, the same electrode design (with $Z_0 \approx 42 \Omega$ and $Z_L = 38 \Omega$) was used across all wavelengths. Consequently, this characteristic low-frequency peak appears across the entire wavelength range, from 1310 nm to 2000 nm, as seen in the simulated curves in Fig. 3(b). The good agreement between these simulations and our measured EO S_{21} responses also validates this design approach.

Firstly, we have revised the "Design of the traveling-wave electrode" section on page 5-6 and added further details in Supplementary Note 3 to clarify the impedance design principle.

“The traveling-wave electrodes feature a push-pull configuration based on a coplanar waveguide (CPW) structure. 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 $H = 1 \mu\text{m}$ and a 2- μm -thick SiO_2 cladding layer. The characteristic impedance (Z_0) of the CPW is approximately 42Ω , as illustrated in the inset of Fig. 2(g). A load resistor of $Z_L = 38 \Omega$ is used, which is intentionally lower than Z_0 to mitigate the low-frequency EO S_{21} roll-off, thereby slightly enhancing the operational bandwidth [37/R2]. Design details regarding the traveling-wave electrode impedance can be found in Supplementary Note 3.”

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 [S3]:

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

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:

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

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 [S4]. 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.

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 O- to 2- μ m 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.

[R1/S3] G. Ghione, “Semiconductor devices for high-speed optoelectronics,” Oxford University (2009).

[R2/37/S4] X. Liu, B. Xiong, C. Sun, et al., “Capacitively-loaded thin-film lithium niobate modulator with ultra-flat frequency response,” IEEE Photonics Technol. Lett. 34(16), 854–857 (2022).

Secondly, we apologize for a typo in the load resistance value within the “Measurement of the EO responses” section on page 7, which has now been corrected. The revised text states:

“The EO responses of the fabricated TFLN modulator were characterized using an 110-GHz lightwave component analyzer (LCA, Ceyear 6433P) in conjunction with a tunable laser (Santec TSL-570). A 110-GHz high-speed RF probe was employed to deliver RF signals from the LCA, while a 38- Ω load resistor was attached at the end of the traveling-wave electrode.”

Finally, we have added a discussion of the low-frequency peak in the simulated and measured S_{21} response curves of the TFLN modulator in Fig. 3(b) on page 7 of the revised manuscript:

“The measured EO S_{21} response at $\lambda = 2\ \mu\text{m}$ reveals a 3-dB bandwidth of $>50\ \text{GHz}$, the highest reported to date for optical modulators operating in the 2- μm band. As further indicated by simulations (Fig. 3(b), dashed lines), this bandwidth could be extended to $\sim 80\ \text{GHz}$. The low-frequency peaks observed in both the simulated and measured responses stem from the deliberate impedance configuration ($Z_L < Z_0$), which was implemented to increase bandwidth by compensating the drop-off at low frequencies [37].”

3: Supplementary information, page 11: In Fig. S10(b), the measured EO response shows fluctuations beyond $\sim 35\ \text{GHz}$, the claim of “smooth transitions up to 50 GHz” seems incorrect.

Reply 3: We thank you for raising this important point. This phrase was intended to describe the smooth fitting method applied to measured frequency response of the GeSn photodetector (PD) in Fig. S10(b) (now Fig. S11(b)). We have removed the phrase “smooth transitions up to 50 GHz” from the manuscript to prevent any potential misunderstanding. The fluctuations beyond $\sim 35\ \text{GHz}$ are attributed to the limited high-frequency stability of the commercial reference modulator in our collaborators' test setup, as confirmed through discussions with the authors of Ref [R3/S5]. Despite these fluctuations, the raw PD response magnitude remains well above the noise floor, bounded between -1 dB and -3.5 dB up to 50 GHz, which justified our use of the characterized PD response up to 50 GHz range. 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 (at a bias of -3 V). As can be seen from the last two figures of Fig. 3(b), the resulting de-embedded response curves for our TFLN modulator for the 2- μm band exhibit relatively stable roll-off, supporting the conclusion of a 3-dB EO bandwidth exceeding 50 GHz.

We have revised Supplementary Note 8 on page 12 of the Supplementary information to clarify the measurement methodology and provide an accurate description of the GeSn PD response.

“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.”

