

## Ultracompact and large-bandwidth silicon modulator in a CMOS-compatible foundry

Corresponding Author: Professor Yikai Su

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

Version 0:

Reviewer comments:

Reviewer #1

(Remarks to the Author)

The authors describe a slow light silicon photonics modulator.

The authors describe an interesting device concept but unfortunately there is unclarity in main aspects of the paper. Also, the demonstrated device properties are not standing out sufficiently to merit publication in Nature Communications.

Additional comments are listed below:

In the introduction the authors write that the enhancement of the light-matter interaction is quantified as 80 pm/V. However, this is not the correct means to represent the enhancement originating from a resonant effect. The resonance or slow light phenomenon does not alter the tuning efficiency in pm/V but the transmission change created by phase detuning. Furthermore, it is stated that photon-lifetime limitations are overcome by using the optical peaking enhancement. This is not correct. The optical peaking is directly related to the resonance enhancement and the photon-lifetime. These effects are correlated and cannot be optimized separately.

The modulator has low power consumption but even in a direct back-to-back measurement it shows a BER on the order of  $10^{-3}$ . For most applications, a much better BER is required, hence, error mitigation and recovery strategies will be required. Such techniques impose large power consumption onto the optical link. Is the obtained BER viable for this application? The low power consumption of the modulator is not a real advantage in case it leads to large power consumption in other parts of the system.

In the results section it is mentioned that a reduced Q factor has a negative impact on the extinction ratio. This must not be the case. A lower Q factor increases the required phase detuning to obtain a defined on/off ratio.

The sentence "Peaking arising from the intrinsic dynamics in the optical domain can be utilized to extend the modulation bandwidth" is not clear. Please explain.

Figure 1a and the background of the curves is not clear, please explain. What was simulated and why are the curves as shown?

Figure 1b shows the layout and concept of the device. What is the transmission and reflection of this device? High transmission is key. The reflected light in the off-resonance state will couple back to the laser and deteriorate the system performance. How can this be solved?

Figure 2c and the mentioned enhanced tuning efficiency are not clear. See also the comment above.

Bert Offrein

Reviewer #2

(Remarks to the Author)

Summary and Significance:

This manuscript presents the design, fabrication, and characterization of a silicon electro-optic modulator based on a photonic crystal nanobeam cavity (PCNC). The authors aim to overcome the trade-off between operational bandwidth and device footprint, a critical challenge for optical interconnects in data centers and high-performance computing. They report noteworthy results including an electro-optic (EO) bandwidth exceeding 110 GHz within an ultracompact  $10\text{ }\mu\text{m}^2$  footprint, enhanced tuning efficiency (80 pm/V) attributed to slow-light effects, and successful 110/130 Gbps NRZ data transmission

below standard FEC thresholds. The device was fabricated in a commercial CMOS-compatible foundry.

If fully validated and practically usable, the simultaneous achievement of >110 GHz bandwidth and a ~10  $\mu\text{m}^2$  footprint using a standard foundry process would represent a significant advancement in silicon photonics. The work addresses a persistent challenge in modulator design. The novelty appears to lie not in discovering new physical principles (PCNCs, slow light, and optical peaking are known concepts) but in the specific engineering and optimization combining these effects to push performance boundaries beyond the current state-of-the-art for silicon modulators in terms of combined speed and compactness. This potentially surpasses conventional MZMs in size and MRMs in speed/footprint, while maintaining CMOS compatibility, distinguishing it from potentially more complex hybrid approaches.

#### Strengths:

Addresses a highly relevant and challenging problem in optical communications: the bandwidth-footprint trade-off.

Demonstrates effective use of slow-light enhancement in a PCNC structure to achieve high tuning efficiency (80 pm/V).

Experimentally measures an EO S21 response extending beyond 110 GHz under specific wavelength detuning conditions, leveraging optical peaking.

Successfully demonstrates high-speed NRZ data transmission (110 Gbps below HD-FEC, 130 Gbps below SD-FEC).

Utilizes a commercial CMOS-compatible foundry process, enhancing the potential for practical application, scalability, and integration.

The described simulation, fabrication, and testing methodologies generally align with expected standards within the field.

#### Major Weaknesses and Concerns:

1. Critically Low Dynamic Extinction Ratio (ER): The most significant weakness is the reported dynamic ER, which is extremely low (< 1 dB at 110 Gbps). This severely hinders the practical usability in optical communication systems that typically require higher ERs (>3 dB) for adequate noise margins. The explanation provided – attributing the low ER primarily to signal attenuation in the external RF path (bias tee, cable, probe) – is insufficiently substantiated. Crucially: The citation used to primarily support this (Ref 26, Chan et al.) does not appear to describe this specific phenomenon based on available information.

The other citation (Ref 23, Han et al.) actually reported a much higher dynamic ER of 2.15 dB at 112 Gbps using a related slow-light silicon technology, despite also using high-frequency components. Han et al. focused their loss analysis on intrinsic device electrical losses (length-dependent electrode/contact effects) rather than predominantly external factors. Citing Ref 23 therefore does not support the authors' explanation and, in fact, suggests better ER should be achievable. The manuscript lacks quantitative evidence (e.g., measured RF path S-parameters, de-embedding analysis) to support the claim that external losses are the dominant cause for such a drastic ER degradation (from a theoretical ~2 dB). Intrinsic device limitations cannot be ruled out.

2. Inconsistent Energy Consumption Claim: There is a fundamental contradiction between the calculated energy consumption (5.9 fJ/bit, based on the ~2 Vpp applied voltage) and the explanation for the low dynamic ER (which implies the effective voltage swing at the device, Veff, must be significantly lower than 2 Vpp due to the claimed attenuation). The energy calculation should be based on the actual voltage swing driving the modulation (Veff). The current presentation is logically flawed and requires reconciliation.

3. Problematic Bandwidth Density Claim: The claimed record "bandwidth density" (>1100 Tbps/mm<sup>2</sup>) appears unconventional compared to standard metrics (e.g., shoreline density, aggregate chip density) and may inflate the perceived performance advantage.

This claim requires substantial clarification, correction, justification, or removal.

4. Limited Discussion of Operational Window: While achieving >110 GHz bandwidth is demonstrated, the data clearly shows this peak performance is highly dependent on specific wavelength detuning (~3 dB from resonance). The practical implications of this potentially narrow optimal operating window (e.g., required laser stability, trade-offs between bandwidth and ER across wavelength) need more explicit discussion.

#### Conclusion and Recommendation:

The manuscript presents potentially exciting results that could significantly advance the field of compact, high-speed silicon modulators. However, the work is currently undermined by several major concerns, primarily the critically low dynamic ER and its unconvincing explanation, the contradictory energy calculation, the flawed bandwidth density claim, and insufficient detail for reproducibility.

Therefore, I recommend Major Revision.

To become suitable for publication, the authors must thoroughly address the following points:

1. Dynamic ER: Provide a rigorous, quantitative, and evidence-based explanation for the observed dynamic ER < 1 dB. This requires substantiating the contribution of external RF path loss (e.g., via measured S-parameters and de-embedding) versus potential intrinsic device limitations. The relevance of cited references (esp. Ref 26 and Ref 23) must be correctly established, acknowledging that Ref 23 achieved significantly better ER. Discuss the practical implications of the low ER for system performance.

2. Energy Consumption: Reconcile the energy consumption calculation with the explanation for the dynamic ER. Provide a revised energy figure based on a justified effective voltage swing (Veff) at the device, or offer an alternative, consistent explanation for the low ER that aligns with the applied Vpp.

3. Bandwidth Density: Thoroughly revise or remove the "bandwidth density" claim. If retained, provide a clear definition of the metric, justify its use and relevance compared to standard metrics.

4. Operational Window: Include a discussion on the practical consequences of the observed strong dependence of peak bandwidth on wavelength detuning, addressing the usable optical bandwidth and associated performance trade-offs.

Addressing these fundamental issues is crucial for establishing the credibility and significance of the reported results.

Reviewer #3

(Remarks to the Author)

In the presented paper, the authors have experimentally demonstrated a Silicon EO modulator with 110 GHz EO bandwidth and 10  $\mu\text{m}^2$  footprint based on photonic crystal nanobeam cavity. The combination of these experimental values is stated as the record point among Si-based modulators (as shown in Fig. 4g), which are noteworthy results. However, several considerations might be needed to the design optimization by 'slow-light design in optical resonator', as described in No. 1 of the list attached. Considering the high impact of Nature Communications, clarification of several points including the above one would be required. Please find the questions and comments for the authors listed below.

1. The authors have explained the enhancement of the tuning efficiency is possible due to the 'slow-light design in optical resonator.' Although the slow-light effect is crucial for waveguide-type modulators, applying it to nanobeam cavity-type modulators might not be so meaningful.

In the nanobeam cavity design, increasing the group index is done by reducing the difference between the mirror region and cavity region by, for example in Fig. 1b, making squeezing of the central region shallower. This effectively makes the group index increase, at the same time the reflection by the mirror gets weaker, making the mode field distribution spread among the entire nanobeam (in the longitudinal axis). Therefore, it is also possible to understand that the enhancement of tuning efficiency is achieved by spreading the mode in the longitudinal direction, instead of the slow-light effect. Discussions about these points are not clearly shown in the current manuscript and it would be important.

Clarifying these points would also be important to discuss the trade-offs between this strategy and the footprint.

Moreover, the authors have not clearly pointed out the strategy of designing the slow-light photonic crystals, in which at least several design parameters might be compared to show the best design. The authors have shown that the group index for the center part of the cavity is 4.2 where the light is concentrated. However, this value might not be so large as compared to other slow-light devices.

2. I would like the authors to describe the detailed design of the nanobeam cavity. For example, the Q factor of the cavity can be decomposed into the coupling ratio to the waveguides, absorption by the doped regions, and scattering loss. With these values, the excess loss of the device (2.8 dB) can be understood.

3. In page 4, line 94, the authors have cited [45] as the comparison of their work to the state-of-the-art FOM. However, this would not be a fair comparison because Ref. [45] reported on an IQ modulator.

4. Supplementary Information Note IV seems to be missing in the supplementary file.

Version 1:

Reviewer comments:

Reviewer #1

(Remarks to the Author)

Thank you for implementing the changes you made in the manuscript.  
I agree with the current state of the paper and publication thereof.

Reviewer #2

(Remarks to the Author)

I have carefully examined the revised manuscript together with the new Supplementary Notes and your point-by-point response. Your revision represents a clear effort to engage with the previous critique: the unconventional "bandwidth-density" claim has been removed, and a thoughtful discussion supported by additional data now clarifies the practical wavelength-detuning window. These improvements fully resolve those two issues. Unfortunately, the two most critical technical concerns—the extremely low dynamic extinction ratio (ER) and the logically inconsistent energy-per-bit figure—remain insufficiently addressed. Because they strike at the heart of the paper's performance claims, the manuscript cannot yet be considered for publication.

First, on the dynamic ER, your new Supplementary Note V supplies manufacturer S-parameter curves for the electrical amplifier, bias-tee, and related components, and it asserts that external high-frequency loss dominates the observed < 1 dB

eye penalty. However, no quantitative de-embedding of the complete RF chain has been performed. In the absence of measured S-parameters for the specific cables, probes, pads and device under test, the reader still cannot determine how much of the voltage drop occurs externally and how much is intrinsic to the nanobeam modulator itself. The additional qualitative remark that the optical peaking mechanism “inherently increases insertion loss” may be physically plausible, but without modeling or experiment it remains speculative. Moreover, the citation of Han et al. continues to be invoked only to show that ER generally degrades with increasing data rate; it does not justify an ER that is an order of magnitude lower than that achieved in that work under comparable drive conditions. A rigorous, experiment-based separation of external and intrinsic contributions is therefore indispensable.

Second, the energy-per-bit calculation still employs the full 2 V<sub>pp</sub> applied at the probe tips, even though your own explanation for the low ER presumes a much smaller effective swing at the device terminals. By continuing to quote 5.9 fJ/bit without an experimentally validated V<sub>eff</sub>, the manuscript presents mutually inconsistent statements: a large, unquantified RF attenuation is invoked to explain the ER, yet the energy figure silently ignores that same attenuation. Simply noting that a careful study of V<sub>eff</sub> is “future work” does not resolve the contradiction; it leaves the central efficiency metric misleading and unverifiable.

Because the manuscript's headline claims—simultaneous > 110 GHz bandwidth, sub-10 μm<sup>2</sup> footprint, and sub-10 fJ/bit efficiency—depend critically on a believable account of both ER and electrical drive voltage, these two issues must be settled with quantitative evidence. In practice this means providing a complete de-embedding analysis of the RF path, reporting the verified voltage swing at the device pads, recalculating (or at least bounding) the energy-per-bit with that swing, and discussing whether any intrinsic device physics further limits the ER. Absent those corrections, the reader cannot judge whether the impressive bandwidth figure has been achieved at a power cost and signal quality that are competitive with existing silicon modulator platforms.

### Reviewer #3

#### (Remarks to the Author)

Although the authors have answered the reviewer's questions, there still are several points that need to be clarified. The main concern in the current manuscript is that the physical effect of the slow light is not described in sufficient detail. Firstly, could the authors describe the physical meaning of Eq. (4) especially in connection with the tuning efficiency in unit [pm/V]? Also, it is required to explain the reason why the sum was taken from -5 to 5, and whether the mirror region is included or not. Since the edge of the taper region should have very large n<sub>g</sub>, which may go infinite, Eq. (4) may diverge in that case. Moreover, n<sub>g</sub> cannot be obtained in the mirror region. Because Eq. (2) from Ref. 23 is derived for the waveguide-type modulator, mathematical derivation of the accumulated phase for Fabry-Perot (FP) cavity would be required.

