

Unifying Optical Gain and Electro-Optical Dynamics in Er-doped Thin-Film Lithium Niobate Platform

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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 work demonstrates optical gain and intensity and phase modulation in erbium-doped thin film lithium niobate waveguides. High gain is shown at 1531nm (38 dB) and low noise figure (4.3 dB). RF operation up to 170 GHz is shown, including demonstrations of broadband electro-optic conversion and analog RF receiving with an 8-12 GHz FMCW signal, both using an amplified on-chip waveguide. The combination of high gain with low noise and high-speed electro-optic modulation on a monolithic thin film lithium niobate chip is novel and of interest to the integrated photonics community. Below are some comments to be addressed:

- The prior art has not been fully addressed, specifically bulk lithium niobate chips. See the work of Sohler et al., (for example Suche et al., IEEE Photonics Technology Letters 7, 505, 1995, where phase modulation and erbium gain are both shown on a lithium niobate chip). It is also suggested to change the title accordingly, e.g. specifically referring to thin film lithium niobate, or LNOI.
- The doping is quite high and might introduce extra background loss. How does the loss compare to undoped LNOI MM waveguides?
- Why is the coupling loss so high? Can't inverse tapers be used to get significantly lower coupling loss?
- Fig. 3b is missing the pump/no signal spectrum (i.e. ASE) to properly assess the gain and proper pump background/ASE in the gain calculation
- It shows that an optimal balance is achieved with low optical loss and minimal microwave loss as the oxide layer thickness is set to 1 μm -> is this true? Isn't it a bit better at $> 1\mu\text{m}$?
- Page 5: "Highest gain..." The gain is impressive but highly wavelength dependent (as shown in Fig. 3c). Most applications (WDM systems, tunable lasers, etc.) require amplification over a broad wavelength range. A better wording might be highest single wavelength gain. Table 1 in the supplementary material should also include the wavelength the gain is measured at and pump wavelength for better comparison. More importantly, the high gain in this system at the peak emission wavelength should be justified. Is this typical for lithium niobate? If so, why? Under 1480nm in-band pumping of Er, the inversion is lower and the gain is usually flatter. See for example ref [24] where the gain is lower near 1530nm.
- Page 5: it is stated that the gain saturates, but higher pump power could provide more gain which seems to be contradictory
- More details on the parasitic lasing, at what pump power and gain it sets in, etc. should be provided.
- The saturation output power of the waveguide amplifier...on-chip signal power." This statement seems to be describing external saturation, so the on-chip part is confusing in the explanation.
- Fig. 5: What is the 100 kHz showing in the inset of Fig. 5a. This should be stated in the caption. There are several sidebands in Fig. b that should be explained, especially in terms of the levels indicated in the SNR measurements. It should also be stated and/or shown where the EDFA is in the setup figure.
- The lifetime is compared to commercial silica fiber amplifiers, but what about lithium niobate? Is the lifetime similar to prior lithium niobate measurements and what is expected in theory for this host? The higher n host would typically lead to a shorter lifetime.
- The noise figure measurement needs more justification: Was the noise figure measurement qualified with a commercial amplifier? This should be stated to ensure the method is accurate here. The measurement of noise 0.4 nm from the peak would seem to underestimate the noise figure, given ASE would be strongest at the peak where the gain is measured.
- The cross-sections in Fig. S5 look abnormal and perhaps mixed up in the legend. The shape seems strange particularly compared to the gain with 3 peaks in Fig. 3c (and see gain spectra with 3 peaks in Brinkman IEEE Journal of Quantum Electronics 30, 2356, 1994). It looks like the blue cross section is not tending to 0 around 1600nm as expected from the gain measurement and there is perhaps a systematic DC offset due to the measurement method.

- Conclusion:
 - o highest gain should be qualified as single wavelength
 - o again details of the parasitic lasing are mentioned but not explained
 - o 1400nm – Nd, is 1.3μm band meant? And has gain been shown in Dy-doped lithium niobate? (normally specialized low phonon host materials are required)
 - o slow light -> what about the high losses usually associated with such waveguides, which would affect the gain?
- Some additional details would help in several places, including:
 - o Providing the typical bend radius of ridge lithium niobate waveguide in the text for easy comparison
 - o What is the signal and pump polarization used? What is the polarization dependent (TE vs. TM) loss and gain?
 - o Page 3: distancing the microwave field from the high index layer – lithium niobate? Why?
 - o What are the fits in Fig. 3? (should state in caption). Also, high input signal power -> state power
 - o Page 6: a signal enhancement of 30 dB is given but what is the gain?
- Formatting:
 - o Figure 1 is somewhat redundant, and doesn't add much to what is already shown in the other panels. It is suggested to remove it or to improve the overall presentation by adding it as a part a panel in figure 1 (the current part a figures can be shifted to the right).
 - o Parts i – iv are listed out of order in fig. 2
 - o "Mod." short form unnecessary in Fig. 4/caption
- The wording should be adjusted in some places to adhere to normal scientific style, examples are below:
 - o "impressive performance" in abstract
 - o "electro-optic operation" in abstract – be specific
 - o "unprecedented" in abstract
 - o Page 3: fatal blocks
 - o Page 3: indicating additional loss of pump light
 - o Page 3: Delicate adiabatic
 - o Fig. 3 caption: intensely pumped
 - o Page 4: which is intuitive -> remove
 - o Generally, the net gain dynamically changes... -> too general/obvious – consider rewording
 - o Page 6: delicately
 - o Etc.
- The manuscript requires another careful check of English, some examples are below:
 - o Fig. 2 caption: an sine wave
 - o Page 3: is adopt
 - o Fig. 3 caption: Optical spectra of signals output
 - o Page 4: As the electrode apart
 - o Page 4: A optical spectrum analyzer
 - o Page 7: analogy RF
 - o continuous wave (FMCW) -> word missing
 - o in frequency domain
 - o the spectroscopy is obtained
 - o the increasement
 - o Etc.

Reviewer #2

(Remarks to the Author)

Dear Authors,
Dear Editor,

I have carefully read and analyzed the paper titled "Unifying Optical Gain and Electro-Optical Dynamics in Er-doped Lithium Niobate Platform" and the supplementary information provided with the manuscript.

The authors describe in detail the fabrication, design, and characterization of a photonic chip that utilizes a thin-film erbium-doped lithium niobate layer. The photonic chip contains both an amplitude modulator used for on-off keying (with a length of 8 mm) and a phase modulator used for FMCW style modulation, combined with a 6 cm long amplifier spiral. In figure 2, the modulator design is discussed together with a photoluminescence spectrum from the waveguide. In figure 3, the amplification of a single laser line is presented and discussed. In figure 4, the authors present the modulator devices together with the results of a 50 Gbps on-off keying system experiment. It also includes optical spectra of a high-RF-frequency phase-modulated optical carrier. Finally, in figure 5, the modulation of a laser line with an FMCW signal is presented. In the discussion, ways for further improvement of the performance metrics are given and possible future applications are presented. In the supplementary information, the authors present additional technical details on the measurements they performed and the simulations that were used for the device design.

The results presented in the paper are interesting and highly relevant given the fast-moving field of photonic integration, with many recent advances in both thin-film lithium niobate and rare-earth doped waveguides. Moreover, the figures that present the results are highly detailed and very well thought through, with great attention to visual clarity. In general, the paper presents interesting results with excellent graphics.

My main comment is that the writing is sometimes not fully clear, and in many sentences, hard-to-understand phrasing is used. I would recommend that the authors try to rewrite the text to improve this issue. Some examples of the language issues:

Page 3: Fig. 2. a(iii) "Pseudo color picture images..." — it is my understanding that this is a false-color SEM image?

Page 3: "... is the most fatal blocks compared with..."

Page 3: "... height of 600 nm is adopt to decrease ..."

Page 3: "...waveguide with a fully-etch process..."

Moreover, in general, I would comment that the way the text is written can be improved to make the technical results clearer.

I would recommend the manuscript for publication with several, in my opinion mandatory, improvements:

1. Can the authors clarify why this electrode geometry was chosen exactly? If I understand correctly, the lithium niobate modulators realized in 2018 had a much smaller VpiL (see for example <https://doi.org/10.1038/s41586-018-0551-y>).
2. Given that the performance of the amplifier relies also on the in- and outcoupling, can the authors comment on why facets with relatively high losses were used?
3. What are PC fibers? (Fig. 3 a)
4. Please clarify what you mean exactly by net internal gain when you first introduce the term in the text. What exactly does this include and exclude?
5. In most of the experiments, measurements are performed with and without pump. It is sometimes unclear to me what conclusions can be taken from this. As erbium is a 3-level system, the signal will be heavily absorbed when there is no pump present. Therefore, comparing the signal strength with and without the pump laser does not provide information on amplification. Can the authors clarify what model they use exactly to infer the amplification from these experiments?
6. Can the authors clarify what exactly they expect for the EO S21 as shown in Fig. 4(c)? As I understand it, this just implies that the light was amplified. Or is it expected that the pump would somehow influence the shape of the EO S21?
7. Please add a very detailed set-up description to the supplementary information where the exact power level is described at each point in your set-up, so it is easier to understand how the numbers used are calculated.
8. I think for the experiments shown in Fig. 3(f) and Fig. 4, the comparison of with and without pump is not very relevant. When not pumped, the 6 cm spiral will strongly absorb the signal light. The correct comparison would be with and without the amplifier waveguide if the authors want to demonstrate amplification. Can the authors comment on how they would improve this experiment to extract the amplification from the spiral? Moreover, the change in SNR with and without pump in Fig. 5(b) is also not relevant, as without pump the signal is absorbed by the amplifying waveguide. I would ask the authors to explain why they chose this approach.

Reviewer #3

(Remarks to the Author)

The authors present what they believe to be the first integrated modulator-amplifier in LNOI, a material platform that has garnered significant attention in recent years due to its excellent modulation capabilities. The integration of modulation and amplification opens the door to promising developments, such as lossless modulators and other advanced photonic building blocks. However, the reviewer remains uncertain about the platform's potential for developing complex PICs, as suggested by the authors. The need for erbium doping necessitates circuit-wide pumping, which could be undesirable and lead to unnecessarily high power consumption. That said, this concern is speculative and will only be clarified with further research. Overall, the reviewer finds the work presented in this manuscript worthy of publication in Nature Communications, particularly after addressing the comments outlined below, which aim to further enhance the quality of the paper.

In the abstract the authors mention the NF of 4.3 dB, which is really good. Please, specify whether this is internal or external (fiber-to-fiber).

Page 1 second column: please, clearly state that the 30dB of net gain in reference 24 is "internal" net gain. Overall, please try to be very concise and specify whether a gain is internal or fiber-to-fiber. The same with the powers, state very clearly whether they are on-chip or off-chip. This will enhance the readability of the paper and the understanding of the reported measurements. Adding to this comments, the authors mention the 30 dB in reference 24 as the highest internal net gain reported (or one of the highest), while as they show in the Table comparing the different erbium amplifiers in the supplementary materials, Bonneville et. Al, have shown an even higher internal net gain. Maybe rewrite a bit the sentence to include both references.

In Page 2 first paragraph the authors write: "Furthermore, these systems still face challenges, including relatively high waveguide loss, inherent amplification noise, and significant nonlinearity, which limits performance, especially in applications that demand high fidelity and low crosstalk". Please, compare the non-linearity and expected performance between the silicon platform and the LNOI platform. The LNOI is highly non linear. Please, explain why the LNOI is expected to behave in a better way in terms of non linear effects, signal distortion and power handling.

In Page 2 second paragraph, the authors refer to other materials with limited optical properties. It would be good to specify which material the authors refer to and also what lack of properties they refer to. The LNOI is proposed as a great material thanks to it high n and EO coefficient. What about the non linear properties (χ^2 and χ^3), which can lead to signal distortion etc? Als what about the power handling? Please, comment.

The authors report a background loss of 0.4dB/cm, and they mention that it is very low. However, it is much higher than in other amplifier materials (see ref. to the Liu et al Science paper). Please, comment.

At the end of the introduction the authors propose this platform as a better platform for complex PICs. However, as I mentioned above, the necessity to having to pump the whole system can lead to an excessive power consumption. Also, as systems get larger and more complex, it adds complexity to ensure a good level of pumping all along the devices. It would be good if the authors revise this claim and sharpen the application space for the building block proposed in the manuscript.

In the second page second column, the authors mention the erbium concentration of 0.5% mol. Would it be possible to convert it also to at.% and ions/cm³? Those are two metrics that used in the EDFA literature and it will facilitate the reader to compare different amplifier designs easier. Also, how was the concentration of erbium measured?

The authors mention: "... exhibiting stimulated radiation of Er³⁺ ions". The erbium ions are not stimulated emitted, what is emitted are photons. It would be good to rephrase the sentence.
Figure 2(c): please, add the PL spectrum from 1460nm (or below that even) to 1640nm (at least). This will enable to see the full range of emission of the erbium ions.

Figure 2(f): Why is the signal at 1600nm? Can you please add the signal in the C-band (eg. 1532nm or 1550nm?).

Page 3 paragraph 1: the lifetime was "calculated". However, this introduces too many unnecessary errors. It would be desirable to directly measure the lifetime. Please, add this experimental measurement to the manuscript.

The authors write: "For efficient amplifiers in the integrated Er:LNOI platform, the background loss, especially the scattering loss, is the most fatal blocks compared with their fiber-based competitor." The words: "fatal blocks" are not very understandable.

Although the reviewer understands that larger cores will lead to higher gain, how is the multimode behavior handled in the rest of building blocks? Eg., MZI modulators? Mode conversion in the bends?

Reference 40: "Gaafar, M. A. et al. Femtosecond pulse amplification on a chip. arXiv preprint arXiv:2311.04758 (2023)."

Should be changed by the journal publication in Nature Communications.

The authors write: "Figure. 2b shows the measured loss of amplifiers with different lengths with the off-chip input signal power of 4 mW". The loss in erbium doped waveguides should be measured for very small launched signals, in the uW region, as otherwise variations in the ground state population will result in variation of the propagation losses. As the signal power increases, the losses should decrease till a saturable absorption. The same happens at the pump wavelength. It would be good to see the loss measured at very small signals and also the scan of the losses as a function of signal power and pump power till reaching saturation.

In page 3 the authors write: "For moderate modulation efficiency, the electrode gap is set to 3.5 μm ." Why do they choose to go for "moderate" EO efficiency instead of "high"?

The authors write: "Generally, the net gain dynamically changes under different pump powers". Does it not happen always? What case are the authors thinking about to say "Generally"? It would be good to explain in the manuscript.

The authors write: "The internal net gain increases with the pump power, which is intuitive". I believe this is not "intuitive" but represents the physics of the device.

Figure 4 (f): On-chip or off-chip?

The authors write: "Significantly, the highest on-chip net gain under 115 mW off-chip pump power is around 38 dB (with the consideration of 2.9 dB fiber link loss and 6.7 dB/facet coupling loss, as shown in Fig. 3b) in the 9.16 cm waveguide amplifier, corresponding to an average gain of 4.1 dB/cm": please, indicate that it is at 1531nm (it is in the figure, but it would be good for clarity and precision to also write it in the text).

In figure 3 (c), the gain saturates with pump power. However, in the text the authors mention that they can get more gain by pumping harder. It think it would be good to add an explanation.

The authors write: "When the pump light is turned off, the on-chip loss decreases the output optical power to -27 dBm, resulting in a detected SNR of less than 5 dB, as depicted in Fig. 5b(i). The low SNR prevents the extraction of the instantaneous frequency. With the pump light, the output signal is boosted to -12 dBm, resulting in a SNR >15 dB. A clear FMCW signal is observed in Fig. 5c(ii). For comparison, the output signal without pump light is amplified to -12 dBm using a commercial EDFA" The reviewer is not sure whether this comparison makes sense: the SNR ratio increases when pumping. When not pumped, the losses of the circuit are high. It makes sense that the performance improves with pumping. In the opinion of the reviewers the good comparison should be with an undoped modulator in LNOI amplifier by an EDFA. Can this comparison be made/ Otherwise, the reviewer is not sure whether the proposed comparison by the authors is relevant.

In Figure S1d the authors show results from the erbium model. However, it is necessary to show how the model fits the experimental data to ensure that it is correct. Can the authors add a graph showing how the model fits the experimental data? Ideally for different amplifier lengths, signal powers and erbium concentrations.

In page 3 of the supplementary information, the authors mention parasitic lasing. Do they authors do anything to prevent it in the design?

In Figure S2 a Cr mask is used. In Figure S3 a PR mask is used. Why?

In Figure S4c, please keep increasing the signal power, since it is supposed to go to saturate at the background loss and it did not happen yet in the figure.

In Figure S5, why is the absorption cross-section in the C-band higher than the emission? Also, it would be good to extend the wavelength range to cover the spectrum till both ends of the PL band. Finally, why does the PL spectrum do not resemble a typical erbium emission/absorption cross-section spectrum? Please, add an explanation in the paper.

Version 1:

Reviewer comments:

Reviewer #1

(Remarks to the Author)

I have carefully reviewed the revised manuscript and response to reviewers. In my opinion, the authors have carried out a very careful and thoughtful revision of the manuscript and satisfactorily addressed almost all of my comments. However, there are still several remaining/additional comments for the revised manuscript and supplementary material that I believe are important to address before publication:

- Perhaps I am missing it and it has been indicated somewhere, but for Fig. S7a, the pump power used to obtain that ASE spectrum should be indicated

- *Most important: The gain equation outlined in the Methods section and response doesn't seem to be correct:

-> It mixes power units (dBm) and relative power units (dB) - it works out ok but it should be slightly revised.