[R3/S5] Cui J et al, High-speed GeSn resonance cavity enhanced photodetectors for a 50 Gbps Si-based 2 μm band communication system, Photonics Research, 12(4), 767-773, (2024).

Reviewer #2 (Remarks to the Author):

The authors' effort for responding to the detailed comments is commended, but the rebuttal did not answer the main concern on the timeliness and impact. Therefore, the reviewer suggests the same conclusion that the manuscript will be worth for publication in some technical journals but not so in high impact journals like Nature Communications.

We are grateful for your positive comments regarding our response to the detailed technical concerns. We have carefully considered your new comments regarding the timeliness and impact of our work, and done our best to address them. We hope these clarifications affirm the suitability of our work for high impact journals like Nature Communications, and we thank you for your insightful suggestions.

Major concerns:

1: It says, "Our work, however, identifies a critical co-development opportunity: while advancing existing O-to-U band technologies by improving the full spectrum broadband optical modulator, we advocate for simultaneous exploration of emerging spectral windows such as the 2- μ m band." The reviewer agreed that 2- μ m band is an emerging spectral window and worth to investigate, but again a wider bandwidth is in general always welcomed, but the 2- μ m band is not really a focus of recent research. More specifically, for the low-loss hollow-core fibres (HCFs) the authors raised, the very latest impactful result presented in the post-deadline session of ECOC 2025, one of the most prestigious conferences in this field, showed an ultra-low loss of 0.052 dB/km centered at 1550nm in the range of 1450nm to 1650nm.

Reply 1: We thank you for your comment and acknowledging the 2- μ m band as an emerging and worthwhile spectral window. We agree that advancements in the conventional O-U bands are crucial and that a wider bandwidth is always beneficial. This recognition aligns with the core motivation for our work: to develop a full-spectrum broadband optical modulator that covers both the traditional O-U bands and the promising 2- μ m band. However, we would like to kindly point out the significance of the 2- μ m band. Since it has been established by the pioneering vision of Prof. Soref (Enabling 2 μ m communications. Nat. Photonics 9, 358–359, 2015), the 2- μ m band has evolved into a dedicated research field for telecoms applications, nonlinear and quantum photonics [R4-R13]. The following selection of high-impact works from the past decade demonstrates the sustained development of core photonic components for 2- μ m band:

- [R4]. J. J. Ackert, et al., "High-speed detection at two micrometres with monolithic silicon photodiodes," Nat. Photonics 9, 393–396 (2015).
- [R5]. S. Latkowski, et al., "Monolithically integrated widely tunable laser source operating at 2 μ m," Optica 3, 1412-1417 (2016).
- [R6]. Wei Cao, et al., "High-speed silicon modulators for the 2 μ m wavelength band," Optica 5, 1055-1062 (2018).
- [R7]. Yaojiang Chen, et al., "High-speed uni-traveling carrier photodiode for 2 μ m wavelength application," Optica 6, 884-889 (2019).
- [R8]. H. Jones, et al., "Low-noise high-temperature AlInAsSb/GaSb avalanche photodiodes for 2- μ m applications," Nat. Photonics 14(9), 559–563 (2020).
- [R9]. S. Prabhakar, et al., "Two-photon quantum interference and entanglement at 2.1 μ m," Sci. Adv. 6(13), eaay5195 (2020).
- [R10]. J. Guo, et al., "High-performance silicon-graphene hybrid plasmonic waveguide photodetectors beyond 1.55 μ m," Light: Sci. Appl. 9, 29 (2020).
- [R11]. D. Kong, et al., "Super-broadband on-chip continuous spectral translation unlocking coherent optical communications beyond conventional telecom bands," Nat. Commun. 13, 4139 (2022).
- [R12]. M. Huang, et al., "Raman amplification at 2.2 μ m in silicon core fibers with prospects for extended mid-infrared source generation," Light: Sci. Appl. 12, 209 (2023).

[R13]. Zhong, et al., “Graphene/silicon heterojunction for reconfigurable phase-relevant activation function in coherent optical neural networks,” *Nat. Commun.* 14, 6939 (2023).