In addition, it is required to describe the physical meaning of using the slow-light effect. In single-pass devices such as waveguide modulators, the slow-light effect may be the only way to enhance the light-matter interaction with fixed length. However, in multi-pass devices such as FP cavities, the light reflects between mirrors, and the light-matter interaction is enhanced even without the slow-light effect. Therefore, to enhance the light-matter interaction in FP cavities, there would be at least two ways: One is to increase the reflectance of the mirrors, and another is to use the slow-light effect. These explanations would be required in the manuscript to clearly state the physical meaning of the slow-light effect in the proposed device.

Secondly, could the authors describe the meaning of the red arrow in Fig. 2(c) shown as “80 pm/V @ -3V”? Because the unit of the x-axis [μm], the unit [pm/V] is unmatched.

Thirdly, in supplementary Section III, the authors have shown the optimization process. However, it is unclear what objective function was employed. If we see Fig. S5(g) and (h), the star symbol is plotted, but it is unclear why the plotted point is optimal. Specifically, there seems to be higher reflectivity in the region to the right of the star symbol in Fig. S5(g).

Finally, in the revised line 84-89 in the manuscript, it is unclear which structures were employed for the comparison. In particular, it was unclear whether the comparison was made with experimental results or simulations with what kind of settings.

### Version 2:

#### Reviewer comments:

### Reviewer #2

#### (Remarks to the Author)

The authors have demonstrated a commendable commitment to addressing the reviewers' feedback. The two most critical technical issues have been resolved satisfactorily through detailed analysis and simulation. The manuscript presents a significant advance in silicon photonics, achieving an impressive combination of bandwidth (>110 GHz) and footprint (10 μm<sup>2</sup>).

I am satisfied with the revisions and am pleased to recommend this manuscript for publication in Nature Communications.

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## Response Letter

*Date: July 23<sup>rd</sup>, 2025*

*Subject: response letter for NCOMMS-25-25057*

Dear Reviewers,

We would like to thank you for your efforts in reviewing our manuscript entitled “Ultracompact and large-bandwidth silicon modulator in a CMOS-compatible foundry”. We greatly appreciate your insightful suggestions, which have helped us to improve the quality and clarity of our work.

We have carefully revised the manuscript according to your valuable comments and addressed each point in detail in this response letter, with the original comments in *italic* and our revisions highlighted in **red**. We hope that these revisions clarify all concerns and further strengthen the scientific rigor and impact of our manuscript. The changes are also highlighted in the revised manuscript.

### Comments from Reviewer #1:

#### Comment 1:

*In the introduction the authors write that the enhancement of the light-matter interaction is quantified as 80 pm/V. However, this is not the correct means to represent the enhancement originating from a resonant effect. The resonance or slow light phenomenon does not alter the tuning efficiency in pm/V but the transmission change created by phase detuning.*

#### Response 1:

We agree with the reviewer that the resonance or slow-light phenomenon alter the transmission change created by phase detuning. We have carefully revised our description of the light-matter interaction enhancement in the slow-light resonant cavity and clarified the relationship between the phase detuning and the tuning efficiency. The tuning efficiency is commonly used to characterize modulation capability of the resonant-type modulators as reported in previous works<sup>1-3</sup>. Specifically, we have revised the Introduction (Line 84–89) to better explain the underlying physics as follows:

**With the slow-light enhancement in the resonant cavity, the inherently weak light-matter**

interactions are significantly amplified, leading to a 3.36-fold increase in phase detuning over conventional silicon waveguide cavities. Importantly, the slow-light effect amplifies the phase shift per unit voltage, rather than directly altering the material's electro-optic properties. This enhancement, combined with an appropriate doping concentration provide by the commercial foundry, enables a tuning efficiency of 80 pm/V for our optimized PCNC.

- [1] Timurdogan, E. et al. An ultralow power athermal silicon modulator. *Nat. Commun.* **5**, 1–11 (2014).
- [2] Zhang, W. et al. Harnessing plasma absorption in silicon MOS ring modulators. *Nat. Photonics* **17**, 273–280 (2023).
- [3] Zhang, Y. et al. 240 Gb/s optical transmission based on an ultrafast silicon microring modulator. *Photon. Res.* **10**, 1127-1133 (2022).

#### **Comment 2:**

*Furthermore, it is stated that photon-lifetime limitations are overcome by using the optical peaking enhancement. This is not correct. The optical peaking is directly related to the resonance enhancement and the photon-lifetime. These effects are correlated and cannot be optimized separately.*

#### **Response 2:**

We sincerely appreciate the reviewer's insightful comment. The original statement regarding "By utilizing the optical peaking enhancement<sup>44</sup> in the modulator, we overcome the photon-lifetime-limited bandwidth constraint, broadening the EO bandwidth from 59 GHz to 110 GHz with only a 1.84 dB roll-off within an ultracompact footprint of 10  $\mu\text{m}^2$ " was indeed ambiguous and has been revised accordingly.

As correctly pointed out, the optical peaking is inherently linked to the photon-lifetime and the resonance enhancement. In the revised manuscript (Introduction, Lines 89–93), we have rephrased the relevant sentences, which is now supported by references<sup>4-7</sup>. We thank the reviewer for pointing out this critical point to ensure theoretical rigor.

Through precise control of the resonator's dynamic response via carrier-wavelength tuning, we exploit the optical peaking enhancement<sup>44</sup> to optimize the trade-off between photon-lifetime and resonance conditions<sup>44-47</sup>. This approach effectively extends the EO bandwidth from 59 GHz to 110 GHz with only a 1.84 dB roll-off within an ultracompact footprint of 10  $\mu\text{m}^2$ .

- [4] Notomi, M. & Mitsugi, S. Wavelength conversion via dynamic refractive index tuning of a cavity. *Physical Review A* **73**, 051803 (2006).
- [5] Soref, R. A. & Bennett, B. R. Electrooptical effects in silicon. *J. Quantum Electron.* **23**, 123–129 (1987).
- [6] Lin, Q., Painter, O. J. & Agrawal, G. P. Nonlinear optical phenomena in silicon waveguides: Modeling and applications. *Opt. Express* **15**, 16604–16644 (2007).
- [7] Müller, J. et al. Optical Peaking Enhancement in High-Speed Ring Modulators. *Sci. Rep.* **4**, 6310 (2014).

### Comment 3:

*The modulator has low power consumption but even in a direct back-to-back measurement it shows a BER on the order of  $1e-3$ . For most applications, a much better BER is required, hence, error mitigation and recovery strategies will be required. Such techniques impose large power consumption onto the optical link. Is the obtained BER viable for this application? The low power consumption of the modulator is not a real advantage in case it leads to large power consumption in other parts of the system.*

### Response 3:

We thank the reviewer for the comments and questions, below are our clarifications regarding the BER and power consumption concerns:

- (a) In our high-speed data generation measurement, the BERs can drop to well below the hard-decision forward error coding (HD-FEC) threshold ( $3.8 \times 10^{-3}$ ) at a data rate of 110 Gbps and below the soft-decision forward error coding (SD-FEC) threshold ( $2 \times 10^{-2}$ ) at a data rate of up to 130 Gbps, respectively. The BER thresholds we adopted are widely used for this transmission rate, as reported in previous works<sup>8-11</sup>.
- (b) The power consumption of the proposed modulator was estimated using a universal methodology<sup>8,12-14</sup>. While this power consumption constitutes a relatively small portion compared to that required for driving and signal recovery, the power needed for external drivers and signal DSP circuits is similarly required for other modulators with error corrections in detection. In response to the reviewers' concerns, we have revised the relevant statements in the "Discussion" section (Line 277–279) as follows:

The proposed modulator achieves an EO bandwidth of 110 GHz with a 1.84 dB roll-off and an optical power penalty of 3 dB, which are enabled by the peaking enhancement. High-speed data modulation is successfully achieved for 110 Gbps and 130 Gbps NRZ signal transmissions, with BERs below  $3.8 \times 10^{-3}$  and  $2 \times 10^{-2}$ , respectively, while maintaining a power consumption of 5.9 fJ/bit, calculated as  $CV_{pp}^2/4$ . Nevertheless, the modulator's intrinsic power consumption represents merely a fraction of the total system power, with the signal driving and recovery processes demanding substantially higher power budgets<sup>53</sup>.

- [8] Dubé-Demers, R., LaRochelle, S. & Shi, W. Ultrafast pulse-amplitude modulation with a femtojoule silicon photonic modulator. *Optica* **3**, 622-627 (2016).
- [9] He, M. et al. High-performance hybrid silicon and lithium niobate Mach–Zehnder modulators for 100 Gbit s<sup>-1</sup> and beyond. *Nat. Photonics* **13**, 359–364 (2019).
- [10] Xue, Y. et al. Breaking the bandwidth limit of a high-quality-factor ring modulator based on thin-film lithium niobate. *Optica* **9**, 1131-1137 (2022).
- [11] Xie, X. et al. A 3.584 Tbps coherent receiver chip on InP-LiNbO<sub>3</sub> wafer-level integration platform. *Light Sci. Appl.* **14**, 172 (2025).
- [12] Miller, D. A. B. Energy consumption in optical modulators for interconnects. *Opt. Express* **20**, A293-A308 (2012).
- [13] Li, M. X. et al. Lithium niobate photonic-crystal electro-optic modulator. *Nat. Commun.* **11**, 4123 (2020).

[14] Yuan, Y. et al. A  $5 \times 200$  Gbps microring modulator silicon chip empowered by two-segment Z-shape junctions. *Nat. Commun.* **15**, 918 (2024).

**Comment 4:**

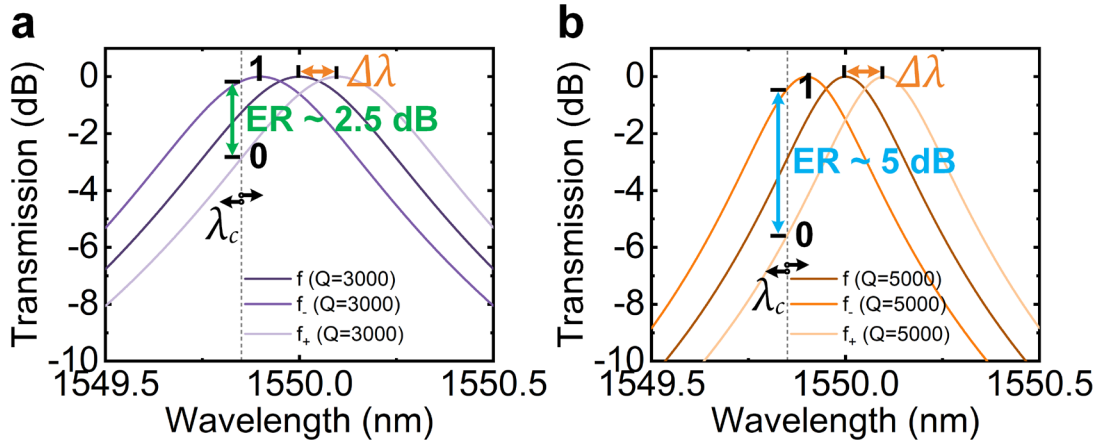
*In the results section it is mentioned that a reduced  $Q$  factor has a negative impact on the extinction ratio. This must not be the case. A lower  $Q$  factor increases the required phase detuning to obtain a defined on/off ratio.*

**Response 4:**

In fact, our intended meaning aligns with the reviewer's perspective. We have employed two scenarios with two various  $Q$  factors to illustrate this point, as shown in Fig. R1. Specifically, it is illustrated that:

- (a) At higher  $Q$  factor: The same spectral shift yields greater dynamic ER.
- (b) At lower  $Q$  factor: Achieving equivalent dynamic ER requires either larger spectral shifts, or higher phase detuning.

Certainly, the insights provided by the reviewer are highly valuable. To convey the intended



**Fig. R1 Signal generation with various  $Q$  factors.** With the same spectral shift, dynamic ER can be achieved to be **a**  $\sim 2.5$  dB and **b**  $\sim 5$  dB.

meaning more accurately, we have refined the relevant paragraphs (Line 112–120) as follows, hoping to address the concerns raised by the reviewer.

While a low  $Q$  factor inherently broadens the  $BW_O$ , it simultaneously necessitates greater phase detuning to achieve a defined dynamic extinction ratio (ER). However, in high-speed EO modulation on the silicon platform, it is typically implemented using a reverse-biased PN junction, whose tuning efficiency is generally constrained by the specifications of a standard CMOS-compatible foundry process. Consequently, a low  $Q$  factor in the resonator leads to a reduction in the dynamic ER. This reduction can significantly lower the signal quality and increase the BER, which is a critical consideration for practical applications. To mitigate the adverse effects of a low  $Q$  factor on the dynamic ER, an effective strategy is to improve the

tuning efficiency of the modulator, thereby optimizing its performance under these constraints.