-> Also the internal net gain should account for any on-chip loss. Therefore, as I understand it, the + L_{link} term should not be included in the G_{net} equation, and the reported internal net gain should be slightly (2.9 dB) lower (it doesn't affect the overall story, but the number should be correct). *But now as I read the corresponding description in the manuscript (page 5, bottom right), it seems to describe this as the fiber loss of the system, not the background loss as it seems to represent in the Methods description. It is important to clarify this.*

-> Also, I know it is a bit picky, but since the coupling might change slightly and the L_{coupling} term is important in the gain calculation (effectively adding a lot of internal gain - $2 \times 6.7 \text{ dB} = 13.4 \text{ dB}$ - when you add it into the equation because of the relatively high coupling loss), somewhere it should be stated how it was verified to be consistent for pump on and off measurements. Perhaps there is already a statement, but a single sentence ensuring consistency of the L_{coupling} term across gain measurements in the supplementary material would suffice.

-> Check the added text in Methods - L_{coupling} is repeated

- Fig. 1 caption - "picture": should perhaps indicate they are SEMs (perhaps this is indicated in the text though...I can see that simplifying language for an overview panel is helpful, just double check what is typical for such overview pictures)

- Response to Comment 18.10: The absorption cross-section for a given dopant ion and transition is an ion and host material property and can typically only be changed slightly by changing the host material...if another method is suggested it should be indicated.

- I believe it is important to clarify internal vs. external NF throughout because other recent works are referring to an external noise figure that accounts for fibre-chip coupling losses. The fiber-chip coupling loss is important for minimizing NF.

- Is the ion concentration really exactly 10^{20} cm^{-3} , or is it missing a number in front? 1×10^{20} is relatively low for EDWAs and given the typical (actually slightly lower than silica) cross sections in Fig. S5 doesn't seem to match with the high gain.

- Why are there thick bars for individual wavelengths in the PL spectrum in Fig. 2a? Also photo luminescence -> photoluminescence. And why does the spectrum cut off sharply before 1500nm - is this a setup artifact or truly the shape of the PL spectrum??? It does not seem to match the emission cross-sections in Fig. S5. This should be clarified. Furthermore, a statement with comparison to literature erbium-doped lithium niobate cross-sections should be included.

- Supplementary note 12: chirp -> chirped; and what is the spiral waveguide length and why does it introduce significant loss if the background loss is only 0.4 dB/cm?

Reviewer #2

(Remarks to the Author)

Dear authors and editor,

I have carefully reviewed the updated manuscript, supplementary information and response to the comments of the reviewers.

My concerns have been addressed by the authors and I find the manuscript almost ready for publication.

I especially appreciate that the authors extended the supplementary information with detailed setup and power level descriptions of the relevant experiments clarifying conditions for the readers of the paper.

It is my opinion that the paper represents an a very relevant and detailed technical work with interesting experiments and photonic integrated circuit design.

However, I do have a concern that the manuscript needs a final in depth review by the authors themselves to assure quality. For example in the supplementary information on page 4 the authors calculate the density of the ions which they find to be 10^{23} per cm^3 : "... is the Er^{3+} molar fraction, $\rho=4.64 \text{ g/cm}^3$ is the density of LiNbO_3 , $M=147.9 \text{ g/mol}$ is its molar mass, and $N_A=6.022 \times 10^{23} \text{ mol}^{-1}$

is Avogadro's constant. Substituting these values yields an Er^{3+} ion density of 10^{23} ions/ cm^3

."

This is clearly not correct and a quick calculation yields approximately $9 \times 10^{19} \text{ cm}^{-3}$ for the ion density. Please assure that this error is not propagated into the other parts of the manuscript, where the value for N_{Er} is not explicitly given.

Pending this minor correction and any associated updates, I recommend the manuscript for publication.

Version 2:

Reviewer comments:

Reviewer #1

(Remarks to the Author)

I really appreciate the authors' attention to detail and effort to address all the comments. I am satisfied with the responses and changes and recommend that paper can be published

Reviewer #2

(Remarks to the Author)

Dear authors and editor,

After examining the updated manuscript and the detailed response to the reviewers, I recommend this paper for publication.

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Response to the report from the Referee #1

General comments: *"The work demonstrates optical gain and intensity and phase modulation in erbium-doped thin film lithium niobate waveguides. High gain is shown at 1531 nm (38 dB) and low noise figure (4.3 dB). RF operation up to 170 GHz is shown, including demonstrations of broadband electro-optic conversion and analog RF receiving with an 8-12 GHz FMCW signal, both using an amplified on-chip waveguide. The combination of high gain with low noise and high-speed electro-optic modulation on a monolithic thin film lithium niobate chip is novel and of interest to the integrated photonics community. Below are some comments to be addressed."*

Our reply: We thank the reviewer for carefully reading our manuscripts and evaluating our work. We made the point-by-point response according to your comments as follows.

Comment 1: *"The prior art has not been fully addressed, specifically bulk lithium niobate chips. See the work of Sohler et al., (for example Suche et al., IEEE Photonics Technology Letters 7, 505, 1995, where phase modulation and erbium gain are both shown on a lithium niobate chip). It is also suggested to change the title accordingly, e.g. specifically referring to thin film lithium niobate, or TFLN."*

Our reply: We thank the reviewer for raising this critical point. We have now expanded the discussion of prior work on bulk LiNbO₃ in the revised manuscript and highlighted the key innovations of our study. Previous works based on bulk lithium niobate platforms pioneered doping strategies and achieved modulation in bulk waveguides. While such platforms inherently suffer from weak optical confinement, limited electro-optic bandwidth, and high driving voltage. These constraints arise from the large waveguide dimensions and low refractive index contrast of bulk LiNbO₃, which restrict both pump-signal overlap for efficient optical amplification and microwave-optical velocity matching for high-speed EO modulation. In contrast, our work leverages thin-film Er-doped lithium niobate on insulator (Er:TFLN). Such a compact platform enables submicron optical confinement and high-speed traveling-wave electrodes for high optical gain and efficient wideband EO modulation.

To emphasize the innovation of Er:TFLN over bulk Er:LN, we have modified the description in the revised manuscript:

(Introduction, page 2) In order to embed the amplification function into high-speed opto-electrical circuitry, **Erbium-doped lithium niobate** ~~Er:LN~~^{31,32} is a promising alternative.

(Introduction, page 2) Early explorations of combining optical gain and electro-optic effects in lithium niobate were reported in bulk platforms³³. Recent breakthroughs in thin-film lithium niobate (TFLN) technology further enables stronger optical confinement and higher E-O bandwidth compared to its bulk counterpart³¹.

For enhanced descriptive rigor, we have revised all performance claims to explicitly qualify their applicability to thin-film LiNbO₃ platforms, avoiding generalizations that might conflate bulk and thin-film material properties. And following the reviewer's suggestion, we have revised the title to: "**Unifying Optical Gain and Electro-Optical Dynamics in Er-Doped Thin-Film Lithium Niobate Platform**" to emphasize this integrated platform.

[33] Suche, H. et al. Er-doped Ti:LiNbO₃ waveguide laser mode locked via loss modulation. IEEE Photon. Technol. Lett. 7, 505–507 (1995).

Comment 2: "The doping is quite high and might introduce extra background loss. How does the loss compare to undoped TFLN MM waveguides?"

Our reply: We appreciate the reviewer's insightful question. It is true that the quite high doping leads to high absorption loss. In this manuscript, the propagation loss is attributed to two factors, one is the scattering loss due to the etching process and the other is the absorption loss of the doped Er^{3+} ions. To minimize the influence of the Er^{3+} absorption, we measured the propagation loss at 1600 nm, a wavelength where Er^{3+} ions exhibit negligible absorption. The measured loss coefficient is about 0.4 dB/cm, comparable to the reported values for undoped TFLN waveguides ($\sim 0.33 \text{ dB/cm}^{[R1]}$). Subtracting the loss coefficient measured at 1600 nm, we can estimate the absorption loss at other wavelengths, as shown in the revised Fig. S4. The high doping leads to about 3~5 dB/cm loss under small-signal conditions, and the propagation loss decreases as the input optical power increase due to the saturation effect. The high absorption also indicates a high gain factor with the pump at these wavelengths.

[R1] Li M, Chang L, Wu L, et al. Integrated pockels laser[J]. Nature communications, 2022, 13(1): 5344.

(Fig. S4, Page S6)

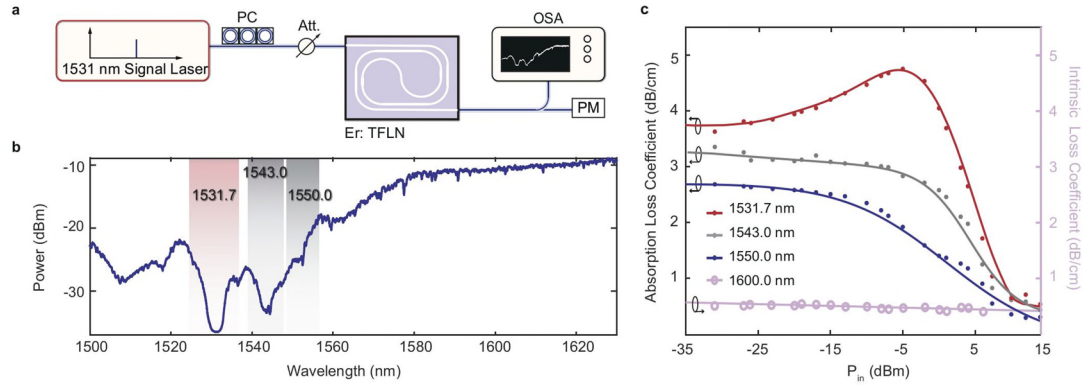


Fig. S4. Passive characteristics of Er:TFLN waveguide amplifier. a, Experimental setup; PC, Polarization controller; Att., Attenuator; OSA, Optical spectrometer analyzer. b, Measured transparent spectrum of the waveguide amplifier at low signal power; c, Measured loss factor of amplifiers under different input powers.

Comment 3: "Why is the coupling loss so high? Can't inverse tapers be used to get significantly lower coupling loss?"

Our reply: Thank you for your insightful comments. We do design an inverse taper considering an input mode diameter of $3 \mu\text{m}$, with a simulated coupling loss of 0.8 dB/facet at 1530 nm (Fig. R1). While the estimated coupling loss in experiment is 3 dB/facet for lensed fibers with a mode diameter of $3 \mu\text{m}$ and a numerical aperture (NA) of 0.25. The SEM of the fabricated edge coupler is depicted in Fig. R2. The larger coupling loss may be due to unideal fabrication such as under/over-etching and minor chip-edge wear^[R2]. In experiment, we find that the index mismatch between the fiber-air-chip facet leads to great reflection, resulting in severe parasitic lasing. Thus, we use UHNA7 fiber with index-matching gel to suppress the reflection. The UHNA7 fiber has the same mode diameter as the lensed fiber but a larger NA of 0.41. The larger NA leads to a higher coupling loss of 6.7 dB/facet. The detailed selection of fibers to suppress the parasitic lasing can be found in "Reply to Comment 8".

In addition, we would like to highlight the 24.6 dB off-chip net gain despite the large coupling loss at the present setup, validating the high-performance amplification of the integrated Er:TFLN platform. With advanced edge coupler designs^[R3], the coupling loss could be down to <1 dB/facet in undoped TFLN, promising higher off-chip net gain in Er:TFLN platform.

[R2] Mu X, Chen Z, Cheng L, et al. Effects of fabrication deviations and fiber misalignment on a fork-shape edge coupler based on subwavelength gratings[J]. Optics Communications, 2021, 482: 126562.

[R3] Liu X, Gao S, Zhang C, et al. Ultra-broadband and low-loss edge coupler for highly efficient second harmonic generation in thin-film lithium niobate[J]. Advanced Photonics Nexus, 2022, 1(1): 016001-016001.

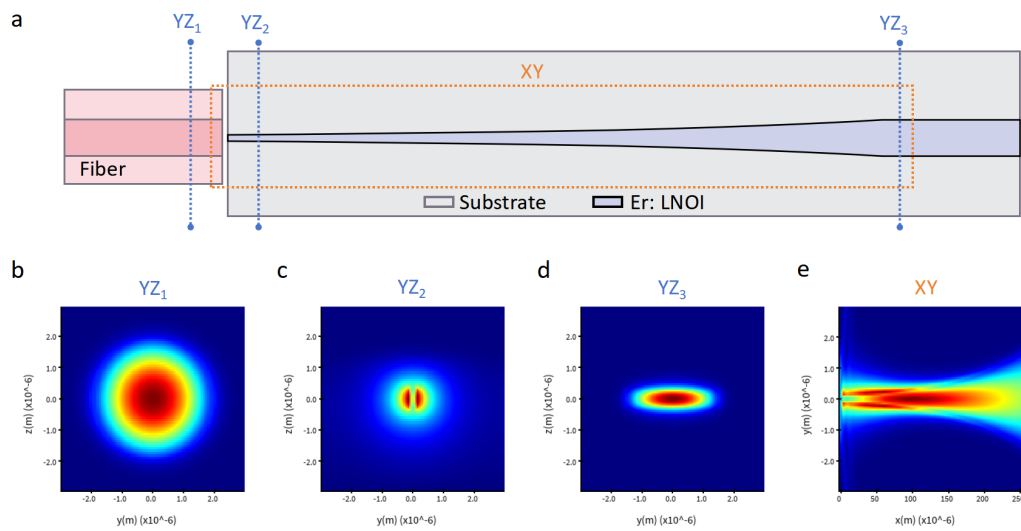


Fig. R1. Simulation of the edge coupler tapering from 200 nm to 3 μm width over 250 μm length. (a) Schematic illustration of the edge coupler structure, (b) Mode profile at the optical fiber interface, (c) Mode profile at the edge coupler input port, (d) Mode profile coupled into the 3-μm-wide waveguide, (e) Intensity distribution during light transmission through the edge coupler (propagation direction: left to right).

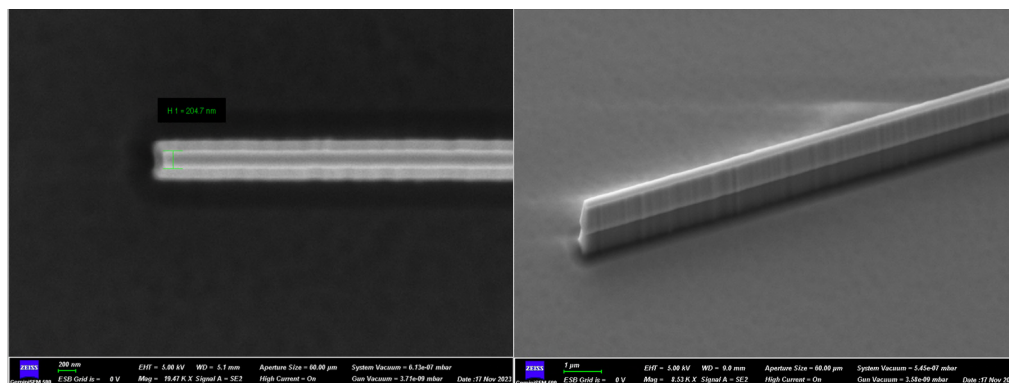


Fig. R2. Scanning Electron Microscope (SEM) images of the fabricated edge coupler. (a) Top-view SEM image. (b) Side-view SEM image.

Comment 4: "Fig. 3b is missing the pump/no signal spectrum (i.e. ASE) to properly assess the gain and proper pump background/ASE in the gain calculation"

Our reply: We understand the reviewer's concern regarding the absence of ASE spectra in Fig. 3b. The spectrum with the pump and without the signal is given in the revised Supplementary Information VI. In this manuscript, we extract the signal powers directly through the spectra. With the high spectral resolution of 0.05 nm, only the ASE/pump background around the signal wavelength may influence the signal power estimation. While pump background and ASE noise at the signal wavelength could theoretically influence signal power estimation, the amplified signal power in Fig. 3b is higher than the surrounding noise floor. Thus, we believe the present gain extraction method is accurate. A similar gain extraction method is also adopted in [R4]. In the revised manuscript, we give a detailed description of the gain extraction.

[R4]Liu, Y. et al. A photonic integrated circuit-based erbium-doped amplifier. Science 376, 1309–1313 (2022).

(Supplementary Note VI, page S9)

Supplementary Note VI: The spectra of the pump laser and the amplified spontaneous emission.

The characterizations of the pump laser and erbium-doped waveguide fluorescence under pump-on/no-signal conditions are essential to quantify the influence of pump background noise and amplified spontaneous emission (ASE) noise. As shown in Fig. S7a, the pump laser exhibits a peak at 1480 nm. Meanwhile, Fig. S6b reveals the Er:TFLN waveguide's broadband fluorescence under pumping. The absence of pump-induced noise floor on the short-wavelength side (<1500 nm) is attributed to the use of a 1531/1480 nm wavelength-division multiplexer (WDM) in the experimental setup (inside penal in Fig. S6b). The ASE noise shows a peak value of -51.3 dBm at 1531.6 nm. The noise floor contributed to the pump laser background and the ASE noise is too low to influence the estimation of the amplified signal power. For example, as shown in Fig. 3b, the amplified signal power is about -17.6 dBm and the surrounding noise floor is about -43 dBm.