More importantly, we fully agree with you that the recent breakthrough in Hollow-Core Fibers (HCFs) is a pivotal development. We would like to add that using HCFs for data transmission at 2- μm waveband is also an active research direction. The first demonstration of 2- μm band HCF transmission achieved a single lane rate of 8-Gbps in 2013 [R14]. The current record attenuation value for the 2- μm waveband is 0.85 dB/km at around 1985 and 2040 nm [R15] and the most recent work demonstrated single line rate of 112-Gbps data transmission using HCFs in 2024 [R16]. Ref. [R11] also demonstrated coherent transmission over 1 km of HC-PBGF at the 2- μm waveband, and was highlighted by News & Views published in *Nature Photonics* (Spectral translation unlocks 2- μm window. *Nat. Photon.* 16, 744–745, 2022).

[R14]. M. N. Petrovich, et al., “Demonstration of amplified data transmission at 2 μm in a low-loss wide bandwidth hollow core photonic bandgap fiber,” *Opt. Express* 21, 28559–28569 (2013).

[R15]. X. Zhang, et al., “Low loss nested hollow-core anti-resonant fiber at 2 μm spectral range,” *Opt. Lett.* 47(3), 589–592 (2022).

[R16]. X. Zhang, et al., “Hollow-core NANF for high-fidelity and low-latency transmission at 2-micron waveband,” *J. Lightwave Technol.* 42(23), 8093–8101 (2024).

As you noted, the very latest ECOC post-deadline work about ultra-low loss HCFs, its operational window (1450-1650 nm) indeed matches perfectly with the high-performance band of our modulator. Our work demonstrates a broadband optical modulator that supports both the emerging 2- μm band and the state-of-the-art in conventional O-U bands. We would like to point out that our TFLN modulator exhibits >67 GHz 3-dB electro-optic (EO) bandwidths for all conventional optical communication bands (O–U bands). Notably, the modulator achieves a 3-dB EO bandwidth of ~100 GHz at 1310 nm (O-band), 1485 nm (S-band), 1550 nm (C-band), and 1590 nm (L-band). These performance metrics are comparable to state-of-the-art TFLN modulators optimized for single-waveband operation.

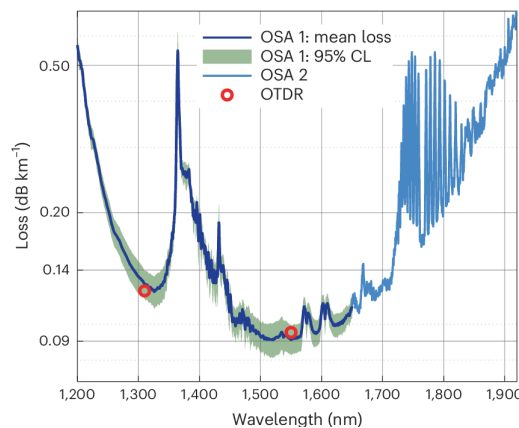


Fig. R3. Mean loss and 95% confidence level (CL) of four separate cutbacks (1,200–1,650 nm) compared with OTDR results and a fifth cutback to show the spectral loss in the 1,650–1,950 nm range [R17].

Furthermore, we note that a HCF recently published in *Nature Photonics* [R17] reports not only ultralow attenuation below 0.1 dB/km but also demonstrates an ultrabroad low-loss window from ~1200 to 1900 nm, with attenuation under 0.5 dB/km across this entire range (Fig. R3). This breakthrough opens the potential for building a complete high-speed ultrabroadband communication system, also requiring tunable lasers, our broadband modulator, and photodetectors. We are currently collaborating with colleagues in fabricating HCFs to realize the extended full spectrum optical communication system from the O to the 2- μm band.

[R17]. M. Petrovich, E. N. Fokoua, Y. Chen, et al., "Broadband optical fibre with an attenuation lower than 0.1 decibel per kilometre," *Nat. Photonics* 19, 1203 (2025).

We have revised the descriptions in the first two paragraphs of the "Main" section on page 2 to emphasize the importance of broad optical bandwidth for integrated devices. We have also updated the references to include state-of-the-art HCFs and integrated photodetectors with broad bandwidth [R4, R7, R8, R17].