**Comment 5:**

*The sentence “Peaking arising from the intrinsic dynamics in the optical domain can be utilized to extend the modulation bandwidth” is not clear. Please explain.*

**Response 5:**

We appreciate the reviewer’s request for clarification. The phrase "peaking arising from the intrinsic dynamics in the optical domain" refers to the optical peaking enhancement phenomenon where bandwidth extension is achieved by strategically detuning the operating wavelength from the cavity's intrinsic resonance peak. To better convey this physical mechanism, we have accordingly rephrased the related sentences (Line 121–128) as follows:

In Supplementary Information Note II, we systematically analyze the interplay between the dynamic ER, EO bandwidth, Q factor and tuning efficiency. Through rigorous optimization, we identify a balanced trade-off by setting the Q factor to 3000, corresponding to a photon-lifetime of  $\tau = Q\lambda/2\pi c = 2.5$  ps. This approach limits the optical bandwidth to 63.7 GHz, yielding an EO bandwidth of 60 GHz (obtained from Eq. 1). To extend the modulation bandwidth, the optical peaking enhancement can be utilized in the modulator as reported in previous works<sup>5,41</sup>, which is achieved by strategically detuning the operating wavelength from the cavity's resonance peak. Additionally, as shown in Fig. 1a, the dynamic ER is directly affected by the tuning efficiency with a given swing voltage (Supplementary Information Note II).

**Comment 6:**

*Figure 1a and the background of the curves is not clear, please explain. What was simulated and why are the curves as shown?*

**Response 6:**

We appreciate the reviewer’s feedback and have carefully addressed the concerns regarding the clarity of Fig. 1a and the interpretation of the curves. Below is our detailed response:

- (a) The figure illustrates the theoretical relationship between the dynamic ER, EO bandwidth, Q factor, and tuning efficiency of the proposed modulator. The curves are derived from Eq. S1 & S7 (provided in Supplementary Information Note I & II).
- (b) As illustrated in the Supplementary Information Note II, we have redrawn the Fig. S1b (same as Fig. 1a) and provided a detailed explanation of how the proposed modulator responds to the electrical drive signal and generates the on/off optical signal theoretically, as illustrated in Fig. S1a.
- (c) As addressed in our response to Comment 4, the spectral shift and Q factor collectively determine the dynamic ER. Specifically, the spectral shift is influenced by both tuning efficiency and swing voltage  $V_{pp}$ , while the Q factor governs the EO bandwidth. That is why we study the relationship between dynamic ER, EO bandwidth, Q factor, and tuning efficiency.

- (d) We have incorporated specific qualifying conditions in response to the reviewer's inquiries, including the carrier wavelength and the swing voltage.

The revisions have been added to the Supplementary Information Note II as follows:

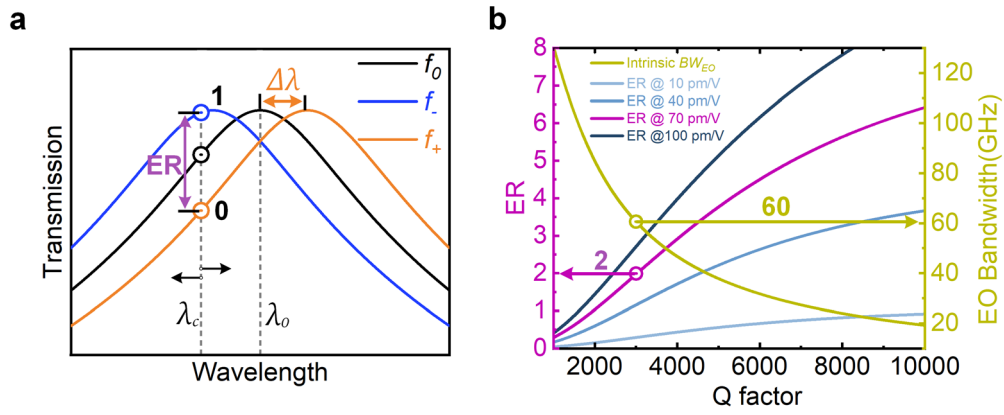
The spectral curves that blueshift and redshift under the applied electric field can be expressed as follows:

$$f_-(\lambda, Q) = f_0(\lambda - \Delta\lambda, Q) \quad (S5)$$

$$f_+(\lambda, Q) = f_0(\lambda + \Delta\lambda, Q) \quad (S6)$$

where  $\Delta\lambda$  represents the wavelength detuning under a peak-to-peak driving voltage of  $2 V_{pp}$ , which is numerically equivalent to the tuning efficiency. As shown in Fig. S1a, the carrier wavelength  $\lambda_c$  is lower than the resonant wavelength  $\lambda_0$  with a detuning point, and the dynamic ER at a low modulation frequency can be expressed as

$$ER_{dynamic} = |f_-(\lambda_c, Q) - f_+(\lambda_c, Q)| \quad (S7)$$



**Figure S1. Numerically calculated results.** **a** Schematic of a Lorentzian line shape-based modulator that generates the optical signal in the theoretical model. **b** Numerically calculated results: the intrinsic EO bandwidth in relation to Q factor, and the dynamic ER in relation to Q for various tuning efficiencies.

#### Comment 7:

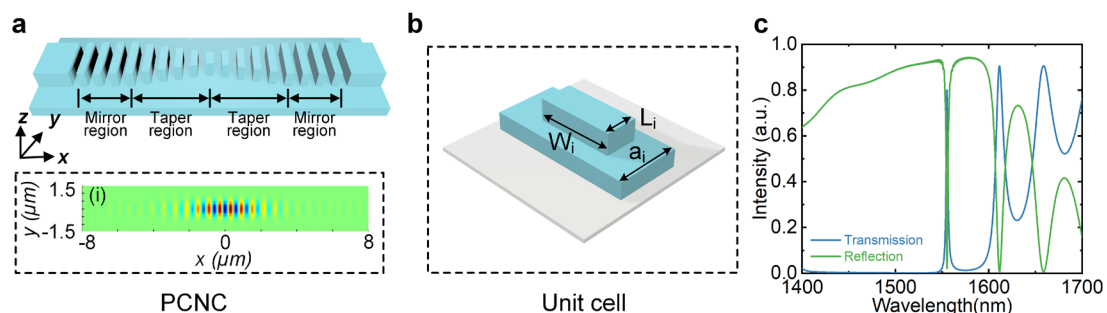
Figure 1b shows the layout and concept of the device. What is the transmission and reflection of this device? High transmission is key. The reflected light in the off-resonance state will couple back to the laser and deteriorate the system performance. How can this be solved?

#### Response 7:

In response, we have included the reflection spectrum of the device in Fig. S3c in the Supplementary Information Note III, which shows that the PCNC exhibits high reflection for non-resonant light. Indeed, such reflection has an impact on the stability of the laser and should be taken into the optical module design. Normally, optical transmitter modules incorporate isolators to mitigate back-reflection effects on the light source, as reported in<sup>15-17</sup>. The revisions have been added to the Supplementary Information Note III as follows:

The reflection spectrum shown in Fig. S4c reveals that PCNC maintains high reflectivity for non-resonant wavelengths. This parasitic reflection may critically affect both laser stability

and system performance—an issue targeted for improvement in our ongoing research. We evaluate two mitigation approaches: (1) implementing optical isolation (e.g., an isolator/circulator before the input coupler), as indicated in Ref. 6, although this introduces cost and complexity penalties; or (2) developing a side-coupled PCNC-bus waveguide architecture that generates MRR-like notch-filter transmission characteristics. The latter solution provides WDM compatibility, achieves ultra-low off-resonance reflection, and maintains a comparable Q factor while improving dynamic ER performance.



**Figure S4. Schematic and simulation results of the designed PCNC. a** Schematic of the designed PCNC. The inset shows the optical field distribution obtained from FDTD simulation. **b** Schematic of the unit cell. **c** Numerically simulated transmission and reflection spectra of the PCNC obtained via Lumerical FDTD Solutions.

- [15] Mehta, N., Lee, B. G. Overcoming challenges of co-integrated optics to advance accelerated computing. *Proc. SPIE 13372, Optical Interconnects and Packaging*, 1337202 (2025).
- [16] Umeta, K., Sawamura, T., Shiroishi, Y. & Nasu H. Characterization of QSFP and OSFP CPO ELS modules employing an 8-channel CWDM TOSA in practical air-cooling conditions. *IEEE 74th Electronic Components and Technology Conference (ECTC)*, Denver, CO, USA, pp. 112-117 (2024)
- [17] Sawamura, T. et al. Development of an External Laser Source for Co-Packaged Optics. *Furukawa Electric Review* 55, 46-52 (2024).

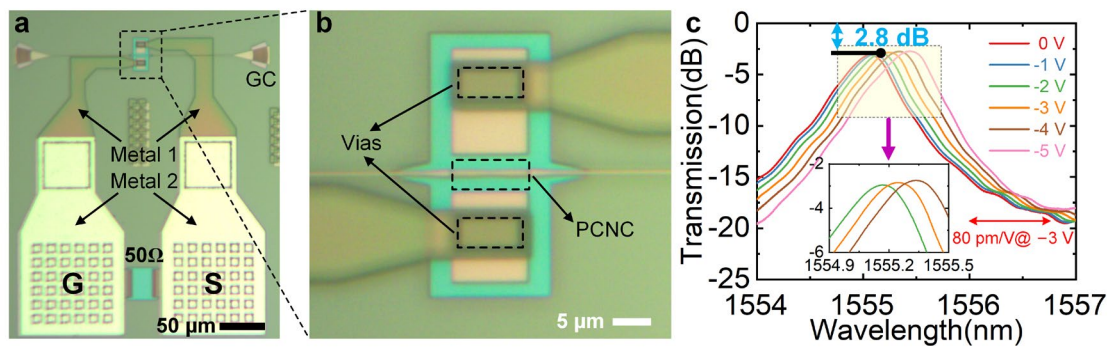
### Comment 8:

Figure 2c and the mentioned enhanced tuning efficiency are not clear. See also the comment above.

### Response 8:

We would like to thank the reviewer for the constructive suggestion. In order to enhance the quality of the figure and include some essential information, we have made detailed adjustments to Fig. 2c, as outlined below:

**Fig. 2 | Fabrication and static characterization of the proposed modulator.**



**a** Optical microscope image of the fabricated PCNC modulator. **b** Magnified optical image of the center of the proposed device. **c** Measured transmission spectra versus reverse bias voltage ranging from  $-1$  V to  $-5$  V; the inset shows the detailed optical spectra under the bias of  $-2$  V,  $-3$  V, and  $-4$  V, respectively. G ground, S signal.

## Comments from Reviewer #2:

### Comment 1:

*Dynamic ER: Provide a rigorous, quantitative, and evidence-based explanation for the observed dynamic ER < 1 dB. This requires substantiating the contribution of external RF path loss (e.g., via measured S-parameters and de-embedding) versus potential intrinsic device limitations. The relevance of cited references (esp. Ref 26 and Ref 23) must be correctly established, acknowledging that Ref 23 achieved significantly better ER. Discuss the practical implications of the low ER for system performance.*

### Response 1:

We appreciate the reviewers' careful review and constructive comments. Below are our point-by-point responses:

- (a) We have added an explanation for the observed dynamic ER < 1 dB in the “Discussion” section and a detailed discussion in the Supplementary Information Note V, including comprehensive S-parameters characterization of the electrical equipment.
- (b) We apologize for the incorrect citation of Ref. 26 where we intended to cite Ref. 27, which has been corrected in the revised manuscript. We would like to clarify our rationale for citing Ref. 27: Its "Table 1" compares the degradation of dynamic ER at various modulation rates.
- (c) Ref. 23 demonstrates the performance of an advanced silicon-based slow-light MZI modulator. It achieves a high dynamic ER by employing a differential signal with  $V_{pp} \sim 5$  V and a slow-light-enhanced modulation region of 124  $\mu\text{m}$  in length. We cited this work because it also exhibits the similar phenomenon of ER degradation with increasing the modulation rate, e.g., 3.15 dB @ 100 Gbps and 2.15 dB @ 112 Gbps.
- (d) In the present work, our device represents near-theoretical-limitation performance under this design scheme, with a theoretical ER of 2 dB versus the experimentally measured value of < 1 dB.

The revisions have been added to revised manuscript and the Supplementary Information as follows:

- (i) In the “Results”, line 245–248:

The lower-than-expected dynamic ERs are attributed to the EO response of the proposed PCNC modulator and the electrical signal attenuation<sup>27</sup> through the bias-Tee, RF cable, and high-speed probe, a detailed analysis is illustrated in the Supplementary Information Note V.

- (ii) In the “Discussion”:

Line 279–282: High-speed data modulation is successfully achieved for 110 Gbps and 130 Gbps NRZ signal transmissions, with BERs below  $3.8 \times 10^{-3}$  and  $2 \times 10^{-2}$ , respectively, while maintaining a power consumption of 5.9 fJ/bit, calculated as  $CV_{pp}^2/4$ . Nevertheless, the modulator's intrinsic power consumption represents merely a fraction of the total system power, with the signal driving and recovery processes demanding substantially higher power budgets<sup>53</sup>.

Besides, it should be noted that the proposed device represents near-theoretical-limit performance under this design scheme. For practical applications requiring long-distance transmission, high transmission capacity, and low BERs, the device validated in this work can be further optimized in future work.

Line 287–290: However, experimental measurements revealed a dynamic ER of less than 1 dB, primarily due to the EO response of the proposed PCNC modulator and the electrical signal attenuation<sup>27</sup> through the 67-GHz bias-Tee, RF cable, and high-speed probe. This attenuation resulted in a smaller wavelength shift than anticipated.