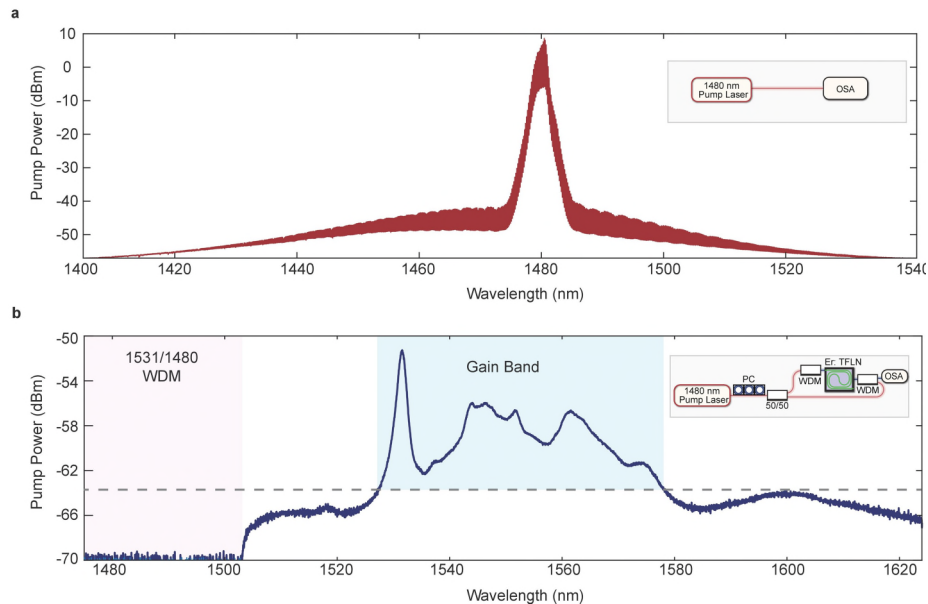


Fig.S7. Characterization of pump laser and Er:TFLN waveguide emission. (a) Pump laser output spectrum, inside panel: experimental setup. (b) Fluorescence emission spectrum from an Er:TFLN waveguide, inside panel: experimental setup.

(Methods, Page 10) The internal net gain refers specifically to the on-chip optical power amplification

within the Er:TFLN waveguide itself, calculated by accounting for all passive losses except input/output coupling. This value represents the pure amplification within the waveguide, exclude coupling losses and link loss. It is defined as:

$$G_{net} = P_{out}^{(off-chip)} - P_{in}^{(off-chip)} + L_{coupling} + L_{link}$$

where:

$P_{out}^{(off-chip)}$: Optical power measured after the chip (e.g., -17.6 dBm at 1531.6 nm in Fig. 3b),

$P_{in}^{(off-chip)}$: Input power launched into the chip (e.g., -39.6 dBm in Fig. 3b),

$L_{coupling}$ =13.4 dB: Total input/output fiber-chip coupling loss,

L_{link} =2.9 dB: Passive propagation loss in the unpumped waveguide.

Comment 5: "It shows that an optimal balance is achieved with low optical loss and minimal microwave loss as the oxide layer thickness is set to 1 μm -> is this true? Isn't it a bit better at > 1 μm ?"

Our reply: Thanks for the comment. According to our simulation, a thicker oxide layer has less influence on the optical propagation loss but significantly decreases the modulation efficiency due to a lower microwave-optical field overlap. In our current fabrication process, the background scattering loss of the lithium niobate waveguides is approximately 0.4 dB/cm. As shown in Fig. 2d, the optical loss caused by metal layer absorption is less than 0.01 dB/cm when the oxide layer thickness exceeds 1 μm . This loss is far smaller than the background loss. Increasing the oxide thickness further (>1 μm) would negligibly reduce optical loss but significantly degrade EO efficiency, as the latter depends not only on microwave loss but also critically on the microwave-optical field overlap. With the electrode gap set to 3.5 μm , the modulation efficiency reaches its maximum when the oxide layer thickness is 1 μm , as seen in the simulation results in Fig. 2e. The 1 μm oxide thickness represents an optimal trade-off between minimizing optical loss and preserving electro-optic interaction efficiency.

(Results, Page 4) ~~It shows that an optimal balance is achieved with low optical loss and minimal microwave loss as the oxide layer thickness is set to $\geq 1 \mu\text{m}$,~~ **both optical loss and microwave loss are maintained at low levels.** Figure. 2d presents the simulated $V_{\pi}L$ of single-drive modulation under different oxide layer thicknesses and electrode gaps⁴³. As the electrode **spacing increases**, the interaction between the applied electrical field and the optical field decreases. **To ensure low levels of optical and microwave losses while achieving high modulation efficiency,** ~~For moderate modulation efficiency, the electrode gap is set to 3.5 μm .~~ **the electrode gap and oxide layer thickness are set to 3.5 μm and 1 μm , respectively.**

[43] He M, Xu M, Ren Y, et al. High-performance hybrid silicon and lithium niobate Mach-Zehnder modulators for 100 Gbit s⁻¹ and beyond[J]. Nature photonics, 2019, 13(5): 359-364.

Comment 6: "Page 5: "Highest gain..." The gain is impressive but highly wavelength dependent (as shown in Fig. 3c). Most applications (WDM systems, tunable lasers, etc.) require amplification over a broad wavelength range. A better wording might be highest single wavelength gain.

Table 1 in the supplementary material should also include the wavelength the gain is measured at and pump wavelength for better comparison.

More importantly, the high gain in this system at the peak emission wavelength should be justified. Is

this typical for lithium niobate? If so, why? Under 1480nm in-band pumping of Er, the inversion is lower and the gain is usually flatter. See for example ref [24] where the gain is lower near 1530nm."

Our reply: We thank the reviewer for this suggestion and we have revised the corresponding parts as shown below. As noted in prior studies of erbium-doped waveguides (Fig. R3, Fig. R4), the 1530 nm wavelength regime consistently exhibits the highest gain due to the intrinsic Stark-split emission characteristics of Er^{3+} ions. Apart from the nature of Er^{3+} ions, the host material will also influence the gain spectrum, for example, with the gain peak at 1535 nm in Er^{3+} -doped phosphate glass [R5] and at 1550 nm in Er^{3+} -doped SiN (Ref. [24]). The presented gain spectrum in our work is consistent with previously reported Er:LN waveguide amplifiers[R6]. The host-dependent amplification performance (e.g., LiNbO_3 vs. SiN vs. silica) warrants deeper investigation. We will continue to investigate these effects in future work.

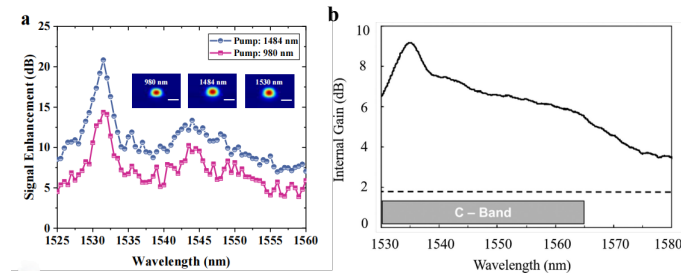


Fig. R3. (a)The signal enhancement spectrum measured from a Er:TFLN waveguide amplifier^[R5]. (b)The internal gain spectrum measured from a Er^{3+} -doped phosphate glass waveguide amplifier with a pump power of 460 mW. The dashed line indicates the insertion loss of the device^[R6].

[R5] Cai M, Wu K, Xiang J, et al. Erbium-doped lithium niobate thin film waveguide amplifier with 16 dB internal net gain[J]. IEEE Journal of Selected Topics in Quantum Electronics, 2021, 28(3: Hybrid Integration for Silicon Photonics): 1-8.

[R6] Della Valle G, Osellame R, Chiodo N, et al. C-band waveguide amplifier produced by femtosecond laser writing[J]. Optics Express, 2005, 13(16): 5976-5982.

(Conclusion and discussion, Page 7) Using a tailored multimode waveguide structure, we achieved a maximum internal net gain of 38 dB at 1531.7 nm in a 9.16-cm-long Er:TFLN waveguide amplifier

Also, we include information of signal and pump wavelengths in Table II as follows:

Table II. Comparison with previously reported on-chip amplifiers and typical commercial erbium doped fiber amplifiers. N/A, data not available

Waveguide material	Active material	Max on-chip output power (dBm)	Max on-chip net gain (dB)	Signal wavelength (nm)	Pump wavelength (nm)	Length (cm)	Reference
Er-doped waveguide							

Er:TFLN	Er:TFLN	14.1	38	1531.7	1480	9.16	This work
Er:Si ₃ N ₄	Er:Si ₃ N ₄	21.6	30	1550	1480	21	Liu et al ⁹
Er:Yb:TFLN	Er:Yb:TFLN	≈-30	27	1532	980	15	Zhang et al ¹⁰
Er:Yb:TFLN	Er:Yb:TFLN	20.5	16	1550	1480	7	Bao et al ¹⁴
Er:Al ₂ O ₃	Er:Al ₂ O ₃	13.2	33.5	1532	1480	12.9	Bonneville et al ¹⁵
Er:Al ₂ O ₃	Er:Al ₂ O ₃	4	20	1532	976	12.9	Vazquez et al ¹⁶
Er:TeO ₂	Er:TeO ₂	13	14	1530	1480	5	Vu and Madden ¹⁷
Er:Ta ₂ O ₅	Er:Ta ₂ O ₅	<-20	4.83	1530	1480	2.3	Subramanian et al ¹⁸
Er:Yb:Al ₂ O ₃	Er:Yb:Al ₂ O ₃	<-8.5	4.3	1533	870	3	Bonneville et al ¹⁹

Waveguide with Er-doped oxide thin film

Si ₃ N ₄	Er:Al ₂ O ₃	2.7	18.1	1532	980	10	Mu et al ¹²
Si ₃ N ₄	Er:TeO ₂	<-1	5	1558	1470	6.7	Frankis et al ²⁰
Si ₃ N ₄	Er:Al ₂ O ₃	-3.5	8.5	1532	980	5.9	Chrysostomidis et al ²¹
GeSbS	Er:Al ₂ O ₃	N/A	6.27	1533	1480	4.6	Wang et al ²²
Si ₃ N ₄	Er:Al ₂ O ₃	<-20	0.4	1533	1470	0.16	Ronn et al ²³

Low confinement waveguide based devices

Er:phosphate glass	Er:phosphate glass	4.4	27	1530	1480	47.4	Hattori et al ²⁴
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Er:Yb:phosphate glass	Er:Yb:phosphate glass	12	20	1550	980	4.1	Barbier et al ²⁵
Er:bismuthate glass	Er:bismuthate glass	≈16	18	1533	980	8.7	Thomson et al ²⁶
Er:Yb:phosphate glass	Er:Yb:phosphate glass	≈19	16.7	1534	980	3.1	Della Valle et al ²⁷
Er:soda-lime glass	Er:soda-lime glass	5.2	15	1550	980	4.5	Nykolak et al ²⁸

Integrated semiconductor optical amplifier (SOA)

Si	III-V material	17.5	27	1575	N/A	0.145	Van Gasse et al ²⁹
Si	III-V material	14	25	1550	N/A	N/A	Davenport et al ³⁰
Si ₃ N ₄	III-V material	8.8	14	1550	N/A	0.115	Op de Beeck et al ³¹
LiNbO ₃	III-V material	<5	11.8	1537	N/A	N/A	Op de Beeck et al ³²

Commercial amplifiers

Er-doped fiber	Er-doped fiber	>20	>30	1530-1565	N/A	N/A	Thorlabs EDFA100S
Er-doped fiber	Er-doped fiber	18	25-35	1530-1565	N/A	N/A	Calmar Laser AMP-PM-18
Er-doped fiber	Er-doped fiber	13	>19	1530-1565	N/A	N/A	Amonics AEDFA-BO-13
No waveguide structure	III-V material	14	13	1528-1562	N/A	N/A	SOA1013S

No waveguide structure	III-V material	9	20	1528-1562	N/A	N/A	SOA111 7S
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Comment 7: "Page 5: it is stated that the gain saturates, but higher pump power could provide more gain which seems to be contradictory"

Our reply: Thanks for pointing it out. As suggested from Fig. 3c, the curve still holds an increasing trend, which means the system approaches but does not fully enter saturation. However, in practice, attempts to operate beyond 115 mW trigger parasitic lasing. This instability prevents reliable gain measurement in the deep saturation regime. The current 38 dB net gain limit (Fig. 3b) is thus constrained by parasitic lasing rather than the intrinsic population inversion capacity of Er^{3+} ions. The original sentence has been revised.

(Results, Page 5) The ~~internal net gain~~ **gain factor** increases **much slower** with the pump power, **as the pump power is > 80 mW compared with that in the low pump power region (0~20 mW)**. ~~which is intuitive, then gradually gets saturated when the off-chip pump power is over 20 dBm.~~ Significantly, the ~~highest~~ on-chip net gain under 115 mW off-chip pump power is around 38 dB. The achieved gain factor not only rivals that of commercial EDFAs but also represents the highest internal net gain reported to date for waveguide-based amplifiers (See Supplementary Note VIII). Higher pump power **of larger than 115 mW** could further increase the gain **before saturation**, while the measurement of such performance is presently affected by the parasitic lasing²⁴, resulting from the internal reflection between the chip facets.

Comment 8: " More details on the parasitic lasing, at what pump power and gain it sets in, etc. should be provided."

Our reply: Thanks for pointing it out. This is a critical question especially for integrated waveguide amplifiers, as the high reflection between the chip edges leads to severe parasitic lasing, limiting the amplification performance. A detailed description of the working conditions, experiment schemes to suppress the parasitic lasing, etc. is given in the revised Supplementary Note VII:

(Supplementary Note VII, Page S10)

Supplementary Note VII: Parasitic Lasing and Mitigation Strategies

Parasitic lasing in our $\text{Er}:\text{TFLN}$ waveguide amplifier was experimentally observed under high pump powers. This phenomenon arises when amplified spontaneous emission experiences feedback from residual reflections at the waveguide facets (LN-air interfaces), forming an unintended Fabry-Pérot cavity. At first, we used lensed fibers, where the mode diameter is about 3 μm , for the coupling between the chip and the fiber links. Due to the large index mismatch between the integrated waveguide and air, parasitic lasing initiated at a pump power of approximately 40 mW with an input signal power of -39.6 dBm, corresponding to a net gain of ~25 dB. The FP-induced lasing and sudden power fluctuations were observed at this threshold, with the lasing wavelength (~1532 nm) aligning with the peak gain region of Er^{3+} ions in LiNbO_3 .

To suppress parasitic lasing and minimize Fresnel reflections at facets, an index-matching gel (Norland

Optical Adhesive 61, refractive index $n = 1.56$ at 1550 nm) was applied at the interface between the Er:TFLN chip and fiber (Fig. S8). As the gel was added, the fiber tip would move and sometimes the tip would hit the chip facet, leading to the break of the fiber tip or the edge coupler. To avoid this, we adopted UHNA7 fibers with the same mode diameter of the lensed fiber for coupling between the fiber links and the chip. The end of such fiber is flat, which will not break itself or the edge coupler if hitting the chip edge as adding the gel. With the help of index-matching gel, we can achieve stable amplification up to a pump power of 115 mW with a net gain of 38 dB. With higher pump power, parasitic lasing is observed and makes the amplification process unstable. For future designs, angled end-facets can be implemented to further suppress feedback.

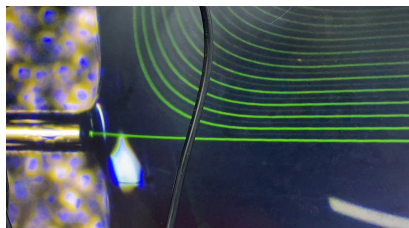


Fig. S8. The photo of the chip-fiber interface with the Index-matching gel applied.

Comment 9: "The saturation output power of the waveguide amplifier...on-chip signal power." This statement seems to be describing external saturation, so the on-chip part is confusing in the explanation."

Our reply: Sorry for the misleading expression. As we focus on the amplification performance instead of the edge coupler design, the saturation output power is estimated for "on-chip" performance. The "on-chip" saturation power is defined as the "on-chip" signal power at which the internal net gain is equal to zero.

(Results, Page 6) The on-chip saturation output power of the waveguide amplifier is defined as the on-chip signal power at which the internal net gain is equal to zero.

Comment 10: "Fig. 5: What is the 100 kHz showing in the inset of Fig. 5a. This should be stated in the caption. There are several sidebands in Fig. b that should be explained, especially in terms of the levels indicated in the SNR measurements. It should also be stated and/or shown where the EDFA is in the setup figure."

Our reply: Thank you for your careful review. The 100 kHz in Fig. 5a indicates the chirping frequency of the FMCW signal, and this has been corrected to 800 kHz in the revised manuscript. To clarify this, we have revised the caption of Fig. 5a and incorporated an explanation into the original manuscript as follows.

(Fig. 5, Page 7) Fig. 5. a, Setup of a frequency-modulated continuous wave (FMCW) signal modulation and amplification chirped between 8 GHz and 12 GHz at a repetition rate of 800 kHz.