"Recent advances in **hollow-core fibres (HCFs)** have unveiled ultra-broad low-loss transmission windows spanning 1240–1940 nm [4–6], **covering the O-U bands and the newly proposed 2- μ m band. At the meantime**, innovations in amplifier technologies—ranging from rare-earth-doped fibres to the newly demonstrated integrated optical parametric amplifiers—deliver broadband gain across these extended spectral regions [7–9]. Together, these developments enable a transformative ultra-wide communication spectrum that seamlessly integrates conventional telecom bands with the emerging 2- μ m waveband. Beyond revolutionizing optical networks, this expanded spectral range also holds promise for applications such as quantum photonics, precision metrology, and biomedical imaging [10–12]. However, the realization of end-to-end optical systems spanning these wavelengths remains hindered by a critical gap: the absence of high-speed broadband optical transmitters and photodetectors (PDs)."

"**Integrated photodetectors (PDs) for the 2- μ m band have achieved bandwidths exceeding 40 GHz, inherently supporting high-speed optical detection across the O-U bands [13–18]. In contrast, the optical bandwidth of their modulator counterparts remains constrained.** Existing integrated modulation platforms, such as silicon and germanium modulators relying on free-carrier effects [19–23], face inherent challenges at longer wavelengths due to waveguide dispersion and carrier velocity mismatch. These limitations confine existing modulators to single-band operations, hindering their adaptation to emerging multi-band or **ultrabroadband** communication systems."

"Although previous TFLN modulators have operated across discrete wavelengths from visible to 2- μ m bands [20, 28–31], achieving seamless ultrabroadband operation for **both the O-U telecom bands and the 2- μ m bands—while maintaining the high EO bandwidth—**remains an unresolved challenge, **which is due to the** intrinsic optical and **EO** bandwidth limitations of conventional **modulator** designs."

2: It also says, "We respectfully disagree with the Reviewer's assertion that accommodating 2- μ m operation merely requires conventional broadband designs of 3-dB couplers and edge couplers. Our work envisions an ambitious goal: leveraging the vast bandwidth resources spanning from the O-band to the 2- μ m band to enable future ubiquitous optical communications with sustainable scalability. This ambition is supported by recent technological advancements, such as photodetectors inherently capable of operating across the O-band to 2- μ m range [12]. A compelling example is a recent Nature Photonics study demonstrating that broadband HCFs exhibit <0.1 dB/km attenuation between 1,481 nm and 1,625 nm and can theoretically support low-loss transmission windows (≤ 0.2 dB/km) spanning from 700 nm to $\sim 2,400$ nm [R6]. These findings further underscore the technical viability of our proposed extended full spectrum optical communications." However, here the reviewer pointed out that the progress of the paper over the already published device was just conventional broadband designs of 3-dB couplers and edge couplers. This is not at all related the other technologies such as photodetectors inherently capable of operating across the O-band to 2- μ m range and broad band HCFs.

Reply 2: We sincerely thank you for your comment and acknowledging the importance of the broadband coupler designs, which are indeed fundamental passive building blocks for our integrated optical modulator. We agree that the design principles for individual broadband couplers are established. However, the key innovation of our work lies in the co-design and monolithic integration of these and other critical components to create a single modulator that simultaneously delivers record-breaking performance from the O-band through the 2- μ m window—a capability not previously

demonstrated. As you rightly note, the parallel progress in components like broadband photodetectors and HCFs, which are building the foundation for a full-spectrum communication system. We believe one of the missing pieces has been a high-performance modulator capable of leveraging the entire spectral range. While current solutions rely on different modulators for discrete wavebands, the telecom industry would require a unified solution that leverages the same components across the entire spectrum.

We appreciate your comment about the broadband designs of 3-dB couplers and edge couplers in our modulator. We would like to take this opportunity to clarify that our core innovation lies not in the individual components, but in their device and system-level integration. This encompasses the co-design of the waveguide and EO structure, a unified fabrication process, and comprehensive validation through performance testing and system-level data transmission. Firstly, we co-designed the edge coupler, power splitter, waveguide, and modulation electrodes for extended full-spectrum operation, integrating them into a single TFLN modulator that functions across the entire target waveband. Secondly, we overcame the fabrication challenges of integrating ultrabroadband passive devices with high-speed electrodes. We developed a unified process that successfully combines double-layer inverse taper-based spot-size converters (SSCs) and adiabatic optical splitters with high-performance traveling-wave electrodes. The fabricated device achieves a record 800 nm operational bandwidth for both the SSC and splitter, while simultaneously enabling the modulator to exhibit large 3-dB EO bandwidths up to 100 GHz across the designed wavebands. Finally, we conducted comprehensive characterizations across the entire accessible wavelengths for the full O-U bands (1260–1680 nm) and the 2- μ m band (1920–2060 nm). To the best of our knowledge, this work reports the first single modulator capable of single-lane data transmission exceeding 240 Gbps across the entire O-U bands. Furthermore, in the 2- μ m waveband, we achieved a record 170 Gbps, which is the highest data rate reported to date for this band.