(iii) In the Supplementary Information Note V:

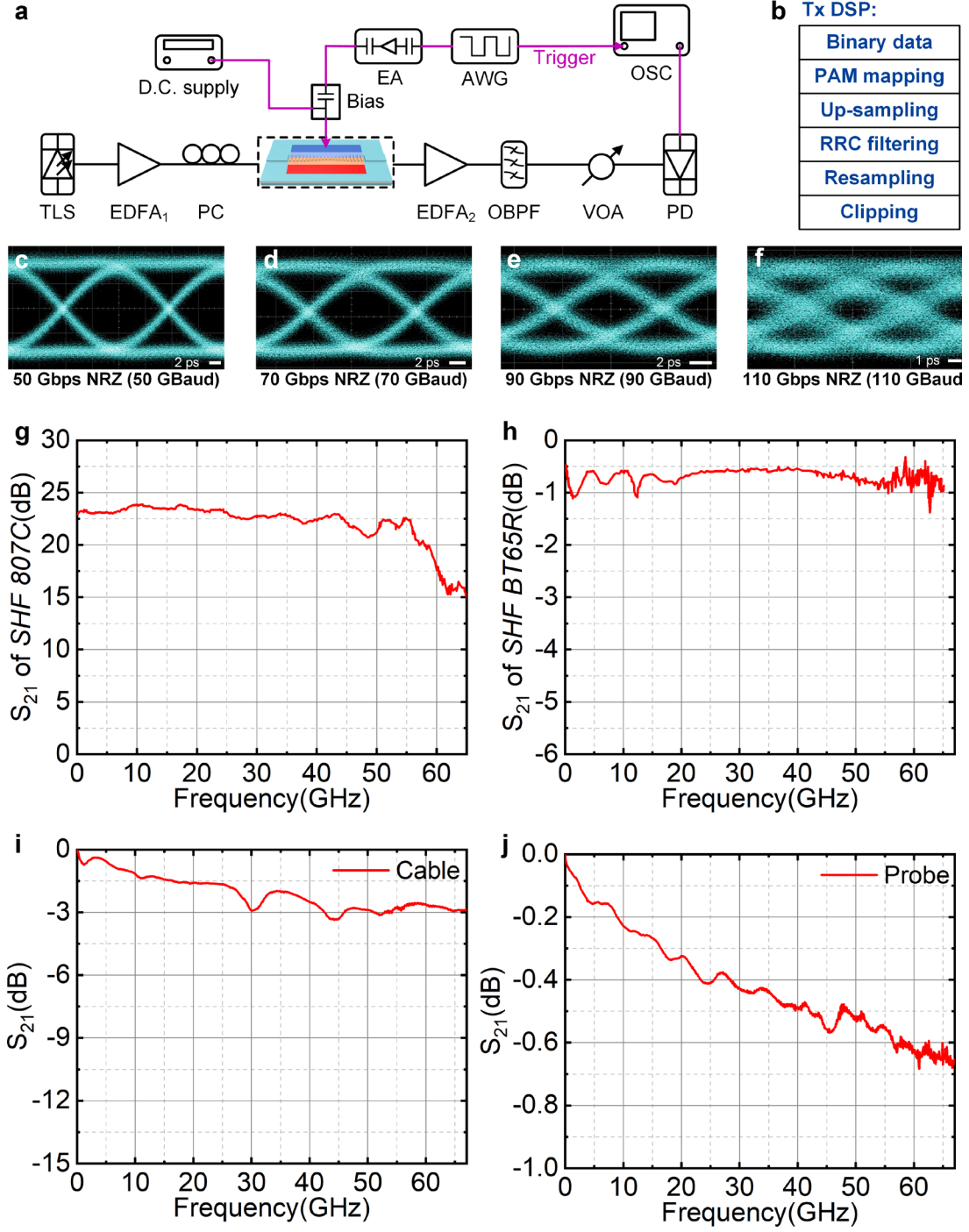
The dynamic ER is a critical performance metric for high-speed optical communication systems. In intensity-modulated direct-detection (IM/DD) schemes, a high dynamic ER ensures minimal signal distortion and an increased signal-to-noise ratio (SNR), directly affecting BER thresholds.

To characterize the data modulation performance of the proposed silicon modulator, we conducted a high-speed data generation experiment. The experimental setup is shown in Fig. S7a. An electrical data signal with a  $(2^{13}-1)$ -bit pseudorandom binary sequence (PRBS) was applied to the modulator, which was generated by a 256-GSa/s arbitrary waveform generator (AWG, Keysight M8199A) and then amplified by an electrical amplifier (EA, SHF S807C) with a peak-to-peak voltage of  $\sim 2$  V<sub>pp</sub>. A bias-Tee (SHF BT65R-B) was used to provide a bias voltage of  $-3$  V, which is crucial for a high-speed EO modulator on the silicon platform. A 67-GHz radio frequency (RF) cable and a high-speed probe were used to inject the electrical signal into the modulator. A trigger signal was employed for clock recovery to generate eye diagrams of the received data captured by an electrically sampled oscilloscope (OSC, Keysight N1030A). Figure S7b shows the transmitter DSP flow charts. By using Nyquist pulse shaping, the signal bandwidth can be suppressed to  $\sim$  half of the baud rate. The eye diagrams for the NRZ signals at 50, 70, 90, and 110 Gbps are shown in Fig. S7c–f, with SNRs of 8.23, 6.07, 3.98, and 3.17 dB, respectively. The measured ERs of the open eyes were 1, 0.9, 0.7, and 0.6 dB.

We have meticulously analyzed the reasons for the measured dynamic ER falling lower than the expected 2 dB. Figures S7g and h present the parameters of the EA and bias-Tee, as extracted from the manufacturer's datasheets<sup>8,9</sup>. On the transmitter side, the electrical signal generated by the AWG for driving the modulator is not spectrally flat after amplification by the electrical amplifier, revealing that the amplification power varies across different radio frequencies. The amplified V<sub>pp</sub> subsequently experiences additional losses as it passes through the bias-Tee, a 30-cm 67-GHz RF cable, a 67-GHz RF probe, and contact with the bond pads. These cumulative losses result in an effective V<sub>pp</sub> at the device that deviates from the target V<sub>pp</sub>, which reduces the dynamic ER. Furthermore, on the basis of the S21 parameters obtained from bandwidth measurements, although the optical peak enhancement effect significantly increases the 3 dB electro-optic bandwidth of the device, it concurrently results in an inherent increase in the IL of the S21 parameter. This additional EO response loss consequently causes a reduction in the dynamic ER of the eye diagram. This phenomenon directly affects the dynamic ER and highlights the challenges in maintaining signal integrity across high-frequency transmission paths.

Notably, our device achieves near-theoretical-limitation performance under this design

scheme. For practical applications requiring long-distance transmission, high transmission capacity, and low BERs, the device validated in this work can be further optimized in future work. First, by side-coupling the PCNC with a bus waveguide, a notch-shaped transmission spectrum, similar to that of an MRR, can be achieved. This spectral profile has advantages in achieving higher ERs and can be used in wavelength-division multiplexing (WDM) systems to increase transmission capacity. Additionally, optimizing the design of the PCNC to increase the Q factor of the resonance peak provides a pathway for achieving higher dynamic ERs. However, this Q factor improvement method requires significant optical power trade-offs when the EO bandwidth is extended, presenting a fundamental limitation in the device design optimization process.



**Figure S7. High-speed data modulation measurement and the  $S_{21}$  of experiment setup.** **a** Experimental equipment for measuring optical eye diagrams. **b** Transmitter DSP flow charts. Eye diagrams for NRZ signals at data rates of **c** 50 Gbps, **d** 70 Gbps, **e** 90 Gbps and **f** 110 Gbps. Typical  $S_{21}$  parameters of **g** EA (SHF S807C), **h** bias-Tee (SHF BT65R-B), **i** 30-cm 67-GHz RF cable and **j** 67-GHz RF probe.

**Comment 2:**

*Energy Consumption: Reconcile the energy consumption calculation with the explanation for the dynamic ER. Provide a revised energy figure based on a justified effective voltage swing ( $V_{eff}$ ) at the device, or offer an alternative, consistent explanation for the low ER that aligns with the applied  $V_{pp}$ .*

**Response 2:**

- (a) Regarding the characterization of the modulator's power consumption, we adopted a widely recognized methodology along with the calculation formula for NRZ signals<sup>8,12-14,18</sup>. While the reviewer's observation on studying the effective voltage applied to the device is highly valuable, establishing this parameter would require more meticulous future investigation.
- (b) Concerning the causes and analysis of the low dynamic ER, we have incorporated a more in-depth discussion and explanation in the Supplementary Information Note V as suggested by the reviewer, including the S21 parameters of equipment used in the experiment, please refer to Response 1 for detailed explanation.

- [8] Dubé-Demers, R., LaRochelle, S. & Shi, W. Ultrafast pulse-amplitude modulation with a femtojoule silicon photonic modulator. *Optica* **3**, 622-627 (2016)
- [12] Miller, D. A. B. Energy consumption in optical modulators for interconnects. *Opt. Express* **20**, A293-A308 (2012).
- [13] Li, M. X. et al. Lithium niobate photonic-crystal electro-optic modulator. *Nat. Commun.* **11**, 4123 (2020).
- [14] Yuan, Y. et al. A  $5 \times 200$  Gbps microring modulator silicon chip empowered by two-segment Z-shape junctions. *Nat. Commun.* **15**, 918 (2024).
- [18] Han, C. et al. Slow-light silicon modulator with 110-GHz bandwidth. *Sci. adv.* **9**, 42, eadi5339 (2023).

**Comment 3:**

*Bandwidth Density: Thoroughly revise or remove the "bandwidth density" claim. If retained, provide a clear definition of the metric, justify its use and relevance compared to standard metrics.*

**Response 3:**

We appreciate the reviewer's comment regarding the "bandwidth density" discussion. After rigorous reevaluation, we have decided to remove the "bandwidth density" metric from the revised manuscript to prevent potential ambiguities.

Specifically, line 96–97:

To the best of our knowledge, the demonstrated modulator has an EO bandwidth exceeding 110 GHz with the most compact device footprint on the silicon platform. As an application example, the proposed modulator is operated with a NRZ signal of up to 110 GBaud, with a BER less than  $3.8 \times 10^{-3}$ . ~~As a result, we achieve a record-high bandwidth density<sup>45</sup> of  $>1100$  Tbps/mm<sup>2</sup>~~

(110 Gbps/10  $\mu\text{m}^2$ ) for an intensity modulator, setting a new benchmark for compact, high-performance photonic devices.

**Comment 4:**

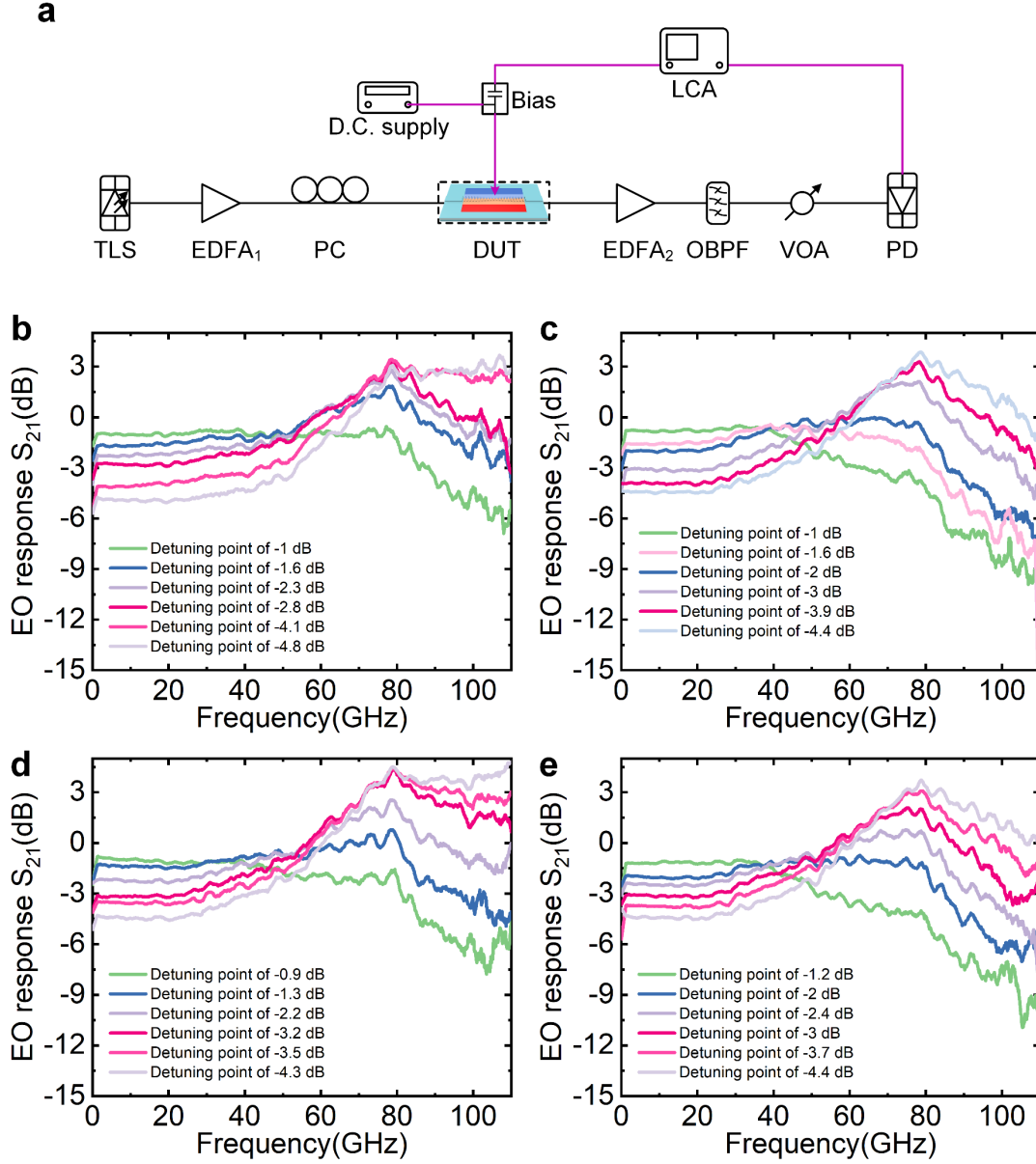
*Operational Window: Include a discussion on the practical consequences of the observed strong dependence of peak bandwidth on wavelength detuning, addressing the usable optical bandwidth and associated performance trade-offs.*

**Response 4:**

We appreciate the reviewer's comment regarding the operational wavelength window, which is a crucial performance metric for optical modulators. In response, we have expanded our discussion in the Supplementary Information Note IV as follows:

To effectively enhance the EO bandwidth of the proposed modulator, we employ the optical peaking enhancement<sup>7</sup> strategy to optimize the trade-off between the photon lifetime and resonance conditions, thereby significantly broadening the EO bandwidth. However, this approach introduces an inherent trade-off with increased ILs, requiring a careful balance between bandwidth expansion and optical ILs adapted to specific application requirements.