(Results, Page 6) A frequency-modulated continuous wave (FMCW), chirped between 8 GHz and 12 GHz at a repetition rate of 800 kHz, is applied to the phase modulator, acting as an RF signal to be received. The FMCW signal is loaded on the optical carrier and amplified through the developed modulator and amplifier.

As for the observed sidebands in Fig. 5b. It may originate from the inherent distorted frequency

Fig. 5. On-chip signal modulation and amplification. a, Setup of frequency-modulated continuous wave (FMCW) signal modulation and amplification **chirped between 8 GHz and 12 GHz at a repetition rate of 800 kHz**. BPF, band pass filter. b-c, The received microwave signal and time-frequency spectra of the beatnote between the carrier and the sideband when the signal light is (i) **at 1600 nm** without pump light, (ii) **at 1550 nm** with pump light and (iii) **with the EDFA at 1550 nm by using a TFLN-based modulator and an EDFA**.

Also, the EDFA has been explicitly labeled and positioned in the optical path as shown in the newly added Fig. S14 and Fig. S15.

(Supplementary Note XII, Page S18)

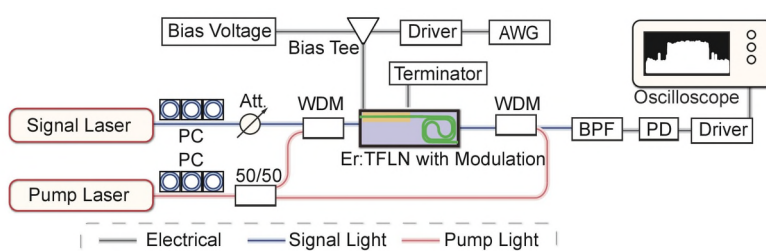


Fig. S14. **Setup of on-chip signal modulation and amplification based on Er:TFLN platform. BPF, bandpass filter.**

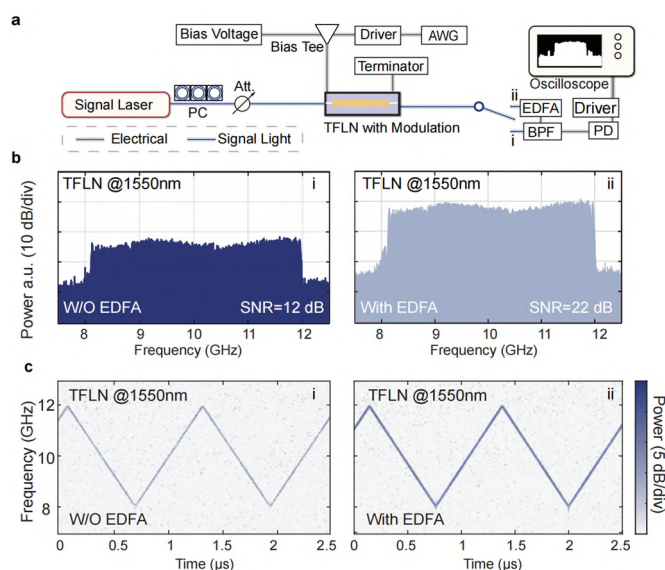


Fig. S15. **Signal modulation and amplification based on TFLN platform. (a) Experimental setup.....**

Comment 11: "The lifetime is compared to commercial silica fiber amplifiers, but what about lithium niobate? Is the lifetime similar to prior lithium niobate measurements and what is expected in theory for this host? The higher n host would typically lead to a shorter lifetime."

Our reply: We sincerely appreciate these questions raised by the reviewers. In our original manuscript, we reported a calculated lifetime of 9.4 ms derived from the Judd-Ofelt (JO) theory. However, the JO framework assumes purely radiative transitions and neglects non-radiative decay pathways (e.g., multi-phonon relaxation, defect-mediated quenching). To address this limitation and validate the lifetime

experimentally, we conducted direct time-resolved photoluminescence (TRPL) measurements using a transient fluorescence spectrometer (Edinburgh FLS980). The revised lifetime is 5.8 ms. We acknowledge that the experimentally measured fluorescence lifetime of 5.8 ms is indeed shorter than typical values reported for commercial Er-doped silica fibers (~10 ms)[R7]. As the reviewer highlighted, lithium niobate's higher refractive index (~2.2 vs. silica's ~1.5) enhances spontaneous emission rates, theoretically reducing lifetimes.

We have updated the manuscript, replacing the initial calculated value with the experimentally determined lifetime and expanding the discussion in Supplementary Note V.

[R7]Taherunnisa, S. et al. Effect of up-conversion luminescence in Er³⁺ doped phosphate glasses for developing Erbium-doped fibre amplifiers (EDFA) and G-LED's. Optical Materials: X 3, 100034 (2019).

(Results, Page 3) ~~According to the emission cross-section (See Supplementary Note IV),~~ The photoluminescence lifetime is ~~calculated~~ **measured to be 5.8 ms (See Supplementary Note V)**, which indicates an ideal doping condition, comparable to the typical value in the commercial EDFA (@ 10 ms³⁹).

(Supplementary Note V, Page S8)

Supplementary Note V: Lifetime measurement

The photoluminescence lifetime of the sample was directly measured using a steady-state/transient fluorescence spectrometer (Edinburgh FLS980, UK) to ensure experimental accuracy and eliminate potential errors associated with indirect calculations. Fluorescence decay curves were recorded over a 0–80 ms time window. The decay profiles exhibited a biphasic behavior, characterized by an initial rapid decay followed by a slower exponential decay. To model this behavior, the data were fitted using a bi-exponential decay function, expressed as¹²:

$$I(t) = I_0 + B_1 * \exp\left(\frac{-t}{\tau_1}\right) + B_2 * \exp\left(\frac{-t}{\tau_2}\right) \quad (1)$$

where I_0 represents the photoluminescence intensity of the tested sample at $t=0$, τ_1 and τ_2 represent the short and long lifetime components, B_1 and B_2 are their respective amplitudes. The measured time-resolved fluorescence decay profile and the fitted profile are shown in Fig. S6. The fitted parameter values are shown in Table I. The measured fluorescence lifetime (τ) of the sample is given by:

$$\tau = \frac{B_1\tau_1^2 + B_2\tau_2^2}{B_1\tau_1 + B_2\tau_2} \quad (2)$$

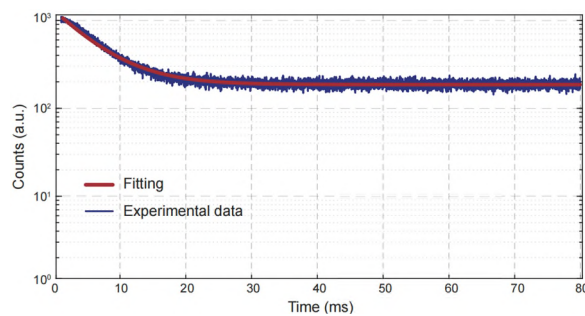


Fig. S6 Time-resolved fluorescence decay profile.

Table I. Biexponential decay fitting parameters for Er³⁺ photoluminescence lifetime

Parameter	Value
τ_1	5.4
τ_2	6.1
B_1	4.9
B_2	4.9

The lifetime is calculated as 5.8 ms, which indicates an ideal doping condition, close to the typical value in the commercial EDFA (@ 10 ms³⁹).

[12] Shrivastava R, Kaur J. Studies on long lasting optical properties of Eu²⁺ and Dy³⁺ doped di-barium magnesium silicate phosphors[J]. Chinese Chemical Letters, 2015, 26(9): 1187-1190.

Comment 12: " The noise figure measurement needs more justification: Was the noise figure measurement qualified with a commercial amplifier? This should be stated to ensure the method is accurate here. The measurement of noise 0.4 nm from the peak would seem to underestimate the noise figure, given ASE would be strongest at the peak where the gain is measured."

Our reply: Thank you for raising these points. The reported noise figure (NF) of 4.7 dB (revised from 4.3 dB) is measured using the optical source subtraction method described in D. Derickson, Fiber Optic Test and Measurement (1998)[R8]. This methodology is consistent in characterizing both EDFAs and integrated waveguide amplifiers[R9]. After our verification, this method requires a wavelength distance of 0.3 nm from the peak instead of the 0.4 nm in the original manuscript. The revised NF figure has been calculated to be 4.7 dB with P_{out}= -53.5 dBm and P_{SSE} = -80.1 dBm, which has been modified in the article.

This methodology was further verified by testing a commercial EDFA (Amonics AEDFA-PA-35-B-FA). Specifically, at a signal wavelength of 1550.0 nm with an OSA resolution bandwidth of 0.02 nm, the measured parameters (G = 25.5 dB, P_{out} = -35.0 dBm, P_{SSE} = -76.0 dBm)—yielded an NF of 4.3 dB, which exactly matches the specification in the product manual (4.3 dB, max 4.5 dB).

We understand the reviewee's concern about a lower noise level far from the gain peak. To evaluate the potential influence, we read the peak value from the ASE spectrum without signal light (Fig. S7b, given in "**Reply to Comment 4**") and the power values at 0.3 nm and 0.4 nm away from the peak, which were -51.3 dBm, -51.7 dBm and -52.1 dBm, respectively. It is true that the present methodology may underestimate the noise level. While this method is also adopted for other optical amplifiers. Thus, we still keep the measured NF in the revised manuscript. Even considering the ~0.4 dB higher noise level at the peak, the NF is about 5.1 dB, comparable to previously reported integrated EDWAs (7.1 dB for Er:SiN[R9] and 4.49 dB for Er:LN[R10]).

We have revised the original manuscript as follows.

(Methods, Page 10)~~Substitution~~ **Substituting** the measured results into the Eq. 5 yields a noise figure of ~~4.3~~ **4.7** dB.

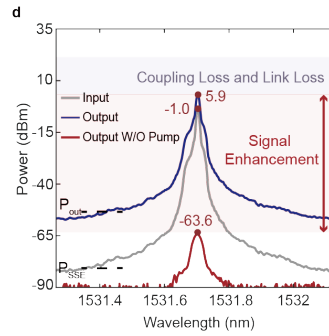


Fig. 3. High gain Er:TFLN waveguide amplifier. d, Optical spectra of the input signal and the amplified signal under a high off-chip input signal power.

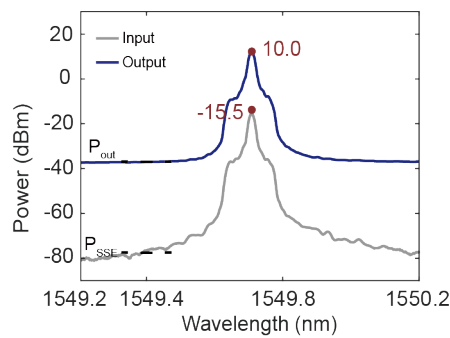


Fig. R4. Optical spectra of the input signal and the amplified signal by commercial EDFA.

[R8] D. Derickson, Fiber Optic Test and Measurement, D. Derickson (Ed). (1998).

[R9] Liu, Y. et al. A photonic integrated circuit-based erbium-doped amplifier. Science 376, 1309–1313 (2022).

[R10] Cai M, Wu K, Xiang J, et al. Erbium-doped lithium niobate thin film waveguide amplifier with 16 dB internal net gain[J]. IEEE Journal of Selected Topics in Quantum Electronics, 2021, 28(3: Hybrid Integration for Silicon Photonics): 1-8.

Comment 13: "The cross-sections in Fig. S5 look abnormal and perhaps mixed up in the legend. The shape seems strange particularly compared to the gain with 3 peaks in Fig. 3c (and see gain spectra with 3 peaks in Brinkman IEEE Journal of Quantum Electronics 30, 2356, 1994). It looks like the blue cross section is not tending to 0 around 1600nm as expected from the gain measurement and there is perhaps a systematic DC offset due to the measurement method."

Our reply: Thank you for raising these points. We sincerely apologize for the inadvertent mislabeling of the absorption and emission cross-sections in the original figure, which has now been corrected.

In the revised Fig. S5, the absorption cross-section (blue curve) indeed decays to near-zero values at 1600 nm, aligning with the expected behavior of Er^{3+} -doped material. The discrepancy in the emission cross-section shape arises from the limited wavelength range (1500-1630 nm) of our tunable laser source (Santec TSL-570), which focuses on the primary Er^{3+} operational band rather than the full photoluminescence spectrum. The complete emission spectrum is available in Fig. 2c, and lifetime measurements (previously derived from cross-sections) have been directly validated in Supplementary Note IV.

The complete absorption spectrum, showing the characteristic structure which is similar as the one in Brinkman et al. IEEE J. Quantum Electron. 30, 2356, 1994, is provided in Fig. S4b.

(Supplementary Note IV, Page S7)

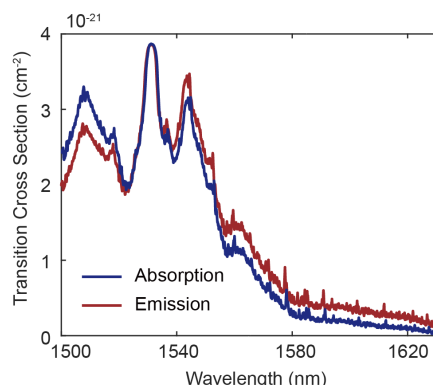


Fig. S5. Extracted emission and absorption cross sections of Er:TFLN waveguide amplifier

Comment 14: *Conclusion:*

Comment 14.1: *highest gain should be qualified as single wavelength*

Our reply: This has been revised as follows:

(Conclusion and discussion, Page 7) Using a tailored multimode waveguide structure, we achieved a maximum internal net gain of 38 dB at 1531.7 nm in a 9.16-cm-long Er:TFLN waveguide amplifier with over 14 dBm saturation power and a noise figure of 4.7 dB.

Comment 14.2: *again details of the parasitic lasing are mentioned but not explained*

Our reply: Thanks for the suggestion. Parasitic lasing in our Er:TFLN waveguide amplifier was experimentally observed under high pump power conditions. This phenomenon arises when amplified spontaneous emission experiences feedback from residual reflections at the waveguide facets (LN-air interfaces), forming an unintended Fabry-Pérot cavity. More details have been given in “Replay to comment 8”.

Comment 14.3: *1400nm – Nd, is 1.3um band meant? And has gain been shown in Dy-doped lithium niobate? (normally specialized low phonon host materials are required)*

Our reply: The reference to "1400 nm" in our original text was a writing error. We intended to refer to the 1300 nm band (O-band, 1260-1360 nm).

It is true that achieving net optical gain in dysprosium (Dy^{3+})-doped lithium niobate for mid-infrared applications remains a significant challenge. Regarding Dy^{3+} -doped lithium niobate, prior studies have observed Dy^{3+} photoluminescence at 585 nm [R11], but mid-infrared emission has not been demonstrated. We have removed speculative discussions of Dy:LN from the manuscript.

(Conclusion and discussion, Page 7) In terms of gain bandwidth, ultra-wide-spectrum amplifiers spanning multiple bands can be achieved by doping multiple rare earth ions simultaneously such as Neodymium (Nd @ 910 nm and 1400 1300 nm band), Thulium (Tm @ 2000 nm band⁴⁹), Dysprosium (Dy @ 3000 nm band) and so on⁵⁰.

[R11] Haro-González P, Martín L L, Martín I R, et al. Pump and probe measurements of optical

amplification at 584 nm in dysprosium doped lithium niobate crystal[J]. Optical Materials, 2010, 33(2): 196-199.

Comment 14.4: *slow light -> what about the high losses usually associated with such waveguides, which would affect the gain? "*

Our reply: We thank the reviewer for raising this critical point. The slow-light design in our work is specifically applied to the electro-optic modulator section, not the waveguide amplifier. The primary advantages of slow-light modulators include their ultra-compact footprint and enhanced modulation bandwidth, enabled by enhanced light-matter interactions. Although slow-light structures often exhibit higher propagation losses per unit length, their compact footprint, which is enabled by strong electro-optic interaction, results in a total device loss comparable to that of conventional modulators [R12]. These losses can be compensated by a subsequent waveguide amplifier in the proposed Er:LN platform.

[R12] Han C, Zheng Z, Shu H, et al. Slow-light silicon modulator with 110-GHz bandwidth[J]. Science advances, 2023, 9(42): eadi5339.

Comment 15: *"Some additional details would help in a several places"*

Comment 15.1: *Providing the typical bend radius of ridge lithium niobate waveguide in the text for easy comparison.*

Our reply: Thanks for your suggestion. We have added a comparison of the typical bend radius of lithium niobate waveguides [R13,R14] to clearly highlight the compactness achieved by using a strip waveguide in our work.

[R13]Zhang Z, Li S, Gao R, et al. Erbium-ytterbium codoped thin-film lithium niobate integrated waveguide amplifier with a 27 dB internal net gain[J]. Optics Letters, 2023, 48(16): 4344-4347.

[R14]Zhou J, Liang Y, Liu Z, et al. On-chip integrated waveguide amplifiers on erbium-doped thin-film lithium niobate on insulator[J]. Laser & Photonics Reviews, 2021, 15(8): 2100030.