We have revised the descriptions in the last paragraphs of the "Main" section (page 2) to emphasize the novelty of our work.

“Here, we co-design the passive components and modulation electrodes and demonstrate a high-speed TFLN EO modulator with a record-breaking continuous operational range of 1260–2060 nm, seamlessly bridging the O-U bands and the 2- μ m band. This broadband capability is enabled by leveraging adiabatic mode evolution engineering in critical passive optical components—such as optimized optical splitters and spot-size converters (SSCs). By integrating the broadband optical splitters and SSCs with high-performance traveling-wave electrodes, our modulator achieves a 3-dB EO bandwidth exceeding 67 GHz across the O-U bands and 50 GHz in the 2- μ m band—the highest reported for this spectral region. Furthermore, the modulator achieves a 3-dB EO bandwidth of $\sim$ 100 GHz in the O-, S-, C-, and L-bands (1310 nm, 1485 nm, 1550 nm, 1590 nm). The modulator exhibits exceptional efficiency, with $V_{\pi} \cdot L$ values of 1.92, 2.48, 2.61, 2.74, and 3.94 V·cm at 1310, 1485, 1550, 1590, and 2000 nm, respectively. For the first time with a single modulator, we demonstrate transmission in the O-, E-, S-, C-, L-, U-, and 2- μ m bands; data rates reached 170/170/170/180/180/170/150 Gbps (On-Off Keying, OOK) and 260/260/260/280/280/240/170 Gbps (4-level Pulse Amplitude Modulation, PAM-4), respectively, with bit error rate (BER) all below the hard-decision forward error correction (HD-FEC) threshold (3.8×10^{-3}). This breakthrough paves the way for universal optical transmitters capable of unifying fragmented spectral resources into a single ultra-broadband communication infrastructure, with transformative potential for next-generation optical networks, quantum systems, and sensing technologies.”

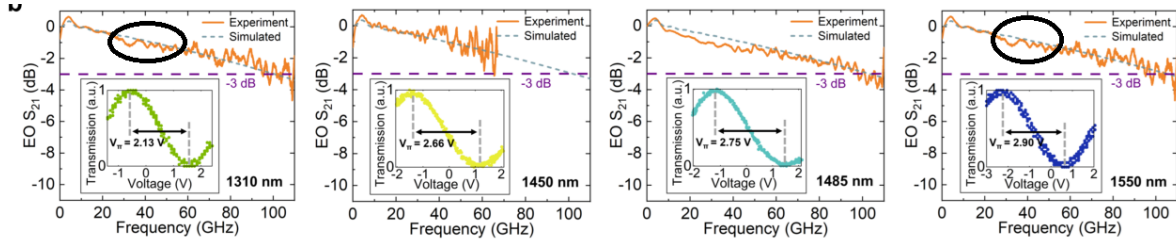
Reviewer #3 (Remarks to the Author):

I co-reviewed this manuscript with one of the reviewers who provided the listed reports. This is part of the Nature Communications initiative to facilitate training in peer review and to provide appropriate recognition for Early Career Researchers who co-review manuscripts.

We would like to thank you for your careful and positive feedback regarding our response to the detailed technical concerns.

The authors have significantly revised the manuscript. I am now convinced that this modulator indeed has an 800-nm operation bandwidth. However, the revised manuscript has raised new concerns, and I must recommend another round of revision.

1. Figure 3(b): two curves (1310 nm & 1550 nm) are identical. The authors should double-check their raw data.



2. Figure 3(b): Why is there a noticeable low-frequency peak in all EO simulated curves?
3. Supplementary information, page 11: In Fig. S10(b), the measured EO response shows fluctuations beyond ~ 35 GHz, the claim of “smooth transitions up to 50 GHz” seems incorrect.