To quantify the operational window of the EO bandwidth, we systematically characterized several fabricated devices, as shown in Fig. S6. The experimental results indicate good uniformity and validate the effectiveness of this strategy. Specifically, within a wavelength detuning range of 0.3 nm, the additional optical IL is controlled between 2 dB and 4.8 dB, achieving a balance between bandwidth enhancement and optical efficiency. These findings highlight the practical applicability of the proposed approach, particularly in scenarios where the optical IL is acceptable for improved bandwidth performance.



**Figure S6. EO bandwidths of some modulators with the same design. a** Experimental setup for the EO bandwidth measurement for 4 modulators. **b-e** Measured EO  $S_{21}$  responses for different wavelength detuning  $\Delta\lambda$  values or optical IL. TLS, tunable laser source; EDFA, erbium-doped fiber amplifier; PC, polarization controller; DUT, device under test; VOA, variable optical attenuator; OBPF, optical bandpass filter; PD, photodetector; and LCA, lightwave component analyzer.

### Comments from Reviewer #3:

#### Comment 1:

*(a) The authors have explained the enhancement of the tuning efficiency is possible due to the 'slow-light design in optical resonator.' Although the slow-light effect is crucial for waveguide-type modulators, applying it to nanobeam cavity-type modulators might not be so meaningful.*

*(b) In the nanobeam cavity design, increasing the group index is done by reducing the difference between the mirror region and cavity region by, for example in Fig. 1b, making squeezing of the central region shallower. This effectively makes the group index increase, at the same time the reflection by the mirror gets weaker, making the mode field distribution spread among the entire nanobeam (in the longitudinal axis). Therefore, it is also possible to understand that the enhancement of tuning efficiency is achieved by spreading the mode in the longitudinal direction, instead of the slow-light effect. Discussions about these points are not clearly shown in the current manuscript and it would be important.*

*Clarifying these points would also be important to discuss the trade-offs between this strategy and the footprint.*

*(c) Moreover, the authors have not clearly pointed out the strategy of designing the slow-light photonic crystals, in which at least several design parameters might be compared to show the best design. The authors have shown that the group index for the center part of the cavity is 4.2 where the light is concentrated. However, this value might not be so large as compared to other slow-light devices.*

#### Response 1:

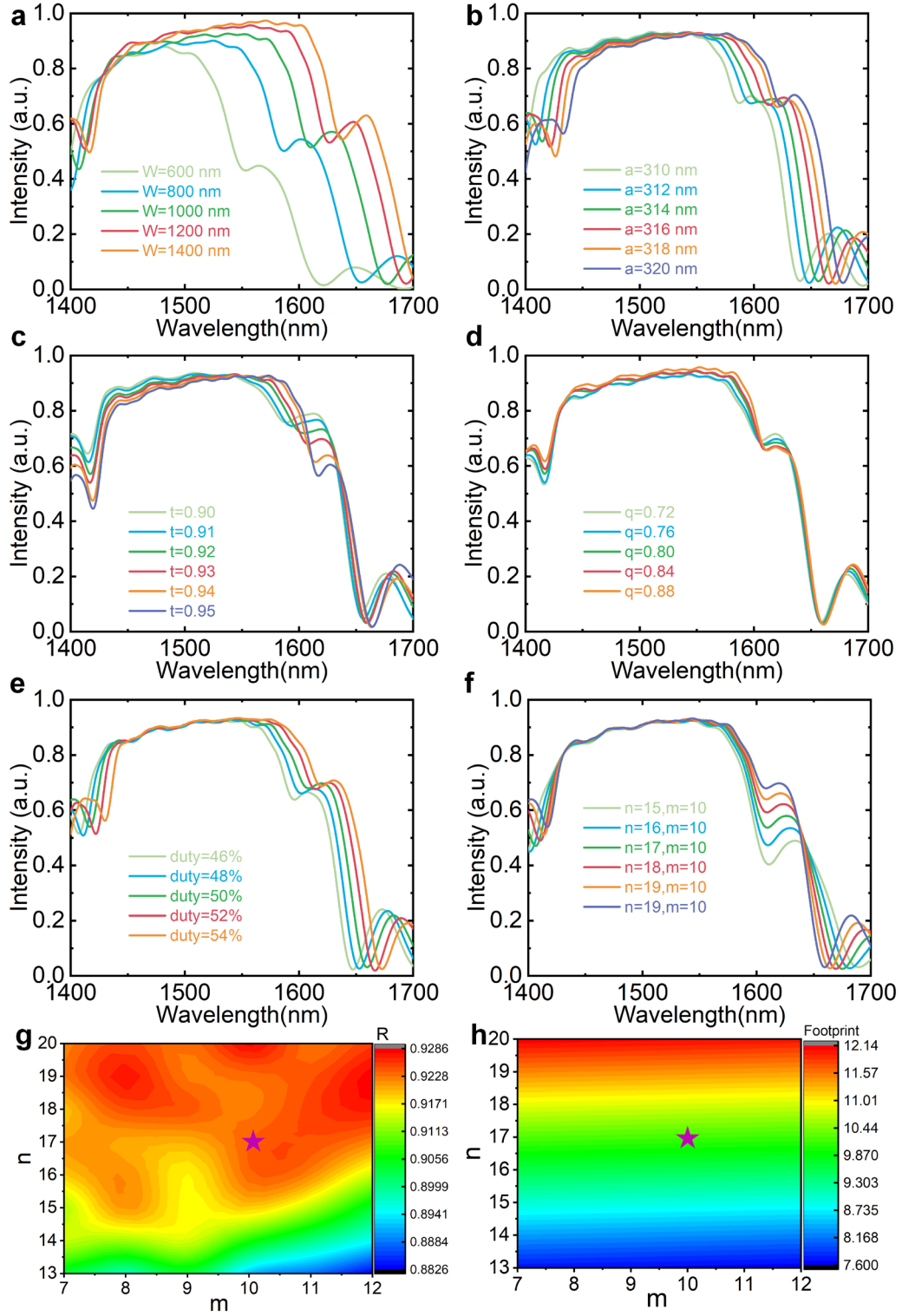
We thank the reviewer for the insightful comments regarding the slow-light effect in our nanobeam cavity design. Below are our point-by-point responses:

- (a) We agree that cavity-type modulators differ fundamentally from waveguide-type modulators. The slow-light effect has been experimentally demonstrated to enhance light-matter interactions, as well as the optical resonators<sup>19-21</sup>. While the waveguide length experiencing slow-light enhancement inside a cavity-type modulator is much shorter than that in conventional slow-light waveguide-type modulators, the effective optical path length is significantly increased due to multiple round-trips of light within the cavity. This allows phase detuning accumulation of the slow-light enhancement effect.
- (b) We have added a detailed discussion of the PCNC optimization to the Supplementary Information Note III. The reviewer's suggestion that enhanced tuning efficiency results from optical field distribution spreading the mode in the longitudinal direction may not accurately reflect the underlying mechanism. To the best of our knowledge, a reduced optical mode volume offers significant advantages in both power efficiency and modulation performance, whereas optical field spreading would conversely increase the mode volume.
- (c) Following the Comment 1 from Reviewer #1, we calculated the phase detuning enhancement factor between our designed slow-light waveguide and a conventional waveguide, yielding an improvement of 3.36-fold. Although this enhancement is relatively

modest compared to reported slow-light devices, it reflects a trade-off with device footprint optimization.

- [19] Lu, X., McClung, A. & Srinivasan, K. High-Q slow light and its localization in a photonic crystal microring. *Nat. Photon.* **16**, 66–71 (2022).
- [20] Lo S., Lee J., Weiss S. & Fauchet P. Bloch mode selection in silicon photonic crystal microring resonators. *Opt. Lett.* **43**, 2957–2960 (2018).
- [21] McGarvey-Lechable K. et al. Slow light in mass-produced, dispersion-engineered photonic crystal ring resonators. *Opt. Express* **25**, 3916–3926 (2017).

To obtain a resonance with low optical intrinsic insertion loss (IL), the desired Q factor, a compact footprint and especially strong slow-light enhancement using PCNC, we optimized the device design via Lumerical FDTD simulations. Given that the PCNC essentially functions as an FP cavity, we explored the relationship between various parameters in Eq. S14–18 and the reflectivity, as shown in Fig. S5. By adjusting the value of  $m$ , we achieve a trade-off between the device footprint and the waveguide length of the slow-light enhancement effect. A larger  $m$  reduces the reflectivity of the mirror but increases the phase detuning accumulation length of the slow-light effect. Therefore, the parameters of the PCNC structure were determined by considering the fabrication feature size, the effective cavity length increased by the slow-light effect, the desired Q factor, and the device footprint, resulting in the following values:  $W = 1000$  nm,  $a = 315$  nm,  $t = 0.93$ ,  $q = 0.78$ ,  $d = 50\%$ ,  $m = 10$ , and  $n = 17$ . On the basis of this configuration, we simulate the designed PCNC, yielding an IL of 1.08 dB, an intrinsic Q factor of  $\sim 5000$ , and a mode volume of  $0.12 \mu\text{m}^3$ , which reveals the optimized performance of the designed structure. These metrics are essential for evaluating the tuning efficiency and compactness of the device, ensuring its suitability for advanced applications.



**Figure S5. Simulation results of the PCNC design with various parameters.** The reflectivity affected by **a** silicon waveguide width  $W$ , **b** unit cell pitch  $a$  in the mirror region, the ratio of the **c** pitch and **d** width of the central unit cell to that of the mirror region, the **e** duty cycle of each unit cell, and the **f** number of total unit cells in the one-sided PCNC; the **g** reflectivity and **h** footprint determined by varying the number of unit cells in taper region  $m$  and the one-sided PCNC.

**Comment 2:**

*I would like the authors to describe the detailed design of the nanobeam cavity. For example, the  $Q$  factor of the cavity can be decomposed into the coupling ratio to the waveguides, absorption by the doped regions, and scattering loss. With these values, the excess loss of the device (2.8 dB) can be understood.*

**Response 2:**

We appreciate the reviewer's comments. Regarding the reviewers' comments on waveguide coupling, absorption loss in doped regions, and scattering loss, these factors are undoubtedly critical for high-speed silicon electro-optic modulators based on resonant cavities. We have added a theoretical analysis in the Supplementary Information Note III to fit and calculate these parameters.

We use temporal coupled-mode theory to describe the model of the PCNC modulator. As shown in Fig. S3, when the light is incident from the left side with  $S_{2+} = 0$ , the temporal coupled-mode equations become:

$$\frac{da}{dt} = -i\omega_0 a - \frac{a}{\tau_r} - \frac{a}{\tau_\alpha} - \frac{2a}{\tau} + \sqrt{\frac{2}{\tau}} S_{1+} \quad (\text{S8})$$

$$S_{1-} = -S_{1+} + \sqrt{\frac{2}{\tau}} a \quad (\text{S9})$$

$$S_{2-} = \sqrt{\frac{2}{\tau}} a \quad (\text{S10})$$

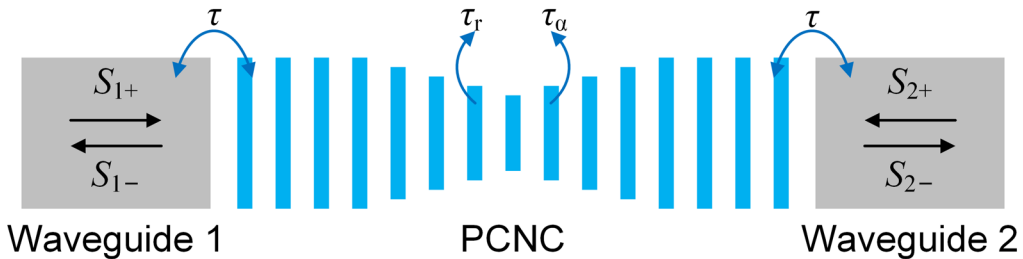
where  $\tau$  denotes the coupling between the PCNC and the input/output waveguide,  $\tau_r$  denotes the radiation coupling between the PCNC and the cladding, and  $\tau_\alpha$  denotes the absorption by the doped regions.

The transmission spectrum can be expressed as

$$T(\omega) = \frac{|S_{2-}|^2}{|S_{1+}|^2} = \frac{\frac{4}{\tau^2}}{(\omega - \omega_0)^2 + \left(\frac{1}{\tau_r} + \frac{1}{\tau_\alpha} + \frac{2}{\tau}\right)^2} \quad (\text{S11})$$

In this work, the intrinsic performance of the designed PCNC exhibited a transmittance  $T$  of ~78% and a  $Q$  factor of ~5000, whereas the doped-PCNC presented a  $T$  of ~52.5% and a  $Q$  factor of ~2930.