(Results, Page 3) Different from the ~~typical-ridged-waveguide in TFLN platform,~~ **ridge waveguide in previous work, with relatively large bending radii of about several hundreds of μm to ensure pure single mode propagation over long delay lines^{33,35}**, the optical amplifier is formed by strip waveguide with a fully-etch process, as shown in Fig. 2a(i). The strip waveguide supports a tighter light confinement for small bend radius and small waveguide gaps for compact structures.

Comment 15.2: *What is the signal and pump polarization used? What is the polarization dependent (TE vs. TM) loss and gain?*

Our reply: Thanks for your question. The signal and pump polarization used in the experiments is TE0 mode, which is ensured by a pre-calibration of the alignment setup. The edge coupler on the Er:TFLN chip in our design exhibits a higher transmission efficiency for TE0-mode input light (83%) compared to TM0-mode (58%), making TM0-mode significantly more challenging to couple into the photonic chip. Moreover, the integrated modulator in the amplifier-modulator structure is designed to operate exclusively on TE0-mode light. The measured gain of the modulated signal further corroborates this design feature, as the observed amplification and noise characteristics align exclusively with TE0-polarized propagation. As this manuscript focuses on the co-functionality of modulation and amplification, we limit the gain characterization to TE polarization due to the constraints of the

modulator design. If the platform is used for amplification of both polarizations, polarization rotators could be employed to convert TM-polarized input light to TE polarization for compatibility with the current architecture.

Comment 15.3: Page 3: distancing the microwave field from the high index layer – lithium niobate? Why?

Our reply: We thank the reviewer for raising this important point. To clarify the device structure, the cross-sectional schematic of the modulator is shown in Fig. R4. The substrate is concluding a 2 μm SiO_2 substrate, and a 400 μm silicon substrate with ~ 3.5 optical index, which refers to the “high index layer”. Since silicon holds a high relative permittivity $\epsilon_r \sim 11.7$ at microwave frequencies, it can cause strong microwave field confinement near the substrate, leading to significant losses [R15]. Distancing the microwave electrodes from silicon can reduce this electrical loss as shown in Fig. 2d. To clarify this confusion in the original description, we have revised the manuscript text as follows.

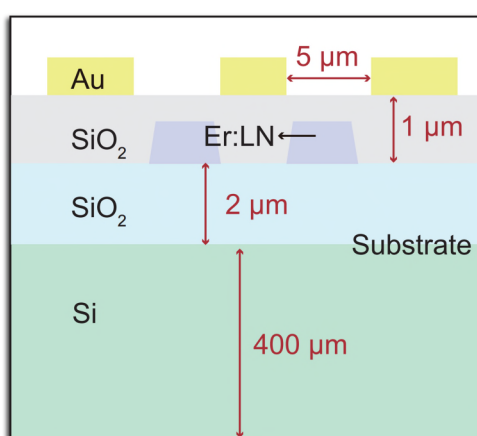


Fig. R4. Cross-sectional schematic of the modulator.

(Results, Page 3) Simultaneously, microwave losses are reduced by distancing the microwave field from the high index layer **the Silicon substrate with high index.**

[R15]Kharel P, Reimer C, Luke K, et al. Breaking voltage-bandwidth limits in integrated lithium niobate modulators using micro-structured electrodes[J]. Optica, 2021, 8(3): 357-363.

Comment 15.4: What are the fits in Fig. 3? (should state in caption). Also, high input signal power -> state power

Our reply: The curves in Fig. 3(c) were generated using cubic spline interpolation (MATLAB spline function) to smoothly connect discrete experimental data points while preserving the underlying trends. Regarding the input signal power, the "high input signal power" referenced in the original text corresponds to off-chip input signal power of -1 dBm.

(Fig. 3, Page 4) Fig. 3. c, (i) Measured internal net gain (blue dots) at 1531.7 nm with different pump power upon 1480 nm pumping; **(ii)** Measured internal net gain with different wavelength **(fitted by cubic spline interpolation)**. **d,** Optical spectra of the input signal and the amplified signal under a high off-chip input signal power of -1 dBm.

Comment 15.5: Page 6: a signal enhancement of 30 dB is given but what is the gain?"

Our reply: Thank you for your insightful question. In the revised Supplementary Note XI, we give the

detailed off-chip input powers and the output powers shown in Fig. S12 and Fig. S13. Due to the fiber link loss and the large coupling loss, we cannot get positive off-chip net gains under a high input power. While the internal net gains are about 10 dB. The lower gain factor compared with that shown in Fig. 3b is related to a shorter length of the spiral and a higher loss in the modulation region, where a single-mode waveguide is adopted.

(Supplementary Note XI, Page S16)

Supplementary Note XI: Amplification with full-band modulation test

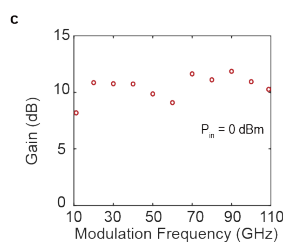


Fig. S12. c, Measured internal net gain under different modulation frequencies.

.....The off-chip input signal light power from 10 to 110 GHz is 0 dBm and from 110G to 170G is 3.86 dBm. Based on the net gain calculation method described in Methods, the calculated net gain is shown in Fig.S12c and Fig.S13c. The lower net gain compared to that in Fig. 3b is due to the shorter delay line (6 cm) and the higher-loss single-mode waveguide used in the modulator.

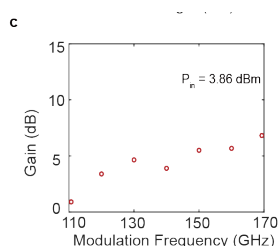


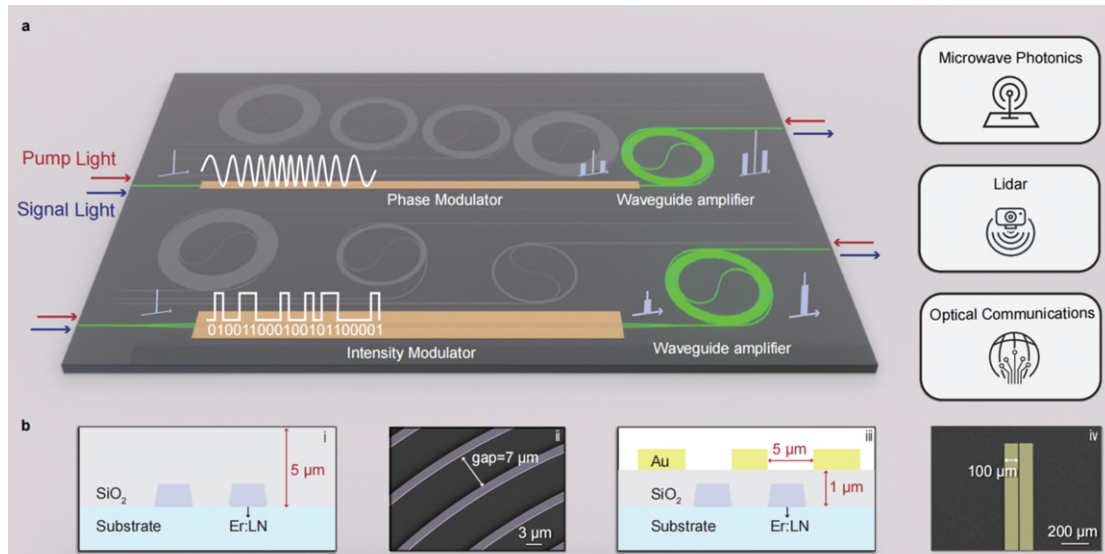
Fig. S13. c, Measured internal net gain with different modulation frequency.

Comment 16: Formatting:

Comment 16.1: Figure 1 is somewhat redundant, and doesn't add much to what is already shown in the other panels. It is suggested to remove it or to improve the overall presentation by adding it as a part a panel in figure 1 (the current part a figures can be shifted to the right).

Our reply: Thank you for your constructive feedback on Fig. 1. We have revised the figure to address these concerns. The updated layout now directly illustrates the functional design of the monolithic chip (including the waveguide amplifier, phase modulator, and intensity modulator) through cross-sectional schematics and false-color picture images. Key structural details, such as material layers and dimensions are highlighted to emphasize the unified architecture of the Er:TFLN platform. The revised diagram streamlines information delivery and ensures a cohesive visual narrative, underscoring the coexistence of on-chip optical gain and electro-optic dynamics.

(Fig.1, Page 2)



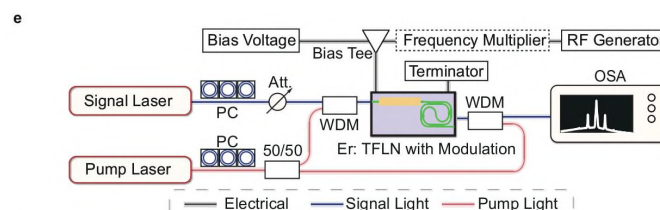
Comment 16.2: *Parts i – iv are listed out of order in fig. 2*

Our reply: We sincerely appreciate the reviewer's careful attention to detail. As noted in Comment 16.1, the original subfigures (i–iv) from Fig. 2 have been relocated to Fig. 1 and reordered to ensure logical consistency with the monolithic chip's architecture. The updated Fig. 1b now clearly sequences the components.

Comment 16.3: *"Mod." short form unnecessary in Fig. 4/caption*

Our reply: In Fig.4 and its caption, the abbreviation "Mod." (short for "Modulation") has been revised to the full term "Modulation" to ensure consistency.

(Fig. 4, Page 5)



(Fig. 5, Page 7)

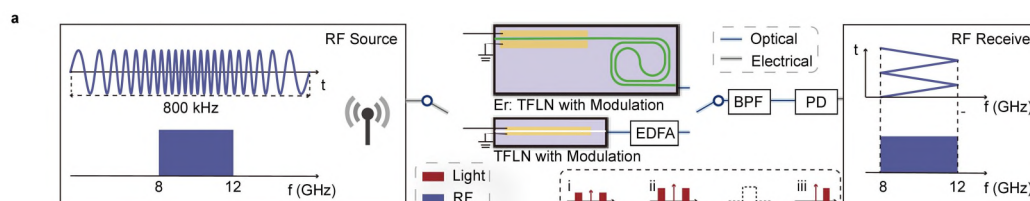


Fig. 5. ... a, Setup of frequency modulated continuous wave (FMCW) signal modulation and amplification chirped between 8 GHz and 12 GHz at a repetition rate of 800 kHz.

Comment 17: *"The wording should be adjusted in some places to adhere to normal scientific style, examples are below:*

Our reply: We thank the reviewer for the constructive feedback on improving the scientific clarity of the text. We have carefully revised the manuscript to adhere to standard terminology and avoid subjective phrasing. Below are the key adjustments.

Comment 17.1: *"impressive performance" in abstract*

Our reply: Deleted the phrase "with impressive performance":

(Abstract, Page 1) In this paper, we unify these two functions in the Er-doped thin-film lithium niobate (Er:TFLN) platform-with-impressive-performance.

Comment 17.2: *"electro-optic operation" in abstract – be specific*

Our reply: Replaced vague "electro-optic operation" with "electro-optic modulation" to clarify the device's role in controlling light:

(Abstract, Page 1) Meanwhile, leveraging the strong Pockels effect of the host material, we realize ultra wide-range ~~electro-optic operation~~ **electro-optic modulation** ~~up to 170 GHz~~ with a bandwidth of 53 GHz **and operation up to 170 GHz**, where the device can be fabricated alongside the waveguide amplifier using a zero-change process.

Comment 17.3: *"unprecedented" in abstract*

Our reply: Removal of "Unprecedented":

(Abstract, Page 1) The ~~unprecedented~~ modulation-amplification integration holds broad potential for increasing system complexity and network depth in applications such as optical interconnections, Lidar, optical computing, and microwave photonics.

Comment 17.4: *Page 3: fatal blocks*

Our reply: The sentence on Page 3 has been revised to clarify the technical comparison:

(Results, Page 3) For efficient amplifiers in the integrated Er:TFLN platform, the background loss, especially the scattering loss, ~~is the most fatal blocks~~ **emerges as the primary limiting factor** compared with their fiber-based competitor.

Comment 17.5: *Page 3: indicating additional loss of pump light*

Our reply: The sentence has been revised to clarify the causal relationship between waveguide propagation losses and their impact on pump-light efficiency and signal gain.

(Results, Page 3) Integrated waveguides typically exhibit orders of magnitude higher propagation loss compared with fibers, **leading to higher** loss of pump light and decreased net gain of signal light.

Comment 17.6: *Page 3: Delicate adiabatic*

Our reply: The phrase "delicate adiabatic" has been revised. The term "adiabatic bend" in photonic

waveguide design refers to a curvature geometry that minimizes mode coupling and radiative losses by ensuring a gradual variation of curvature along the propagation path (i.e., curvature changes smoothly as a function of arc length). Unlike abrupt bends, which induce mode hybridization and scattering losses due to abrupt changes in effective refractive index, adiabatic bends preserve the fundamental mode's propagation characteristics through controlled geometric transitions. Common implementations include Euler bends (based on the Euler spiral/clothoid curve, where curvature increases linearly with arc length) and Archimedean bends (curvature follows an Archimedean spiral profile). Specific details can be found in *Supplementary Note 1: Waveguide amplifier design*.

(Results, Page 3) ~~Delicate~~ The adiabatic bend design is adopted here⁴¹ for quasi-single-mode transmission with compact size.

Comment 17.7: *Fig. 3 caption: intensely pumped*

Our reply: The phrase "intensely pumped" in Fig.3 caption has been revised to "under high-power optical pumping" to adhere to standard terminology and clarify the experimental conditions during imaging.

(Fig. 3, Page 4) Fig.3 Right panel, optical image of an ~~intensely pumped~~Er:TFLN chip **under optical pumping of 115 mW**, ...

Comment 17.8: *Page 4: which is intuitive -> remove*

Our reply: The phrase "which is intuitive" has been removed, and the sentence has been revised to concisely describe the gain-pump power relationship observed in Fig. 4a.

(Results, Page 4) ~~The internal net gain~~ **gain factor** increases **much slower** with the pump power, **as the pump power > 80 mW compared with that in the low pump power region (0~20 mW)**. ~~which is intuitive, then gradually gets saturated when the off-chip pump power is over 20 dBm.~~

Comment 17.9: *Generally, the net gain dynamically changes... -> too general/obvious – consider rewording*

Our reply: We appreciate the reviewer's feedback. The original sentence has been revised to specify the factors influencing net gain dynamics.

(Results, Page 4) ~~Generally, the net gain dynamically changes under different pump powers.~~ **The net gain increases progressively with the pump power and stabilizes when the off-chip pump power exceeds a threshold of 100 mW, as shown in Fig. 3c.**

Comment 17.10: *Page 6: delicately*

Our reply: We thank the reviewer for the suggestion. The phrase "delicately " has been removed from the sentence.

(Results, Page 6) With ~~the delicately~~ designed modulation region on the high-gain optical amplifier, we present, to the best of our knowledge, the first demonstration of broadband modulation characteristics on Er:TFLN.

Comment 18: *"The manuscript requires another careful check of English, some examples are below."*

Our reply: We sincerely thank the reviewer for their meticulous attention to language quality. We have

thoroughly revised the manuscript to address grammatical errors and improve clarity. Below are specific corrections.

Comment 18.1: *Fig. 2 caption: an sine wave*

Our reply: We thank the reviewer for identifying the grammatical error. The phrase "an sine wave" in Fig. 2f caption has been corrected to "a sine-wave signal modulation"

(Fig. 2, Page 3) Fig. 2 f, Spectrum when ~~an~~ a sine wave signal with

Comment 18.2: *Page 3: is adopt*

Our reply: The cited sentence has been revised to correct grammatical errors.

(Results, Page 3) To suppress the scattering loss, the multimode waveguide with width of 3 μm and height of 600 nm is ~~adopt~~ **adopted** to decrease the interaction between the optical field and the etched sidewalls.

Comment 18.3: *Fig. 3 caption: Optical spectra of signals output*

Our reply: The phrase in question has been revised to adhere to standard scientific phrasing.

(Fig. 3, Page 4) Fig. 3.....b, Optical spectra of **output signals** ~~signals output~~ from the pumped amplifier, when the off-chip input signal power is -39.6 dBm.....

Comment 18.4: *Page 4: As the electrode apart*

Our reply: The sentence has been revised for grammatical clarity.

(Results, Page 4) **As the electrode spacing increases**, ~~As the electrode apart from the optical waveguide,~~ the interaction between the applied electrical field and the optical field **decreases**. ~~is decreased.~~

Comment 18.5: *Page 4: A optical spectrum analyzer*

Our reply: The sentence has been revised for grammatical clarity.

(Results, Page 4) To accurately extract the gain performance, the powers of output and input signal are directly measured and compared in the spectra recorded by ~~a~~ **an** optical spectrum analyzer (OSA), where the pump power interference could be eliminated due to the inherent wavelength selectivity of the optical spectrum analyzer.

(Methods, Page 10) ~~A~~ **An** optical spectrum analyzer is employed to capture the spectra of both the input signal light and the amplified signal light.

Comment 18.6: *Page 7: analogy RF*

Our reply: The phrase "analogy RF" has been corrected to "analog RF" to accurately reflect the signal type tested.

(Results, Page 7) To verify the capability of Er:TFLN in real-world applications, the developed chip with both amplification and modulation is used for **analog** ~~analogy~~ RF receiving system.

Comment 18.7: *continuous wave (FMCW) -> word missing*

Our reply: We thank the reviewer for highlighting the missing hyphen in "frequency-modulated" and

the typo in "received." The sentence has been revised to use the standardized term "frequency-modulated continuous wave (FMCW)"

(Results, Page 7) A **frequency-modulated** continuous wave (FMCW), chirped between 8 GHz and 12 GHz, is applied to the phase modulator, acting as an RF signal to be **received** ~~received~~.

Comment 18.8: *in frequency domain*

Our reply: The phrase "in frequency domain" has been corrected to "in the frequency domain" to ensure grammatical accuracy and consistency with technical standards.

(Results, Page 7) The detected RF signal is recorded in **the** frequency domain (depicted in Fig. 5b) with an electric signal analyzer and in **the** time domain with an oscilloscope.

Comment 18.9: *the spectroscopy is obtained*

Our reply: Thank you for identifying this phrasing issue. The sentence has been revised to align with standard terminology and grammar in optical characterization.

(Results, Page 7) Using the short-time Fourier transform, the ~~spectroscopy~~ **spectra** are **recorded** ~~obtained~~, revealing the instantaneous frequency chirping over time, as shown in Fig. 5c.

Comment 18.10: *the increasement*

Our reply: We thank the reviewer for highlighting the non-standard term "increasement." The sentence has been revised to use the correct term "increasing".

(Results, Page 7) Further, the ~~increasement~~ **increment** of the absorption cross-section would help elevate the saturated optical power, which could be achieved by ~~enlarge~~ **enlarging** the mode area⁴⁰.

Response to the report from the Referee #2

General comments: *"I have carefully read and analyzed the paper titled "Unifying Optical Gain and Electro-Optical Dynamics in Er-doped Lithium Niobate Platform" and the supplementary information provided with the manuscript.*

The authors describe in detail the fabrication, design, and characterization of a photonic chip that utilizes a thin-film erbium-doped lithium niobate layer. The photonic chip contains both an amplitude modulator used for on-off keying (with a length of 8 mm) and a phase modulator used for FMCW style modulation, combined with a 6 cm long amplifier spiral. In figure 2, the modulator design is discussed together with a photoluminescence spectrum from the waveguide. In figure 3, the amplification of a single laser line is presented and discussed. In figure 4, the authors present the modulator devices together with the results of a 50 Gbps on-off keying system experiment. It also includes optical spectra of a high-RF-frequency phase-modulated optical carrier. Finally, in figure 5, the modulation of a laser line with an FMCW signal is presented. In the discussion, ways for further improvement of the performance metrics are given and possible future applications are presented. In the supplementary information, the authors present additional technical details on the measurements they performed and the simulations that were used for the device design.

The results presented in the paper are interesting and highly relevant given the fast-moving field of photonic integration, with many recent advances in both thin-film lithium niobate and rare-earth doped waveguides. Moreover, the figures that present the results are highly detailed and very well thought through, with great attention to visual clarity. In general, the paper presents interesting results with excellent graphics.

Our reply: We sincerely appreciate the reviewer's positive assessment of our work. We have implemented the following revisions to address these suggestions.

Comment 1: *"My main comment is that the writing is sometimes not fully clear, and in many sentences, hard-to-understand phrasing is used. I would recommend that the authors try to rewrite the text to improve this issue. Some examples of the language issues:"*

Our reply: Thanks for carefully reading our manuscript. We have revised the corresponding parts as follows.

Comment 1.1: *Page 3: Fig. 2. a(iii) "Pseudo color picture images..." — it is my understanding that this is a false-color SEM image?*

Our reply: Sorry for the improper expression. We have replaced the ambiguous term "pseudo color picture images" with "false-color SEM images" in the caption of Fig. 1. Also, "pseudo-color picture" in the caption of Fig. 4 is revised to "false-color picture".

(Fig. 1, Page 2) Fig. 1. b, (i) Cross-sectional schematic of the waveguide amplifier, (ii) ~~False Pseudo-color picture images~~ of the waveguide amplifier, (iii) Cross-sectional schematic of the modulator, (iv) ~~False Pseudo-color picture images~~ of the modulator.

(Fig. 4, Page 5) Fig. 4. Modulation characteristics on Er:TFLN. a, ~~False Pseudo-color picture~~ of a intensity modulator on Er:TFLN. b, ~~False Pseudo-color picture~~ of a phase modulator on Er:TFLN.....

Comment 1.2: *Page 3: "... is the most fatal blocks compared with..."*

Our reply: The sentence on Page 3 has been revised:

(Results, Page 3) For efficient amplifiers in the integrated Er:TFLN platform, the background loss, especially the scattering loss, ~~is the most fatal blocks~~ **emerges as the primary limiting factor** compared with their fiber-based competitor.

Comment 1.3: Page 3: "... height of 600 nm is adopt to decrease ..."

Our reply: The sentence has been revised to correct grammatical errors.

(Results, Page 3) To suppress the scattering loss, **we implement a 3 μm -wide $\times$ 600 nm-height multimode waveguide** ~~the multimode waveguide with width of 3 μm and height of 600 nm is adopt to~~ decrease the interaction between the optical field and the etched sidewalls.

Comment 1.4: Page 3: "...waveguide with a fully-etched process..."

Our reply: The sentence has been revised to align with standard micro-fabrication terminology

(Results, Page 3) Different from the typical ridged waveguide in TFLN platform, the optical amplifier **employs a** ~~is formed by~~ strip waveguide with a fully-etching process, as shown in Fig. 2a(i).

Comment 2: "Can the authors clarify why this electrode geometry was chosen exactly? If I understand correctly, the lithium niobate modulators realized in 2018 had a much smaller $V_{\pi}L$ (see for example <https://doi.org/10.1038/s41586-018-0551-y>)."

Our reply: We appreciate the reviewer's insightful question regarding the electrode geometry design. While the 2018 LN modulator referenced in the comment achieved a lower voltage-length product ($V_{\pi}L \approx 2.8 \text{ V}\cdot\text{cm}$), our design prioritized balancing low optical loss with modulation efficiency. By placing electrodes on the oxide-clad LN waveguide (rather than directly atop the LN layer), we minimized optical propagation losses while maintaining a competitive $V_{\pi}L$ of 3.1 V·cm (revised from 3.5 V·cm). The slightly higher $V_{\pi}L$ in our work stems from reduced microwave-optical field overlap due to the oxide spacer, a deliberate choice to avoid metal-induced absorption. Future optimizations could adopt slow-wave electrode designs to enhance microwave-optical interaction without compromising loss, further lowering $V_{\pi}L$.

Comment 3: "Given that the performance of the amplifier relies also on the in- and out coupling, can the authors comment on why facets with relatively high losses were used?"

Our reply: Thank you for your insightful comments. We designed an inverse taper considering an input mode diameter of 3 μm , with a simulated coupling loss of 0.8 dB/facet at 1530 nm (Fig. R5). While the estimated coupling loss in experiment is 3 dB/facet for lensed fibers with a mode diameter of 3 μm and a numerical aperture (NA) is 0.25. The SEM of the fabricated edge coupler is depicted in Fig. R6. The larger coupling loss may be due to unideal fabrication such as under/over-etching and minor chip-edge wear[R16]. In experiment, we find that the index mismatch between the fiber-air-chip facet leads to great reflection, resulting in several parasitic lasing. Thus, we use UHNA7 fiber, which is already spliced to single-mode fiber) with index-matching gel for the test, with the same mode diameter but a larger NA of 0.41. The larger NA leads to a high coupling loss of 6.7 dB/facet. The detailed selection of fibers to suppress the parasitic lasing can be found in Reviewer #1's "**Reply to comment 8**".

In addition, we would like to highlight the 24.6 dB off-chip net gain despite the large coupling loss at the

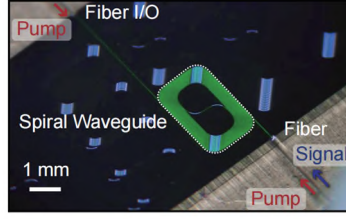


Fig.3 butt-coupled with PC-fibers.

Comment 5: "Please clarify what you mean exactly by net internal gain when you first introduce the term in the text. What exactly does this include and exclude?"

Our reply: We thank the reviewer for raising this important question about the definition of "net internal gain." The term "internal net gain" refers specifically to the on-chip optical power amplification within the Er:TFLN waveguide itself, excluding the external loss such as the fiber-chip coupling loss and the fiber link loss. This value represents the pure amplification within the waveguide amplifier which is a standardized characteristic for optical amplifiers[R4]. To provide a clearer explanation, we have added detailed descriptions in the Methods section (Amplification measurement).

[R4]Liu, Y. et al. A photonic integrated circuit-based erbium-doped amplifier. Science 376, 1309–1313 (2022).

(Methods, Page 10) The internal net gain refers specifically to the on-chip optical power amplification within the Er:TFLN waveguide itself, calculated by accounting for all passive losses except input/output coupling. This value represents the pure amplification within the waveguide, excluding coupling losses and link loss. It is defined as:

$$G_{net} = P_{out}^{(off-chip)} - P_{in}^{(off-chip)} + L_{coupling} + L_{link}$$

where:

$P_{out}^{(off-chip)}$: Optical power measured after the chip (e.g., -17.6 dBm at 1531.6 nm in Fig. 3b),

$P_{in}^{(off-chip)}$: Input power launched into the chip (e.g., -39.6 dBm in Fig. 3b),

$L_{coupling}$ =13.4 dB: Total input/output fiber-chip coupling loss,

L_{link} =2.9 dB: Passive propagation loss in the unpumped waveguide.

Comment 6: "In most of the experiments, measurements are performed with and without pump. It is sometimes unclear to me what conclusions can be taken from this. As erbium is a 3-level system, the signal will be heavily absorbed when there is no pump present. Therefore, comparing the signal strength with and without the pump laser does not provide information on amplification. Can the authors clarify what model they use exactly to infer the amplification from these experiments?"

Our reply: We appreciate the reviewer's question regarding the methodology for evaluating amplification in our experiments. In the experiments related to Fig. 4 and Fig.5, we intend to validate two different aspects. The first is that the amplification process does not degenerate the modulation process, ensuring the co-functionality of both optical amplification and EO modulation. The second is that such co-functionality can be applied to real-world applications. We would like to give a detailed description as below.

In the section “Broadband electro-optic conversion” and Fig. 4, we perform two experiments to demonstrate that **the amplification process does not degenerate the modulation process**. Thus, the comparison for with/without the pump is critical. Firstly, we measured the EO S_{21} response through an intensity modulator (see Fig. 4a), showing a 3-dB bandwidth of 53 GHz. And a clear OOK eye diagram was obtained with the amplification, accompanied by a signal-to-noise ratio (SNR) improvement of the eye diagram. Due to the short length of the intensity modulator (8 mm), there is only a 6 dB enhancement in Fig. 4c. Thus, we test another structure, which consists of a phase modulator and a 6-cm-long spiral. In this experiment, we demonstrate the EO modulation up to 170 GHz. To extract the amplification, in the revised Supplementary Note XI, we give the detailed off-chip input power and the amplified output power. With the input power above 0 dBm, we cannot get a positive off-chip net gain, while the internal net gains are about 10 dB. The worse gain factor compared with that shown in Fig. 3 is due to the shorter spiral and the larger propagation loss in the modulation region where a single-mode waveguide is adopted. With a longer amplifier and a lower coupling loss, a high off-chip net gain is expected.

(Results, Page 6) With the ~~the~~ **delicately** designed modulation region on the high-gain optical amplifier, we present, to the best of our knowledge, the first demonstration of broadband modulation characteristics on Er:TFLN **through pump on/off experiments to validate high-fidelity signal integrity.**

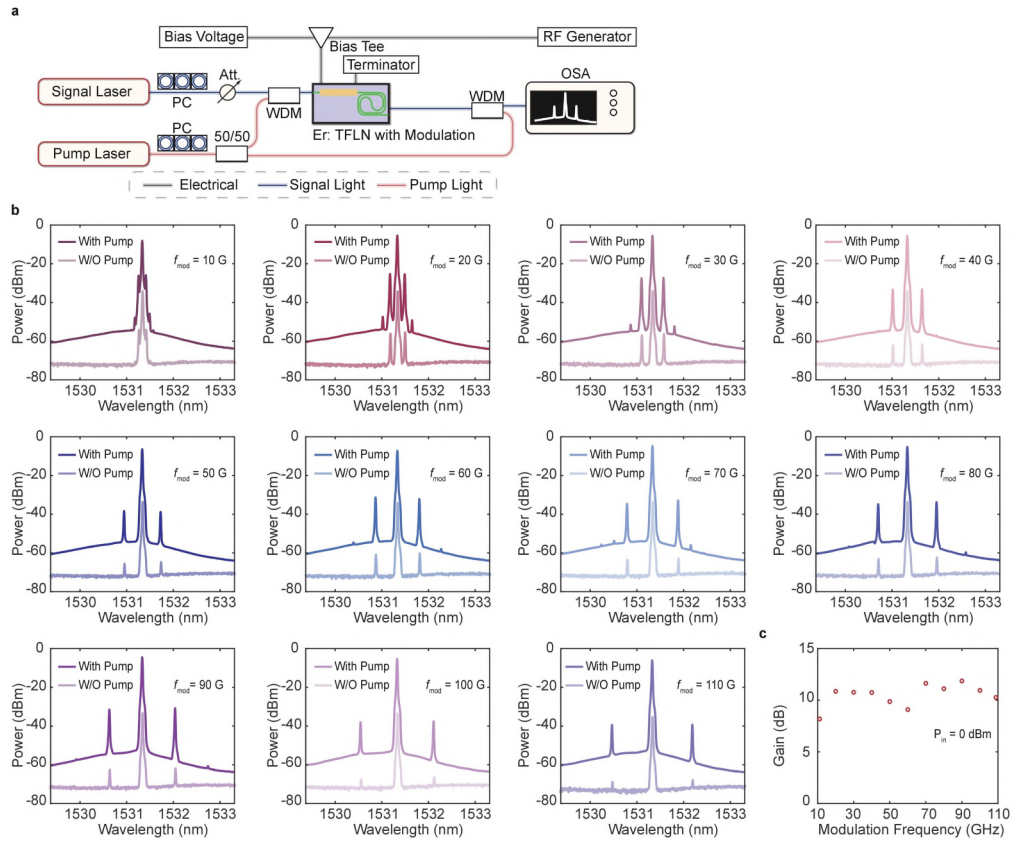


Fig. S12. Amplification experiment of 10 GHz - 110 GHz modulated signals. a, Experimental setup, f_{mod} , Modulation frequency. b, Spectrum of the modulated signal. c, **Measured internal net gain under different modulation frequencies.**

In the section “Analog RF receiving with pre-amplification” and Fig.5, we demonstrate that such co-functionality can be applied for real-world applications. The integrated phase modulator and the 6-

cm-long spiral are employed in an analog RF receiver. We acknowledge that the previous comparative experiment setup was improper and have redesigned the experiment according to the comment.

The revised manuscript presents three sets of results under different experimental conditions. The first is conducted at 1600 nm band using the Er:TFLN chip without the pump. At 1600 nm, the large absorption loss of Er^{3+} ions can be avoided. However, the long spiral waveguide introduces substantial background loss, resulting in an off-chip output power of -15.0 dBm with an off-chip input signal power of 5 dBm. And then the same test is performed at 1550 nm with the pump light. The input signal power remains the same as in the first one. Thanks to the amplification process, the off-chip output power is -4.2 dBm, achieving an internal net gain of 7.1 dB and a received SNR of 30 dB, with a 21 dB improvement over the first one. The third uses an undoped TFLN modulator and a commercial EDFA (Amonics AEDFA-PA-35-B-FA). The TFLN modulator exhibits a half-wave voltage V_π of 5.6 V, coupling loss of 8.9 dB/facet, and 3-dB EO bandwidth of 40 GHz. Despite a smaller EO bandwidth, the frequency response difference has a negligible impact due to the relatively low operating frequency range (8-12 GHz). The test link is similar to the second one while with the commercial EDFA inserted after the modulator. The input signal power and the received optical power are kept the same as the second one. Without a pre-amplification feature as in Er:TFLN, the signal suffers a pure loss during propagation along the waveguide and coupling out from the TFLN chip. Thus, more of the signal is drowned in the noise. Although amplified by a bulk EDFA afterwards, the received SNR is 8-dB lower than in the second one.

With the revised comparative experiment, we validate the feasibility of such co-functionality in Er:TFLN. In addition, we would like to emphasize **the importance of such co-functionality for integrated large-scale photonic systems**. For instance, cascaded architectures are necessary for complex optical computing tasks, to function as multi-layer convolutional networks. In such systems, signal degeneration from layer to layer, mainly limited by the insertion loss of integrated optical devices, can severely limit scalability. **Compared with the amplification after the whole networks, the final signal-noise ratio would be much better to compensate for the insertion loss in the networks, considering a higher input signal power level.** The Er:TFLN platform, enabling both high-speed modulation and low-noise optical amplification, is therefore highly promising for scalable integrated photonic systems.