Combined with



**Figure S3. Schematic of a PCNC modulator.**

$$\frac{1}{\tau_{total}} = \frac{\omega_0}{Q} = \frac{1}{\tau_r} + \frac{1}{\tau_\alpha} + \frac{2}{\tau} \quad (S12)$$

Then, we have

$$\frac{1}{\tau} = \omega_0 \cdot 8.8 \times 10^{-5}, \frac{1}{\tau_r} = \omega_0 \cdot 2.4 \times 10^{-5}, \frac{1}{\tau_\alpha} = \omega_0 \cdot 1.41 \times 10^{-4} \quad (S13)$$

**Comment 3:**

*In page 4, line 94, the authors have cited [45] as the comparison of their work to the state-of-the-art FOM. However, this would not be a fare comparison because Ref. [45] reported on an IQ modulator.*

**Response 3:**

We agree with the reviewer that Ref. [45] is not appropriate for comparison here. We have removed the reference accordingly.

**Comment 4:**

*Supplementary Information Note IV seems to be missing in the supplementary file.*

**Response 4:**

We sincerely thank the reviewer for the careful checking and would like to apologize for our typographical error. In the revised version, we have added the Supplementary Information Note IV.

Thank you again for your consideration.

Sincerely,

Hua Zhong & Yikai Su

On behalf of all the authors

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## Response Letter

Date: Dec. 12<sup>th</sup>, 2025

Subject: Response letter for NCOMMS-25-25057B (second revision)

Dear Reviewers,

We sincerely appreciate the time and effort you have dedicated to evaluating our manuscript entitled “Ultracompact and large-bandwidth silicon modulator in a CMOS-compatible foundry”. We are grateful for the constructive feedback from all the reviewers during the first revision, which has improved our work.

We are pleased that *Reviewer #1* now supports publication, and we are deeply grateful for the positive assessment. In this second revision, we have carefully addressed the remaining comments from *Reviewers #2 and #3* and incorporated their suggestions to further enhance the manuscript’s rigor and clarity. Below, we provide point-by-point responses to each concern, with the reviewers’ comments in *italics* and our revisions marked in **red** in both this letter and the revised manuscript.

We believe that these revisions have resolved all the outstanding issues and hope that the manuscript is now suitable for publication in *Nature Communications*.

### Comments from Reviewer #2:

*I have carefully examined the revised manuscript together with the new Supplementary Notes and your point-by-point response. Your revision represents a clear effort to engage with the previous critique: the unconventional “bandwidth-density” claim has been removed, and a thoughtful discussion supported by additional data now clarifies the practical wavelength-detuning window. These improvements fully resolve those two issues. Unfortunately, the two most critical technical concerns—the extremely low dynamic extinction ratio (ER) and the logically inconsistent energy-per-bit figure—remain insufficiently addressed. Because they strike at the heart of the paper’s performance claims, the manuscript cannot yet be considered for publication.*

#### Comment 1:

- (a) *First, on the dynamic ER, your new Supplementary Note V supplies manufacturer S-parameter curves for the electrical amplifier, bias-tee, and related components, and it asserts that external high-frequency loss dominates the observed < 1 dB eye penalty. However, no quantitative de-embedding of the complete RF chain has been performed. In the absence of measured S-parameters for the specific cables, probes, pads and device under test, the reader still cannot determine how much of the voltage drop occurs externally and how much is intrinsic to the nanobeam modulator itself. The additional qualitative remark that the optical peaking mechanism “inherently increases insertion loss” may be physically plausible, but without modelling or experiment it remains speculative.*
- (b) *Moreover, the citation of Han et al. continues to be invoked only to show that ER generally degrades with increasing data rate; it does not justify an ER that is an order of magnitude lower than that achieved in that work under comparable drive conditions.*
- (c) *A rigorous, experiment-based separation of external and intrinsic contributions is therefore indispensable.*

**Response 1:**

We sincerely appreciate the reviewer's thoughtful analysis and valuable suggestions regarding dynamic ER characterization. In response to these insightful comments, we have carefully revised the relevant descriptions and added additional results to Supplementary Information Note V.

- (a) We performed a quantitative analysis of the S21 parameter across the external RF chain, simulated  $V_{\text{eff}}$  in the time domain, explained the ER degradation induced by the optical peaking mechanism through frequency-domain analysis, and simulated the dynamic ER at various data rates. On the basis of this analysis, the reader can determine how much of the low ER originates from the external RF chain and how much is attributable to the modulator itself. We have revised the relevant analysis accordingly and added it to Supplementary Information Note V.
- (b) We would like to clarify the fundamental differences between the proposed modulator and the implementation in Ref. 23. While Ref. 23 employs an MZI configuration that relies on interference between two phase-modulated arms, our approach utilizes resonant spectral shifting of the cavity transmission spectrum under an applied voltage bias—an entirely distinct operating principle. Our design framework inherently targets a dynamic ER of 2 dB, which represents near-theoretical-limitation performance for the design principle, as detailed in Supplementary Information Note II. With respect to the driving conditions, Han et al. used a  $5 V_{\text{pp}}$  drive voltage, whereas we used a  $2 V_{\text{pp}}$  drive voltage.
- (c) We systematically simulated the influence of the external RF chain on the input driving signals and the dynamic ER at the transmitter, which enables clear discrimination between external and intrinsic contributions to ER degradation.

Lines 293–295: However, experimental measurements revealed a dynamic ER of less than 1 dB, primarily because of the EO response of the proposed PCNC modulator and the electrical signal attenuation<sup>27</sup> through the 67-GHz bias-Tee, RF cable, and high-speed probe (discussed in Supplementary Information Note V).

In Supplementary Information Note V:

The dynamic ER is a critical performance metric for high-speed optical communication systems. In intensity-modulated direct-detection (IM/DD) schemes, a high dynamic ER ensures minimal signal distortion and an increased signal-to-noise ratio (SNR), directly affecting BER thresholds.

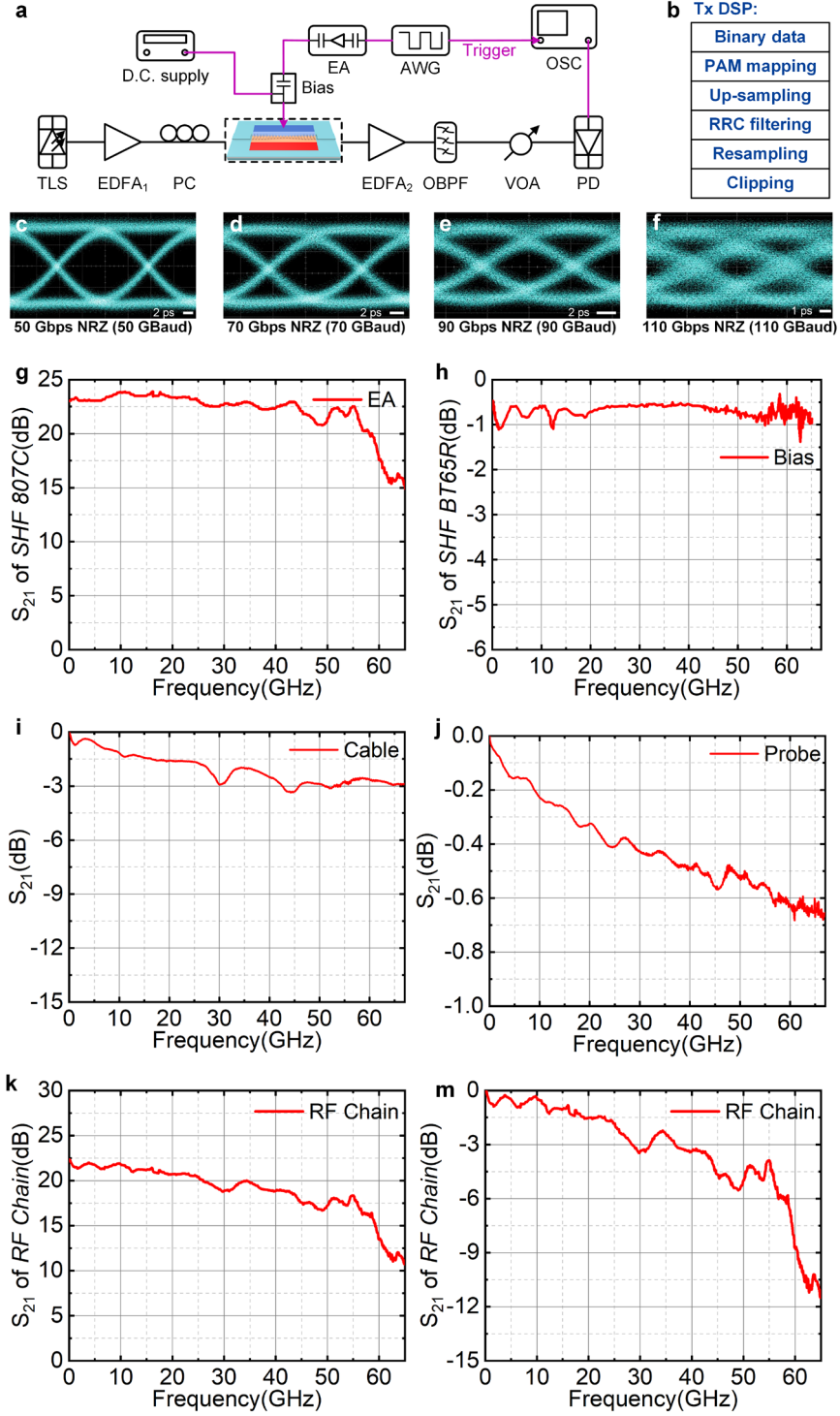
To characterize the data modulation performance of the proposed silicon modulator, we conducted a high-speed data generation experiment. The experimental setup is shown in Fig. S8a. An electrical data signal with a  $(2^{13}-1)$ -bit pseudorandom binary sequence (PRBS) was applied to the modulator, generated by a 256-GSa/s arbitrary waveform generator (AWG, Keysight M8199A) and then amplified to  $\sim 2 V_{\text{pp}}$  by an electrical amplifier (EA, SHF S807C). The voltage amplitude of  $\sim 2 V_{\text{pp}}$  was verified by an electrical back-to-back measurement. A bias-Tee (SHF BT65R-B) was used to provide a bias voltage of  $-3 V$ , which is crucial for a high-speed EO modulator on the silicon platform. A 67-GHz radio frequency (RF) cable and a high-speed probe were used to inject the electrical signal into the modulator. A trigger signal was employed for clock recovery to generate eye diagrams of the received data captured by an electrically sampled oscilloscope (OSC, Keysight N1030A). The transmitter digital signal processing (DSP) flowcharts are shown in Figure S8b. By using Nyquist pulse shaping, the signal bandwidth can be suppressed to  $\sim$  half of the baud rate while unclear transient patterns

are introduced in the eye diagrams, as shown in Fig. S9a–d. The measured eye diagrams for the NRZ signals at 50, 70, 90, and 110 Gbps are shown in Fig. S8c–f, with SNRs of 8.23, 6.07, 3.98, and 3.17 dB, respectively. The measured ERs of the open eyes were 1, 0.9, 0.7, and 0.6 dB.

To quantitatively investigate the discrepancy between the measured dynamic ER and theoretical expectations, we performed frequency- and time-domain studies. Figures S8g–j present the measured S21 parameters of the EA, bias-Tee, and RF cable and that of the probe, as extracted from the manufacturer’s datasheets<sup>8,9,10</sup>. The unnormalized and normalized S21 parameters of the RF chain are presented in Figures S8k and S8m, respectively, and the quantitative values across specific frequencies are provided in Table S1. The measured electrical ILs of the RF chain demonstrate frequency-dependent characteristics: 1.83 dB @ 25 GHz, 2.42 dB @ 35 GHz, 4.66 dB @ 45 GHz, and 3.88 dB @ 55 GHz. These cumulative losses result in a lower-than-expected electrical driving power being delivered to the pads, consequently leading to a reduced effective voltage ( $V_{\text{eff}}$ ) below 2 V. In accordance with the transmitter DSP and the measured S21 parameters of the RF chain, we simulated  $V_{\text{eff}}$  at various data rates via inverse Fourier transform, yielding the values of 1.80 V @ 50 Gbps, 1.65 V @ 70 Gbps, 1.54 V @ 90 Gbps, and 1.42 V @ 110 Gbps, as shown in Fig. S9e–h.

Furthermore, on the basis of the S21 parameters obtained from bandwidth measurements performed with the PCNC modulator, although optical peaking enhancement significantly increases the 3-dB EO bandwidth of the modulator, it concurrently increases the low-frequency IL of the S21 response. In the frequency domain, this additional low-frequency attenuation leads to power degradation, which directly reduces the dynamic ER in the time-domain eye diagram. By combining the transmission spectra under various voltage biases and the S21 characteristics of the PCNC modulator with the simulated  $V_{\text{eff}}$ , we further simulated the dynamic ER at various detuning points and data rates, as shown in Table S2. Specifically, the simulated eye diagrams of the modulated optical signals at the –3 dB detuning point are shown in Fig. S9i–m. On the basis of the simulated eye diagrams, the dynamic ER at the transmitter was observed to decrease to approximately 1 dB during the high-speed data generation experiment. Further degradation occurred because of the receiver's frequency response, ultimately yielding a measured ER below 1 dB at the receiver output. Similar dynamic ERs have been reported in Ref.<sup>11,12</sup> by using the MZM configuration.