Accordingly, we rearrange this section as follows:

(Results, Page 6) Analog RF receiving with pre-amplification

To verify the capability of Er:TFLN in real-world applications, the developed chip with both amplification and modulation is used for analog RF receiving system. The schematic is shown in Fig. 5a and detailed experimental setups are given in Supplementary Note XII). A frequency modulated continuous wave (FMCW), chirped between 8 GHz and 12 GHz **at a repetition rate of 800 kHz**, is applied to the phase modulator, acting as an RF signal to be received. The FMCW signal is loaded on the optical carrier and amplified through the developed modulator and amplifier. A ~~fiber Bragg grating~~ bandpass filter (BPF) is employed to suppress the lower sideband, converting the phase-modulated signal to an intensity-modulated signal. The filtered optical signal is detected by a photodetector, converting it back into an RF signal. The detected RF signal is recorded in the frequency domain (depicted in Fig. 5b) with an electric signal analyzer and in time domain with an oscilloscope. Using the short-time Fourier transform, the spectroscopy is obtained, revealing the instantaneous frequency chirping over time, as shown in Fig. 5c.

When the ~~pump light is turned off~~ **signal light is at 1600 nm without the pump light**, the on-chip loss and coupling loss decrease the output optical power to **-15.0 dBm**, resulting in a detected SNR of **9 dB**, as depicted in Fig. 5b(i). **The low SNR prevents the extraction of the instantaneous frequency.**

When the operation wavelength is tuned to the amplification band, the output signal is boosted to -4.2 dBm with the pump, resulting in a SNR of 30 dB. A clear FMCW signal can be recovered, as shown in Fig. 5c(ii). For comparison, an undoped TFLN phase modulator is adopted to receive the same RF signal and then amplified by a commercial EDFA. The RF power, input optical power and amplified power level are set the same as the previous setup. The recovered RF signal in this configuration shows an SNR of 22 dB. Interestingly, the proposed approach can recover the signal with an increase in SNR than utilizing conventional fiber optics. This can be attributed to the position of the amplifier in the system, besides the difference in insertion loss. When using the on-chip amplifier with the pump light, the signal is modulated and amplified simultaneously, allowing the signal to maintain a high power level with low amplifier noise. In contrast, the EDFA amplification occurs after significant insertion loss from the undoped TFLN chip, which degrades the modulated signal and makes it drown into background noise. Although the EDFA can boost the weakened optical signal, the low input power results in a higher level of amplified spontaneous emission noise.

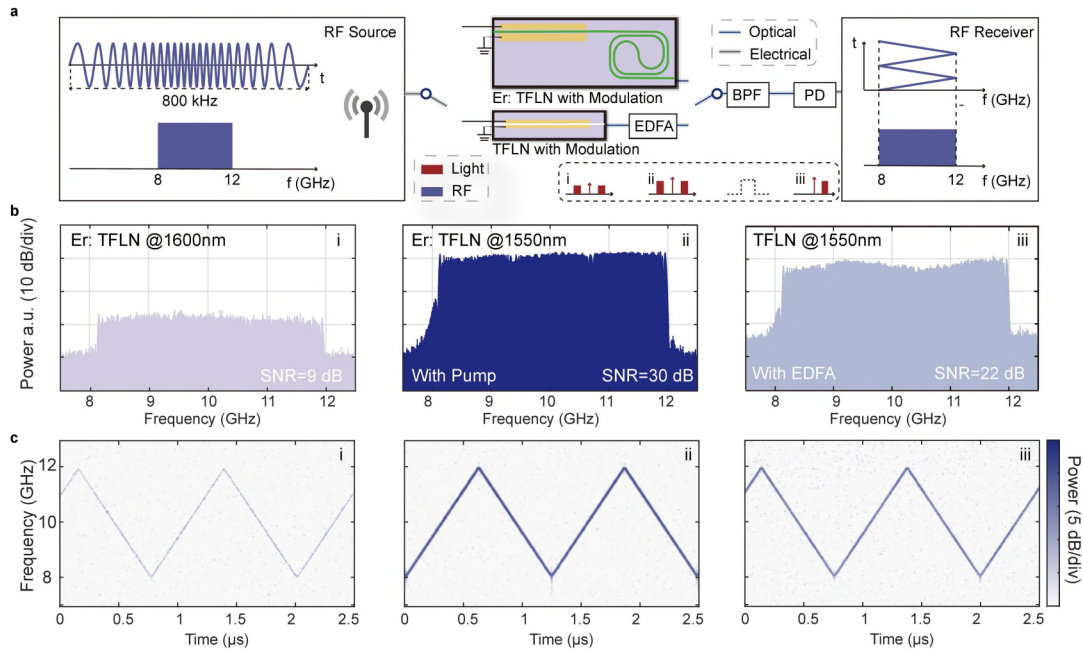


Fig. 5. On-chip signal modulation and amplification. a, Setup of frequency-modulated continuous wave (FMCW) signal modulation and amplification **chirped between 8 GHz and 12 GHz at a repetition rate of 800 kHz**. BPF, band pass filter. b-c, The received microwave signal and time-frequency spectra of the beatnote between the carrier and the sideband when the signal light is (i) **at 1600 nm** without pump light , (ii) **at 1550 nm** with pump light and (iii) **with the EDFA at 1550 nm by using a TFLN-based modulator and an EDFA**.

Comment 7: "Can the authors clarify what exactly they expect for the EO S21 as shown in Fig. 4(c)? As I understand it, this just implies that the light was amplified. Or is it expected that the pump would somehow influence the shape of the EO S21?"

Our reply: Thanks for the insightful question. We try to convey that the Er³⁺ amplifier and EO modulator are functionally decoupled, whether the amplifier is turned on has minimal impact on the modulation characteristic, despite their monolithic integration.

Comment 8: "Please add a very detailed set-up description to the supplementary information where the

exact power level is described at each point in your set-up, so it is easier to understand how the numbers used are calculated."

Our reply: Thank you for your advice. We have incorporated the relevant details in accordance with the reviewers' comments.

1. Half-wave voltage characterization

(Supplementary Note IX, Page S14)

..... The frequency of the applied RF signal is 50 MHz. The off-chip input signal light power is 12 dBm, and the received optical power is plotted from the spectrometer. The spectrometer (APEX AP2081A) with an ultra-high resolution of 0.04 pm is used to record the spectrum. As shown in Fig. 2f and Fig. S10, the carrier and FSB are equal in intensity when V_m is about 3.5 V, which leads to³³:

$$V_m \approx 0.457 \cdot V_\pi \quad (4)$$

Therefore, the V_π is calculated to be 7.6 V. Considering a push-pull modulation, the $V_\pi \cdot L$ could reach 3.1 V·cm. A lower V_π can be achieved by using a longer RF electrode. Additionally, employing a slow-wave electrode can further decrease the half-wave voltage at high frequencies by minimizing microwave losses³⁴.

2. Bandwidth and high-speed data measurement

(Supplementary Note X, Page S15)

For the bandwidth test (Fig. S11a), the linear EO transmission is measured using a vector network analyzer (Keysight PNA-X N5247B) equipped with a 67-GHz lightwave component analyzer (Keysight LCA Optical Receiver N4372E) plug-in. The connection RF wires hold an electrical bandwidth of 50 GHz and are precalibrated over 60 GHz before the test. A pair of high-speed microwave probes were used to deliver the modulation signal to the input port of the transmission line, and to terminate the output of the transmission line with a 50-Ω terminator. We measured the EO S21 parameter with and without pump light. **The off-chip input signal light power is 5 dBm at 1550 nm, and the received optical power is -18 dBm (without pump) and -5 dBm (with pump) at the lightwave component analyzer. The electro-optic responses are plotted from the vector network analyzer (Fig. 4c).**

In the data transmission experiments (Fig. S11b), the high-speed OOK signal with a PRBS pattern is generated by a bit pattern generator (SHF 12104A). The electrical signals are amplified by a commercial driver (SHF S807C) to obtain a 2 V peak-to-peak voltage (V_{pp}) and then injected into the modulator operating in a push-pull configuration. At the receiving end, a 50 GHz photodiode (PD, Coherent HPDV2120R) is used to receive the optical signal. Digitized data are collected using an 80-GSa/s real-time oscilloscope with an analog bandwidth of 62 GHz (Keysight DSA-X 96204Q). **The off-chip input signal light power is 10 dBm at 1550 nm, and the received optical power is -12 dBm (without pump) and 0 dBm (with pump) at the photodetector.** The eye diagrams are also plotted from the oscilloscope (Fig. 4d).

3. Amplification with full-band modulation test

(Supplementary Note XI, Page S16)

For the amplification with modulation test (Fig. S12a), the RF generator (Keysight N5222B + N5292A)

loads microwave signals ranging from 10 GHz to 110 GHz onto the modulator, with the resulting sidebands observable on the optical spectrometer analyzer (YOKOGAWA AQ6370C). The output microwave power from 10 GHz to 110 GHz is approximately 7 dBm. For higher frequency signals (from 110 GHz to 170 GHz), a frequency multiplier (SGFE06) is used to up-convert the signal frequency generated by the RF generator (Keysight E8257D) before it is applied to the modulator (Fig. S13a). The output microwave power from 110 GHz to 170 GHz is approximately 10 dBm.

The off-chip input signal light power from 10 to 110 GHz is 0 dBm and from 110G to 170G is 3.86 dBm. Based on the net gain calculation method described in Methods, the calculated net gain is shown in Fig.S12c and Fig.S13c. The lower net gain compared to that in Fig. 3b is due to the shorter delay line (6 cm) and the higher-loss single-mode waveguide used in the modulator section.

4. Analog RF receiving with pre-amplification

(Supplementary Note XII, Page S18)

When the pump light is turned off signal light is at 1600 nm without the pump light, the on-chip loss and coupling loss decrease the output optical power to -15.0 dBm, resulting in a detected SNR of 9 dB, as depicted in Fig. 5b(i). The low SNR prevents the extraction of the instantaneous frequency. When the operation wavelength is tuned to the amplification band, the output signal is boosted to -4.2 dBm with the pump, resulting in a SNR of 30 dB. A clear FMCW signal can be recovered, as shown in Fig. 5c(ii). For comparison, an undoped TFLN phase modulator is adopted to receive the same RF signal and then amplified by a commercial EDFA. The RF power, input optical power and amplified power level are set the same as the previous setup. The recovered RF signal in this configuration shows an SNR of 22 dB. Interestingly, the proposed approach can recover the signal with an increase in SNR than utilizing conventional fiber optics. This can be attributed to the position of the amplifier in the system, besides the difference in insertion loss. When using the on-chip amplifier with the pump light, the signal is modulated and amplified simultaneously, allowing the signal to maintain a high power level with low amplifier noise. In contrast, the EDFA amplification occurs after significant insertion loss from the undoped TFLN chip, which degrades the modulated signal and makes it drown into background noise. Although the EDFA can boost the weakened optical signal, the low input power results in a higher level of amplified spontaneous emission noise.

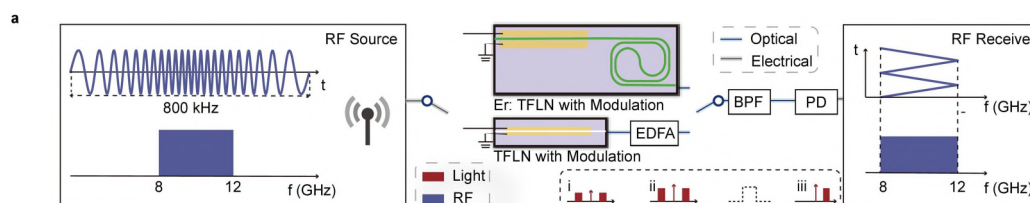


Fig.5 a. Setup of frequency modulated continuous wave (FMCW) signal modulation and amplification.

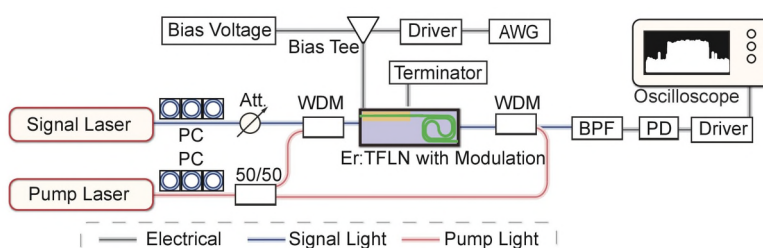


Fig. S14. **Setup of on-chip signal modulation and amplification based on Er:TFLN platform. BPF, bandpass filter.**

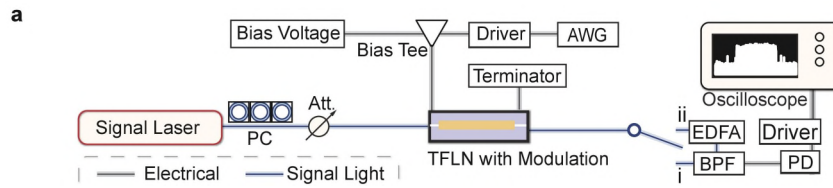


Fig. S15. **Signal modulation and amplification based on TFLN platform. (a) Experimental setup.....**

Comment 9: " I think for the experiments shown in Fig. 4(f) and Fig. 5, the comparison of with and without pump is not very relevant. When not pumped, the 6 cm spiral will strongly absorb the signal light. The correct comparison would be with and without the amplifier waveguide if the authors want to demonstrate amplification. Can the authors comment on how they would improve this experiment to extract the amplification from the spiral? Moreover, the change in SNR with and without pump in Fig. 5(b) is also not relevant, as without pump the signal is absorbed by the amplifying waveguide. I would ask the authors to explain why they chose this approach."

Our reply: Thank you for your question. A detailed discussion is given in "**Reply to comment 6**". We hope the revised manuscript can solve your concerns.

Response to the report from the Referee #3

General comments: *"The authors present what they believe to be the first integrated modulator-amplifier in TFLN, a material platform that has garnered significant attention in recent years due to its excellent modulation capabilities. The integration of modulation and amplification opens the door to promising developments, such as lossless modulators and other advanced photonic building blocks. However, the reviewer remains uncertain about the platform's potential for developing complex PICs, as suggested by the authors. The need for erbium doping necessitates circuit-wide pumping, which could be undesirable and lead to unnecessarily high power consumption. That said, this concern is speculative and will only be clarified with further research. Overall, the reviewer finds the work presented in this manuscript worthy of publication in Nature Communications, particularly after addressing the comments outlined below, which aim to further enhance the quality of the paper."*

Our reply: We sincerely appreciate the reviewer's insightful assessment of our work's significance. The reviewer raises a special concern about circuit-wide pumping, which essentially relates to the integration of laser sources, a common challenge for the TFLN platform. Especially, as the network scales up, achieving circuit-wide pumping with the current external pump configurations will pose even greater challenges in terms of power consumption and system complexity. Further studies to address this issue could explore heterogeneous laser integration and distributed on-chip pump schemes, which build upon insights of the current state-of-the-art work and warrant deeper investigation, as we summarized in "**Reply to comment 6**". We also appreciate the constructive comments, which we have addressed point by point as follows.

Comment 1: *"In the abstract the authors mention the NF of 4.3 dB, which is really good. Please, specify whether this is internal or external (fiber-to-fiber)."*

Our reply: We thank the reviewer for highlighting this important detail. The NF of 4.7 dB (revised from 4.3 dB) in this paper adopts the EDFA's noise figure test method: Optical Source-Subtraction Method[R18], which can remove the source spontaneous emission (SSE) noise from the total noise emitted by the erbium amplifier. As clarified in D. Derickson's Fiber Optic Test and Measurement (1998), this method mandates measuring noise 0.3 nm from the peak (not 0.4 nm, as previously applied). Using the corrected 0.3 nm separation, we re-analyzed the experimental data ($P_{\text{out}} = -53.5$ dBm and $P_{\text{SSE}} = -80.1$ dBm) to derive the updated NF value. Our measurement methodology inherently includes all fiber-chip coupling losses and waveguide propagation losses, aligning with the external NF definition. While the terminology of "internal" or "external" (fiber-to-fiber) NF is not strictly defined in EDFA literature. Therefore, we avoid using the terms "internal" or "external" when referring to the NF in this work. The same test method is also used in the NF characterization of other optical waveguide amplifiers[R4]. We have revised the original manuscript as follows.

(Methods, Page 10)~~Substitution~~ **Substituting** the measured results into the Eq. 5 yields a noise figure of ~~4.3~~ **4.7** dB.

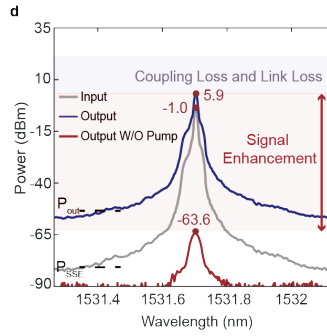


Fig. 3. High gain Er:TFLN waveguide amplifier. d, Optical spectra of the input signal and the amplified signal under a high off-chip input signal power of -1 dBm.....

[R18] D. Derickson, Fiber Optic Test and Measurement, D. Derickson (Ed). (1998).

[R4] Liu, Y. et al. A photonic integrated circuit-based erbium-doped amplifier. Science 376, 1309–1313 (2022).

Comment 2: " Page 1 second column: please, clearly state that the 30dB of net gain in reference 24 is "internal" net gain. Overall, please try to be very concise and specify whether a gain is internal or fiber-to-fiber. The same with the powers, state very clearly whether they are on-chip or off-chip. This will enhance the readability of the paper and the understanding of the reported measurements. Adding to this comments, the authors mention the 30 dB in reference 24 as the highest internal net gain reported (or one of the highest), while as they show in the Table comparing the different erbium amplifiers in the supplementary materials, Bonneville et. al, have shown an even higher internal net gain. Maybe rewrite a bit the sentence to include both references."