Notably, the proposed device achieves near-theoretical-limitation performance with the design scheme. For practical applications requiring long-distance transmission, high transmission capacity, and low BERs, the device validated in this work can be further optimized in future work. First, by side-coupling the PCNC with a bus waveguide, a notch-shaped transmission spectrum, similar to that of an MRR, can be achieved. This spectral profile has advantages in achieving higher ERs and can be used in wavelength-division multiplexing (WDM) systems to increase transmission capacity. Additionally, optimizing the design of the PCNC to increase the Q factor of the resonance peak provides a pathway for achieving higher dynamic ERs. However, this method of improving the Q factor requires significant optical power trade-offs when the EO bandwidth is extended, presenting a fundamental limitation in optimizing the device design.



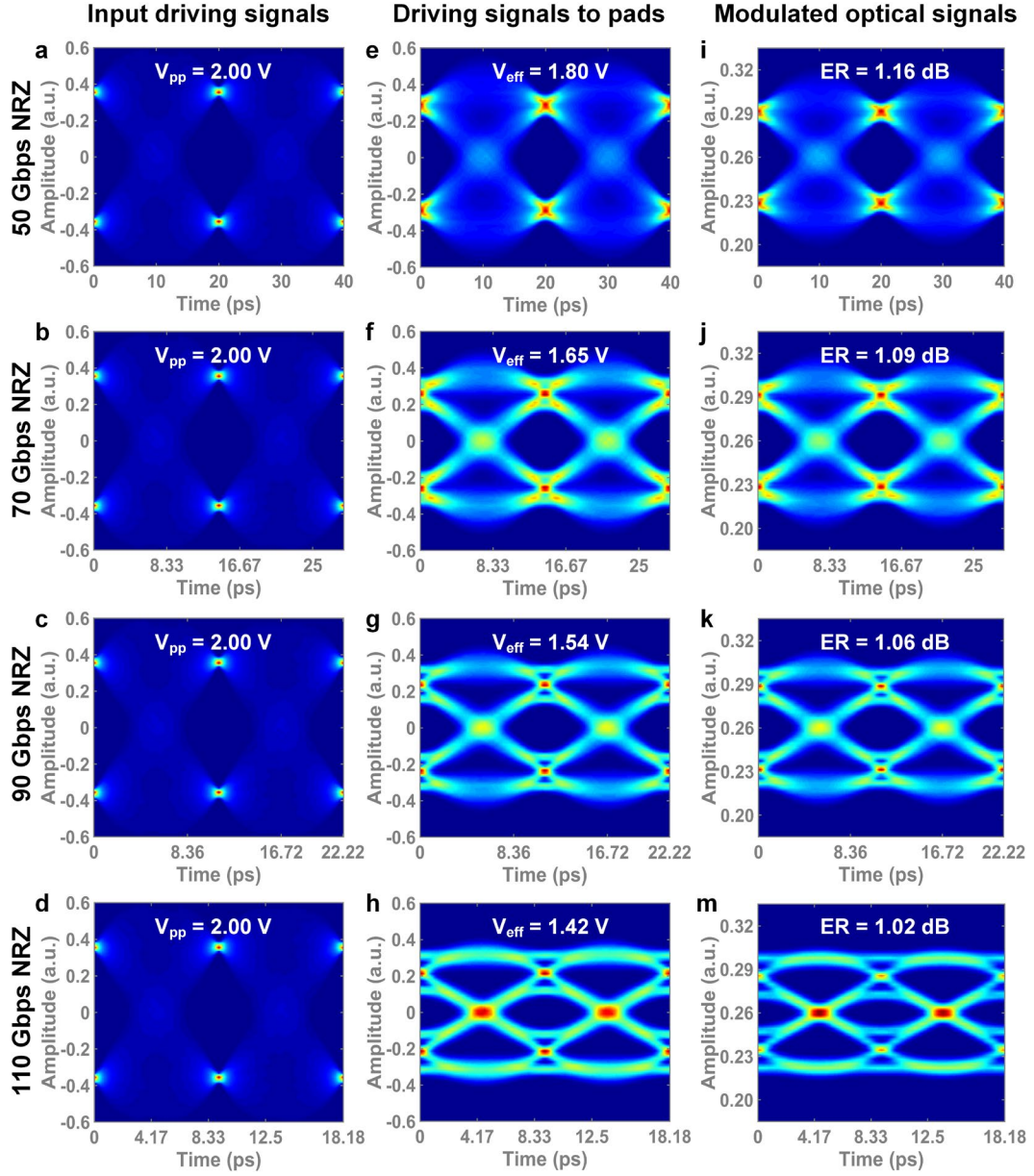
**Figure S8. High-speed data modulation and  $S_{21}$  parameter characterization.** **a** Experimental equipment for measuring optical eye diagrams. **b** Transmitter DSP flow charts. Eye diagrams for NRZ signals at data rates of **c** 50 Gbps, **d** 70 Gbps, **e** 90 Gbps, and **f** 110 Gbps.  $S_{21}$  parameters for the **g** EA (SHF S807C, Ref.<sup>8</sup>), **h** bias-Tee (SHF BT65R-B, Ref.<sup>9</sup>), **i** 30-cm RF cable (measured), and **j** high-speed RF probe (Ref.<sup>10</sup>), **k** unnormalized  $S_{21}$  of the RF chain, and **m** normalized  $S_{21}$  of the RF chain.

**Table S1. Detailed S21 parameters of the entire electrical driver chain, including the EA, bias-Tee, RF cable, and high-speed probe.**

| <i>Freq (GHz)</i><br><i>S21 (dB)</i> | <b>5</b> | <b>10</b> | <b>20</b> | <b>25</b> | <b>35</b> | <b>45</b> | <b>55</b> |
|--------------------------------------|----------|-----------|-----------|-----------|-----------|-----------|-----------|
| <b>EA</b>                            | 23.1     | 24.1      | 23.4      | 23.1      | 22.8      | 22.1      | 22.5      |
| <b>Bias-Tee</b>                      | -0.6     | -0.62     | -0.71     | -0.60     | -0.60     | -0.67     | -0.87     |
| <b>RF Cable</b>                      | -0.56    | -1.18     | -1.60     | -1.66     | -2.01     | -3.30     | -2.75     |
| <b>Probe</b>                         | -0.16    | -0.23     | -0.32     | -0.41     | -0.43     | -0.56     | -0.55     |
| <b>Total</b>                         | 21.78    | 22.07     | 20.77     | 20.43     | 19.76     | 17.57     | 18.33     |

**Table S2. Simulation results for dynamic ER at various detuning points and data rates.**

| <i>Data rates (Gbps)</i><br><i>Detuning points</i> | <b>50</b> | <b>70</b> | <b>90</b> | <b>110</b> |
|----------------------------------------------------|-----------|-----------|-----------|------------|
| <b>-1 dB</b>                                       | 1.27 dB   | 1.17 dB   | 1.09 dB   | 1.00 dB    |
| <b>-2 dB</b>                                       | 1.20 dB   | 1.13 dB   | 1.08 dB   | 1.03 dB    |
| <b>-3 dB</b>                                       | 1.16 dB   | 1.09 dB   | 1.06 dB   | 1.02 dB    |



**Figure S9. Simulated time-domain eye diagrams at various data rates. a–d** Input electrical drive signals. The unclear transient patterns are introduced by Nyquist pulse shaping. **e–h** Electrical signals after they pass through the external RF chain. **i–m** Modulated optical signals at the detuning point of -3 dB.

**Comment 2:**

*Second, the energy-per-bit calculation still employs the full  $2 V_{pp}$  applied at the probe tips, even though your own explanation for the low ER presumes a much smaller effective swing at the device terminals. By continuing to quote 5.9 fJ/bit without an experimentally validated  $V_{eff}$ , the manuscript presents mutually inconsistent statements: a large, unquantified RF attenuation is invoked to explain the ER, yet the energy figure silently ignores that same attenuation. Simply noting that a careful study of  $V_{eff}$  is “future work” does not resolve the contradiction; it leaves the central efficiency metric misleading and unverifiable.*

**Response 2:**

We sincerely appreciate the reviewer's comments regarding the power consumption calculations. The power consumption formula we adopted is a benchmark calculation method used for optoelectronic devices<sup>1-5</sup>. When evaluated at a  $2 V_{pp}$  operating voltage, this methodology provides an upper-bound estimation of the modulator's intrinsic power consumption without considering the RF chain loss. We calculated the power consumption using  $V_{eff}$ , which was simulated using the experimentally measured S21 responses of the external RF chain and included a discussion in Supplementary Information Note VI.

- [1] Dubé-Demers, R., LaRochelle, S. & Shi, W. Ultrafast pulse-amplitude modulation with a femtojoule silicon photonic modulator. *Optica* **3**, 622-627 (2016).
- [2] Yuan, Y. et al. A  $5 \times 200$  Gbps microring modulator silicon chip empowered by two-segment Z-shape junctions. *Nat. Commun.* **15**, 918 (2024).
- [3] Miller, D. A. B. Energy consumption in optical modulators for interconnects. *Opt. Express* **20**, A293-A308 (2012).
- [4] Hsu, WC., Nujhat, N., Kupp, B. et al. Sub-volt high-speed silicon MOSCAP microring modulator driven by high-mobility conductive oxide. *Nat. Commun.* **15**, 826 (2024).
- [5] Geravand, A., Zheng, Z., Shateri, F. et al. Ultrafast coherent dynamics of microring modulators. *Nat. Photon.* **19**, 740–750 (2025).

In Supplementary Information Note VI:

By using the simulated  $V_{eff}$ , as detailed in Supplementary Information Note V, the calculated power consumption tends to decrease with increasing data rates: 4.78 fJ/bit @ 50 Gbps, 4.02 fJ/bit @ 70 Gbps, 3.50 fJ/bit @ 90 Gbps, and 2.97 fJ/bit @ 110 Gbps. Under ideal conditions with RF losses excluded, the intrinsic power consumption of the proposed modulator reaches an upper bound of 5.9 fJ/bit. Notably, the RF amplifier accounts for a major portion of the power consumption in the transmitter<sup>11</sup>.

**Comments from Reviewer #3:****Comment 1:**

*Although the authors have answered the reviewer's questions, there still are several points that need to be clarified. The main concern in the current manuscript is that the physical effect of the slow light is not described in sufficient detail.*

- (a) *Firstly, could the authors describe the physical meaning of Eq. (4) especially in connection with the tuning efficiency in unit [pm/V]?*
- (b) *Also, it is required to explain the reason why the sum was taken from -5 to 5, and whether the mirror region is included or not. Since the edge of the taper region should have very large  $n_g$ , which may go infinite, Eq. (4) may diverge in that case. Moreover,  $n_g$  cannot*

be obtained in the mirror region. Because Eq. (2) from Ref. 23 is derived for the waveguide-type modulator, mathematical derivation of the accumulated phase for Fabry-Perot (FP) cavity would be required.

- (c) In addition, it is required to describe the physical meaning of using the slow-light effect. In single-pass devices such as waveguide modulators, the slow-light effect may be the only way to enhance the light-matter interaction with fixed length. However, in multi-pass devices such as FP cavities, the light reflects between mirrors, and the light-matter interaction is enhanced even without the slow-light effect. Therefore, to enhance the light-matter interaction in FP cavities, there would be at least two ways: One is to increase the reflectance of the mirrors, and another is to use the slow-light effect. These explanations would be required in the manuscript to clearly state the physical meaning of the slow-light effect in the proposed device.

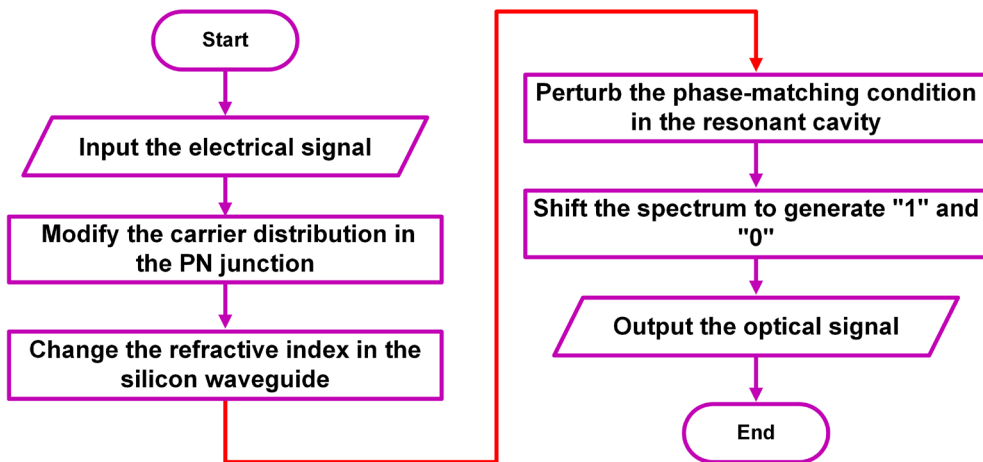
**Response 1:**

- (a) Eq. 4 quantifies the phase accumulation within the resonant cavity. In FP cavities, the resonance wavelength is fundamentally governed by the phase-matching condition, whose sensitivity to the material's refractive index varies with cavity design parameters.

For modulators, the input is an electrical voltage signal, while the output is an optical signal. In resonance-based silicon modulators, signal modulation arises from spectral shifting, as illustrated in Fig. R1. The applied voltage modulates the carrier distribution in the PN junction, inducing refractive index changes that perturb the cavity's phase-matching condition. This phase-matching perturbation directly controls the resonance wavelength shift, which is our primary optimization target.

The [pm/V] tuning efficiency precisely characterizes how effectively the electrical signal perturbs the phase-matching condition. We achieve increased sensitivity through the engineered slow-light enhancement effect, as shown by the red solid curve in Fig. R1. Moreover, the [pm/V] tuning efficiency has been widely adopted as a standard metric for characterizing device modulation performance, as shown in Table 1 of the manuscript.

We contend that the existing discussion (Lines 84–90) adequately captures this physical mechanism.



**Figure R1.** Schematic illustration of the physical principles of the resonant modulator. The red solid curve indicates the slow-light enhancement effect in this study.

Lines 84–90: With the slow-light enhancement in the resonant cavity, the inherently weak light–matter interactions are significantly amplified, yielding a 3.36-fold improvement in phase detuning compared with conventional silicon rib waveguide cavities in our simulation, which were designed with identical waveguide width, length, and slab thickness. Importantly, the slow-light effect amplifies the phase shift per unit voltage rather than directly altering the material’s electro–optic properties. This enhancement, combined with an appropriate doping concentration provided by the commercial foundry, enables a tuning efficiency of 80 pm/V for our optimized PCNC.

(b) The range of  $-5$  to  $5$  corresponds to the 10 linearly graded lattice periods on each side in our design, where some lattices exhibit a photonic bandgap at the target wavelength. Our analysis specifically considers the phase accumulation from in-band lattices within the cavity region, explicitly excluding contributions from the mirror regions. To increase clarity, we have incorporated a detailed discussion of this methodology in the manuscript and provided comprehensive theoretical derivations in Supplementary Information Note VII.

Lines 155–160: Thus, in such a designed PCNC, the total phase accumulation can be derived as follows:

$$\phi = \eta \cdot \frac{2\pi}{\lambda_0} \cdot \sum_{i=-5}^5 n_g(i) \cdot p(i) \quad (4)$$

where  $n_g(i)$  and  $p(i)$  are the group index and period of the  $i$ -th cell of the PCNC, respectively. Notably, the summation range is determined by the specific energy bands and bandgaps of the device (detailed in Supplementary Information Note VII).

The following can be found in Supplementary Information Note VII:

The accumulated phase detuning in the slow-light waveguide is proportional to the group index  $n_g$ , as described by<sup>13</sup>:

$$\phi = \eta \cdot n_g \cdot L \cdot \frac{2\pi}{\lambda_0} \quad (S19)$$

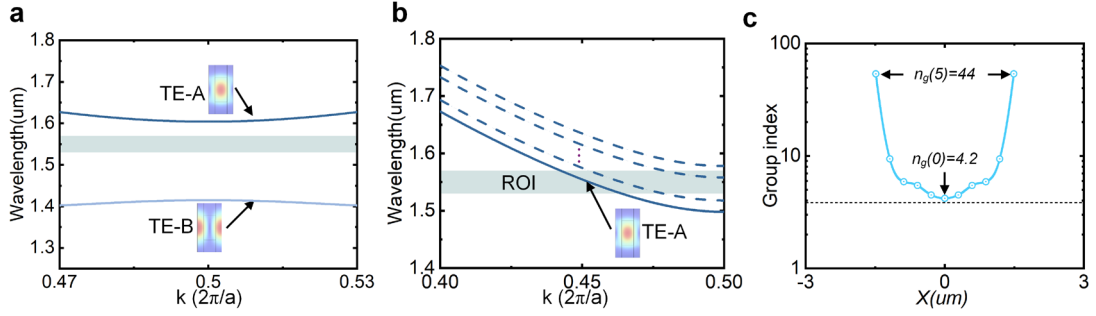
where  $\eta = \eta_0(\sqrt{V + V_{bi}} - \sqrt{V_{bi}})$ , with  $\eta_0$  being a coefficient related to the overlap between the carriers and the optical field;  $V_{bi}$  is the built-in voltage of the PN junction;  $V$  is the applied voltage of the modulator; and  $L$  is the optical travel length.

The proposed PCNC structure incorporates a slow-light region with linearly graded lattice periodicity. In this design, each unit cell exhibits a unique group refractive index  $n_g$  and lattice length  $L$ , thereby leading to the derivation of Eq. S19 as an integral over the slow-light region:

$$\phi = \eta \cdot \frac{2\pi}{\lambda_0} \cdot \int_{cavity} n_g(x) dx \quad (S20)$$

The slow-light cavity behaviour is fundamentally governed by the engineered energy bands and bandgaps, as evidenced in the band diagrams of both the mirror and slow-light regions, as shown in Fig. S10a–b, respectively. The progressive light slowing effect within the resonant cavity is shown in Figure S10c, with a group index range of  $4.2 \leq n_g \leq 44$ . For reference, the dashed line indicates the group index of  $n_g = 3.9$  for a conventional silicon rib waveguide cavity (with identical waveguide width, length, and slab thickness design). Notably, unit cells with  $i > 5$  and  $i < -5$  fall within the photonic bandgap at the target wavelength and are consequently excluded from the integration domain. Thus, Eq. S20 is derived as follows:

$$\phi = \eta \cdot \frac{2\pi}{\lambda_0} \cdot \sum_{i=-5}^5 n_g(i) \cdot p(i) \quad (\text{S21})$$



**Figure S10.** Band diagrams of **a** the mirror regions and **b** the unit cell in the taper regions. **c** Group index  $n_g \geq 4.2$  within the cavity along the x-axis. The dashed line indicates the group index of a conventional silicon rib waveguide for comparison.

(c) We sincerely appreciate the reviewer's insightful comments. The reviewer is correct in noting that in FP cavities, light-matter interactions can be enhanced by increasing the reflectance of the mirrors and by introducing the slow-light effect. In response to this valuable comment, we have expanded the manuscript to include a detailed discussion explaining how our design incorporates a carefully engineered slow-light region to synergistically combine both enhancement mechanisms.

Lines 160–164: In contrast to conventional Fabry–Pérot (FP) cavity modulators that depend exclusively on mirror reflectivity for optical enhancement, our design incorporates an engineered slow-light region to combine both enhancement mechanisms: the FP resonance boosts light-matter interaction through recirculating passes, and the slow-light structure offers enhancement by extending the effective interaction length<sup>50,52</sup>, leading to increased tuning efficiency.

**Comment 2:**

Secondly, could the authors describe the meaning of the red arrow in Fig. 2(c) shown as “80 pm/V @ -3V”? Because the unit of the x-axis [um], the unit [pm/V] is unmatched.

**Response 2:**

The expression “80 pm/V @ -3 V” indicates that the tuning efficiency of the device is 80 pm/V under a bias voltage of -3 V. The tuning efficiency is defined as the spectral blueshift or redshift per unit voltage. In our device, as the voltage changes from -2 V to -4 V, the spectral redshift is approximately 160 pm. Therefore, we calculate the average tuning efficiency using  $\Delta\lambda/\Delta V = 160 \text{ pm}/2 \text{ V} = 80 \text{ pm/V}$  to describe the tuning efficiency of the device as 80 pm/V at a bias voltage of -3 V.

Lines 197–199: At a reverse bias voltage of -3 V, the tuning efficiency was approximately 80 pm/V. This value was obtained from a 160 pm spectral redshift measured from -2 V to -4 V, corresponding to a  $V_\pi \cdot L$  product of  $\sim 0.38 \text{ V} \cdot \text{cm}^7$ .

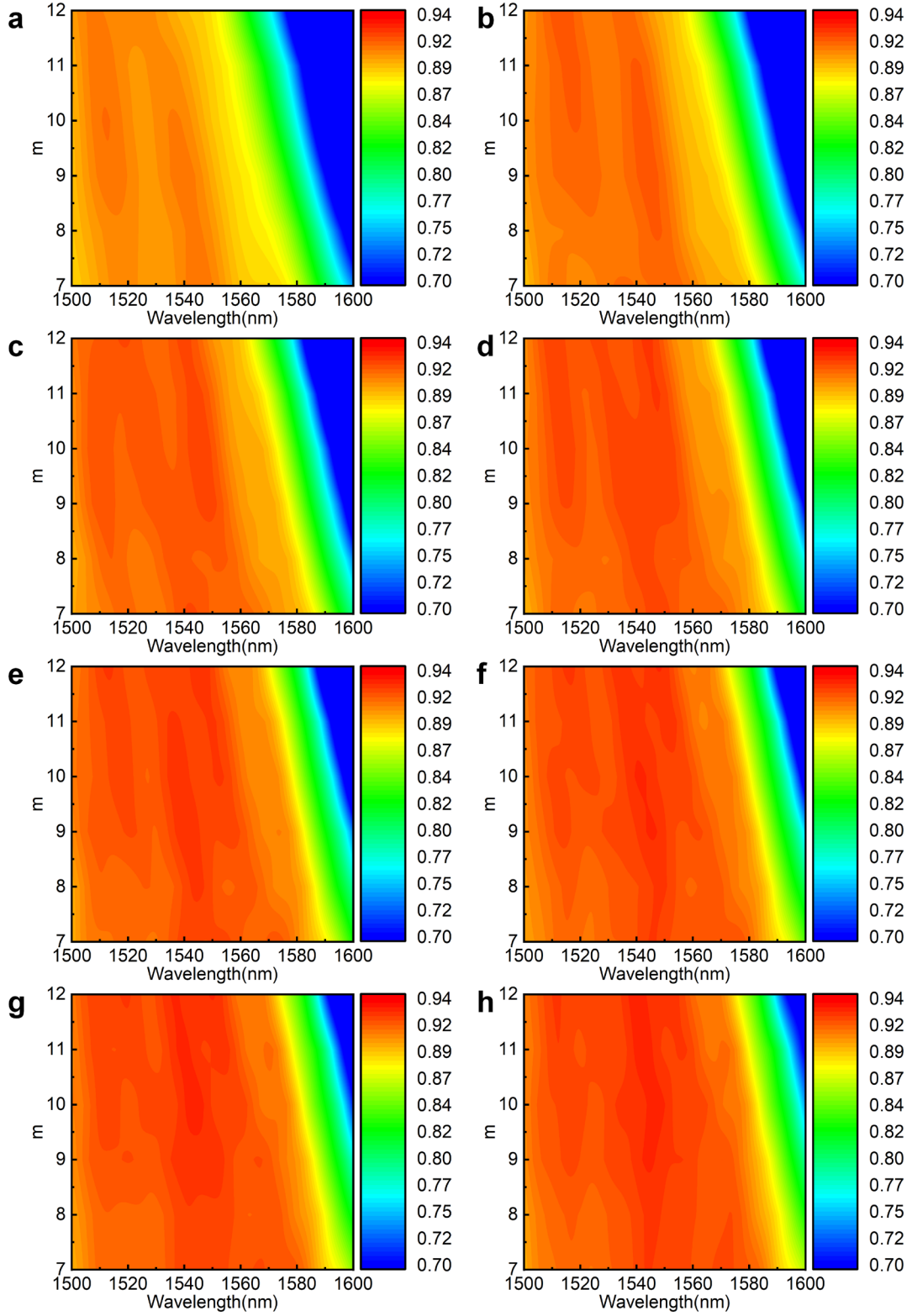
**Comment 3:**

Thirdly, in supplementary Section III, the authors have shown the optimization process. However, it is unclear what objective function was employed. If we see Fig. S5(g) and (h), the star symbol is plotted, but it is unclear why the plotted point is optimal. Specifically, there seems to be higher reflectivity in the region to the right of the star symbol in Fig. S5(g).

**Response 3:**

We appreciate the reviewer's careful observation of our optimization methodology in Supplementary Information Note III. In fact, our optimization was not governed by a single objective function but rather guided by two critical design criteria: maximizing the reflectivity at the target wavelength and maintaining a compact footprint. The simulation results of our device parameter optimization process are shown in Figure S5. Reflectivity is vital for the design of PCNC, which directly determines the Q factor, and it varies with wavelength, as shown in Figs. S5a–f.

With respect to Fig. S5g, we use the reflectivity at 1550 nm; thus, the reflectivity in the region to the right of the star symbol in Fig. S5(g) seems to be higher. We understand that this may have confused the readers. To address this concern, we have added detailed simulation results to Fig. S6. On average, the reflectivity is greater when  $m = 10$  than when  $m = 11$  or 12.



**Figure S6. Detailed simulation results for the PCNC design.** Simulated reflectivity in the wavelength range of 1500~1600 nm for  $m = 7\sim 12$  and  $n = \text{a } 13, \text{ b } 14, \text{ c } 15, \text{ d } 16, \text{ e } 17, \text{ f } 18, \text{ g } 19, \text{ and h } 20$ .

**Comment 4:**

*Finally, in the revised line 84-89 in the manuscript, it is unclear which structures were employed for the comparison. In particular, it was unclear whether the comparison was made with experimental results or simulations with what kind of settings.*

**Response 4:**

We appreciate the reviewer's question, and we understand that the original expression might confuse readers. Therefore, we have revised the related description of the comparison as follows:

Lines 84–87: **With the slow-light enhancement in the resonant cavity, the inherently weak light–matter interactions are significantly amplified, yielding a 3.36-fold improvement in phase detuning compared with conventional silicon rib waveguide cavities in our simulation, which were designed with identical waveguide width, length, and slab thickness.**

Lines 148–151: **As shown in Fig. 1f, light is progressively slowed within the resonant cavity with a group index of  $4.2 \leq n_g \leq 44$ . For reference, the dashed line indicates  $n_g = 3.9$  for a conventional silicon rib waveguide cavity with identical waveguide width, length, and slab thickness design.**

Thank you again for your consideration.

Sincerely,

Hua Zhong & Yikai Su

On behalf of all the authors

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