Our reply: We agree that clarifying the distinction between internal and external metrics is critical for the readability of the paper and the understanding of the reported measurements. In the revised manuscript, we have explicitly specified all gains and powers as internal (on-chip, excluding fiber coupling losses) or external (fiber-to-fiber, including coupling losses). Regarding the 30 dB net gain in Ref. 24, we acknowledge that our original phrasing inadvertently omitted the higher internal net gain of 33.5 dB reported by Bonneville et al. (Ref. 26) in the supplementary table. To address this, we have revised the relevant sentence as follows.

(Introduction, Page 1) Although Er-doped waveguide amplifiers²⁴ with a an **internal** net gain exceeding 30 dB^{24,26}, comparable to commercial standards, have been demonstrated on the SiN platform **and Al₂O₃ platform**, the passive nature of ~~this platform~~ **these platforms** impedes further monolithic manipulation of EO conversion.

Comment 3: " In Page 2 first paragraph the authors write: "Furthermore, these systems still face challenges, including relatively high waveguide loss, inherent amplification noise, and significant nonlinearity, which limits performance, especially in applications that demand high fidelity and low crosstalk". Please, compare the non-linearity and expected performance between the silicon platform and the TFLN platform. The TFLN is highly non linear. Please, explain why the TFLN is expected to behave in a better way in terms of non linear effects, signal distortion and power handling."

Our reply: Sorry for the misleading description. The "**nonlinearity**" in the mentioned sentence is

intended to mean the **nonlinear EO conversion** and the **nonlinear effect associated with the amplification process**, which can lead to signal distortion.

For the **nonlinear EO conversion**, it is a serious limitation in silicon photonic (SiPh) modulators. The EO modulation in silicon photonics mainly relies on the plasmonic dispersion effect, which is an inherently nonlinear EO process. The modulation in LN relies on the Pockels effect, which is a **linear EO effect**. The typical spurious-free dynamic range (SFDR), which is a standard characteristic for the modulation linearity, of MZM-intensity modulators on SiPh and TFLN is 85 and 100 respectively [R19-20]. This reveals a **better modulation linearity of LN-based modulators**.

For the **nonlinear effect associated with the amplification**, it is a serious limitation in semiconductor optical amplifiers (SOAs). Considering the amplification process, due to a much shorter **response time (ns-level for SOA compared with ms-level for Er-doped amplifier)**, SOA suffers from severe cross gain modulation (XGM) and cross phase modulation (XPM). In addition, the third nonlinear index of III-V material is about one order higher than that of LN, SiN, Al₂O₃, etc., leading to severer XPM and four-wave mixing (FWM). These nonlinear effects lead to inter-channel crosstalk and signal distortion for multi-wavelength amplification. Thus, **compared with SOAs, one of the commercial integrated optical amplifiers, Er:LN optical waveguide amplifier presents weaker nonlinearity**.

As for the **high nonlinearity of TFLN platforms**, it tends to refer to the **high optical nonlinearity** including second order and third order nonlinearity, compared with bulky waveguides such as single-mode fibers and bulk LN. This originates from a higher energy density with the integrated waveguide, where the mode profile shrinks from hundred-square-millimeters to sub-square-micrometers. While it is worth noting that a delicate phase matching design is necessary for an effective second order nonlinear process. Such effects can be ignored in a common waveguide. As the third order nonlinearity of TFLN is comparable with that of integrated SiN, **watt-level input power [R21] is needed to stimulate the optical nonlinearity in a waveguide**, which is a quite high power level for integrated photonics. Thus, in the Er:TFLN platform, **the optical nonlinearity will not influence its application for most cases**. For certain cases where optical nonlinearity is needed, microring structures with the intracavity power enhancement or high pump powers can be employed.

As for the **power handling**, this has been experimentally demonstrated in [R22], where lithium niobate waveguides were shown to support and **guide optical powers at the watt level**.

In conclusion, **the Er:TFLN platform expresses good modulation linearity and amplification linearity** thanks to the linearity EO effect of LN and the long response time of Er³⁺ ions. For a clearer claim, we have revised the manuscript:

(Introduction, Page 2) Furthermore, these systems still face challenges, including relatively high waveguide loss, inherent amplification noise, and signal ~~nonlinearity~~, **distortion caused by nonlinear gain process in III-V material and nonlinear silicon based EO conversion^{17-19,31}**, which limits performance, especially in applications that demand high fidelity and low crosstalk.

[R19]S. Chen, G. Zhou, L. Zhou, L. Lu and J. Chen, "High-Linearity Fano Resonance Modulator Using a Microring-Assisted Mach – Zehnder Structure," in Journal of Lightwave Technology, vol. 38, no. 13, pp. 3395-3403, 1 July1, 2020, doi: 10.1109/JLT.2020.2971094.

[R20]Hanke Feng, Ke Zhang, Wenzhao Sun, Yangming Ren, Yiwen Zhang, Wenfu Zhang, and Cheng Wang,

"Ultra-high-linearity integrated lithium niobate electro-optic modulators," *Photon. Res.* 10, 2366-2373 (2022)

[R21] Zhao, P., Shekhawat, V., Girardi, M. et al. Ultra-broadband optical amplification using nonlinear integrated waveguides. *Nature* 640, 918 – 923 (2025).

[R22] Changran Hu, An Pan, Tingan Li, Xuanhao Wang, Yuheng Liu, Shiqi Tao, Cheng Zeng, and Jinsong Xia, "High-efficient coupler for thin-film lithium niobate waveguide devices," *Opt. Express* 29, 5397-5406 (2021)

Comment 4: " In Page 2 second paragraph, the authors refer to other materials with limited optical properties. It would be good to specify which material the authors refer to and also what lack of properties they refer to.

The TFLN is proposed as a great material thanks to its high n and EO coefficient. What about the non linear properties (χ^2 and χ^3), which can lead to signal distortion etc? Also what about the power handling? Please, comment."

Our reply: Thanks for the valuable suggestion. We are intended to compare with SiN and Al₂O₃, which are excellent host materials with high amplification. While these materials platform lack an effective and high-speed EO modulation mechanism. We have revised the corresponding part as shown below.

As we discussed in "**Reply to Comment 3**", the second-order optical nonlinear effect can be ignored without specific phase matching designs, and watt-level input power is necessary to stimulate the third-order optical nonlinear effect. Thus, the optical nonlinearity will not influence applications in Er:TFLN for most cases.

(Results, Page 2) Compared to previous host materials (such as Si₃N₄, Al₂O₃) lacking fundamental properties and functions (such as Pockels effect effect for EO modulation or second-order optical nonlinearity), ~~thin-film~~ lithium niobate distinguishes itself through its diverse optical properties, including high refractive index contrast and pronounced electro-optic effect³².

Comment 5: " The authors report a background loss of 0.4 dB/cm, and they mention that it is very low. However, it is much higher than in other amplifier materials (see ref. to the Liu et al Science paper). Please, comment."

Our reply: We thank the reviewer for raising this critical point regarding the background loss in our Er:TFLN waveguides. The 0.4 dB/cm loss reported here, while higher than the sub-0.1 dB/cm losses achieved in SiN platforms via Damascene processes (e.g., Liu et al., Science), also represents an advancement for lithium niobate-based photonic systems. This difference arises from fundamental material and fabrication constraints. LiNbO₃'s an-isotropic crystal structure inherently induces stronger scattering losses compared to isotropic SiN. Recent research for undoped TFLN waveguides (0.33 dB/cm [R23]) highlights that our doped system achieves performance near the undoped TFLN material, despite the additional losses introduced by Er³⁺ incorporation. Notably, in similarly structured Er:TFLN waveguides, our loss is 6× lower than prior demonstrations (2.5 dB/cm [R24]).

[R23] Li M, Chang L, Wu L, et al. Integrated pockels laser[J]. *Nature communications*, 2022, 13(1): 5344.

[R24] Cai M, Wu K, Xiang J, et al. Erbium-doped lithium niobate thin film waveguide amplifier with 16 dB internal net gain[J]. *IEEE Journal of Selected Topics in Quantum Electronics*, 2021, 28(3): Hybrid

Integration for Silicon Photonics): 1-8.

Comment 6: " At the end of the introduction the authors propose this platform as a better platform for complex PICs. However, as I mentioned above, the necessity to having to pump the whole system can lead to an excessive power consumption. Also, as systems get larger and more complex, it adds complexity to ensure a good level of pumping all along the devices. It would be good if the authors revise this claim and sharpen the application space for the building block proposed in the manuscript."

Our reply: Thank you for pointing out this concern. At the current stage, our amplification-modulation demonstration does require an external pump laser, which adds some system complexity due to additional external coupling and raises concerns about maintaining pump efficiency across the entire chip, especially as the system's cascading level increases. While this can be solved by the heterogeneous or monolithic integration of lasers. Specifically, heterogeneously integrated lasers (e.g., III-V lasers bonded to TFLN [R14-R15]) can serve as on-chip pump sources. Recent advances, such as wafer-bonded InP lasers on thin-film lithium niobate achieving 1.3 mW on-chip output with 92% coupling efficiency [R14], demonstrate the feasibility of high-performance, energy-efficient pumping. We firmly believe this challenge can be addressed through pump laser bonding techniques and the deployment of distributed transfer pump chips at each relay node, ensuring equalized and efficient amplification, which we are actively exploring in our ongoing work.

In the concluding part of our introduction, our aim is to highlight the unique strength of a monolithic amplification-modulation scheme, not only enabling more functional devices, but also help preserve signal integrity (as we clarified in the experiments) as it propagates through the network, which is a crucial aspect for enabling deeper and higher throughput optical networks. The claim does not intend to focus on reducing the system complexity. To avoid misleading, we have revised the claim according to the reviewer's suggestion.

[R14] Zhang X, Liu X, Liu L, et al. Heterogeneous integration of III – V semiconductor lasers on thin-film lithium niobate platform by wafer bonding[J]. Applied Physics Letters, 2023, 122(8).

[R15] Li M, Xiang C, Peters J, et al. Heterogeneously-Integrated Self-injection Locked Lasers on Thin Film Lithium Niobate[C]//Optical Fiber Communication Conference. Optica Publishing Group, 2024: W1K. 3.

(Introduction, Page 3) Through modulation-amplification integration, our work unlocks new prospects for integrated photonics, **with the potential to enable more advanced functional modules, such as tunable and mode-locked lasers, while also facilitating deeper on-chip photonic networks due to enhanced signal integrity.** ~~paving the way for more sophisticated, multifunctional modules like tunable and mode-locked lasers and complex on-chip optical applications such as high-throughput interconnections and optical neural networks.~~

Comment 7: " In the second page second column, the authors mention the erbium concentration of 0.5% mol. Would it be possible to convert it also to at.% and ions/cm³? Those are two metrics that used in the EDFA literature and it will facilitate the reader to compare different amplifier designs easier. Also, how was the concentration of erbium measured?"

Our reply: To facilitate comparison with standard EDFA literature, we have converted the 0.5 mol% Er-doped LiNbO₃ concentration to atomic percentage and ion density. The atomic percentage (at.%) is approximately 0.45%, calculated by considering Er³⁺ substitution at Li⁺ sites in the LiNbO₃ lattice. The ion density is derived as 10²⁰ ions/cm³ based on the material's density (4.64 g/cm³) and molar mass

(147.9 g/mol), following the formula $n_{Er} = \frac{\text{mol}\%}{100} \times \frac{\rho}{M} \times N_A$.

Regarding the measurement methodology, while techniques like SIMS or PIXE are standard for ion concentration quantification, our laboratory currently lacks access to these instruments. The Er^{3+} concentration in this work was defined by the stoichiometric ratio during crystal growth ($\text{LiNbO}_3:\text{Er}^{3+} = 99.5:0.5$ in raw materials), a common practice in bulk-doped crystalline systems where precursor control ensures compositional accuracy. We acknowledge that direct experimental verification would further strengthen the analysis and plan to collaborate with facilities equipped for such measurements in future studies. These conversions and methodological clarifications have been added to Supplementary Note II.

(Supplementary Note II, Page S4) The erbium oxide is introduced during the growth and preparation process of the lithium niobate crystal⁶. **Erbium ions were introduced into the lithium niobate (LiNbO_3) crystal lattice via a controlled solid-state reaction. High-purity Li_2CO_3 , Nb_2O_5 , and Er_2O_3 powders were stoichiometrically mixed according to the target composition of $\text{LiNbO}_3:0.5 \text{ mol}\% \text{ Er}^{3+}$. The homogeneous distribution of Er^{3+} ions was ensured by iterative grinding and re-sintering steps prior to single-crystal growth via the Czochralski method.**

The Er^{3+} concentration in ions per cubic centimeter (ions/ cm^3) was derived from the molar percentage (mol%) using the following relationship:

$$n_{Er} = \frac{\text{mol}\%}{100} \times \frac{\rho}{M} \times N_A$$

Where $\chi=0.5 \text{ mol}\%$ is the Er^{3+} molar fraction, $\rho=4.64 \text{ g/cm}^3$ is the density of LiNbO_3 , $M=147.9 \text{ g/mol}$ is its molar mass, and $N_A=6.022 \times 10^{23} \text{ mol}^{-1}$ is Avogadro's constant. Substituting these values yields an Er^{3+} ion density of $10^{20} \text{ ions/cm}^3$. This approach ensures a more uniform distribution of Er^{3+} ions within the crystal, thereby enhancing the effective concentration of erbium doping. Subsequently, the wafers underwent thin-film exfoliation and were transferred onto silicon dioxide substrates.

Comment 8: " The authors mention: "... exhibiting stimulated radiation of Er^{3+} ions". The erbium ions are not stimulated emitted, what is emitted are photons. It would be good to rephrase the sentence.

Our reply: The phrase "exhibiting stimulated radiation of Er^{3+} ions" has been revised to accurately reflect the underlying physics.

(Introduction, Page 2) Figure. 2a depicts the photo luminescence (PL) spectrum of the $\text{Er}:\text{TFLN}$, exhibiting **amplified photon emission via stimulated emission from** ~~stimulated radiation of~~ Er^{3+} ions across 1520 - 1570 nm and a notable peak emerges around 1531.7 nm.

Comment 9: " Figure 2(c): please, add the PL spectrum from 1460nm (or below that even) to 1640nm (at least). This will enable to see the full range of emission of the erbium ions."

Our reply: We thank the reviewer for suggesting the extended PL spectrum range. In the revised manuscript, we have expanded the PL spectrum in Fig. 2(a) to cover the full emission range of erbium ions from 1460 nm to 1645 nm (previously 1500–1600 nm). This revision confirms the characteristic Er^{3+} emission bands, including the primary 1.5- μm band and weaker emission shoulders near 1480 nm and 1620 nm, consistent with prior studies of erbium-doped materials.

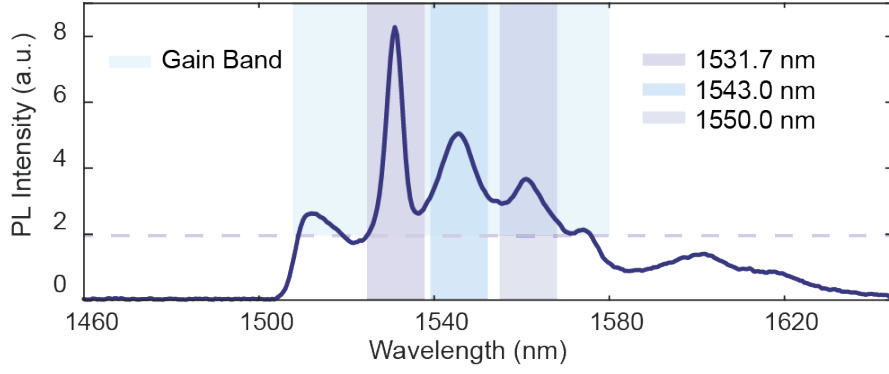


Fig. 2. a, Photo luminescence (PL) spectrum of the Er:TFLN waveguide amplifier;.....

Comment 10: "Figure 2(f): Why is the signal at 1600nm? Can you please add the signal in the C-band (eg. 1532nm or 1550nm?)."

Our reply: The 1600 nm signal in Fig. 2(f) was intentionally selected to isolate the modulator's intrinsic electro-optic (EO) performance from the influence of erbium's absorption/gain effects. At 1600 nm, erbium ions exhibit negligible absorption or amplification (as shown in Fig. S4), allowing us to directly characterize the EO bandwidth and half-wave voltage of the modulator itself.

To address the reviewer's request, we have now added C-band (1550 nm) characterization data in the revised manuscript (Fig. S10 in Supplementary Note IX: Half-wave voltage characterization), confirming consistent EO performance across wavelengths.

The revised manuscript also resolves a prior error: this method is only valid for phase modulator while previous measurement is carried out with a single-driven intensity modulator. The modulation efficiencies at 1550 nm and 1600 nm are 3.1 V·cm (revised from 3.5) for push-pull modulation.

(Supplementary Note IX. Page S14)

Supplementary Note IX: Half-wave voltage characterization

Halfwave voltage (V_{π}) is a major characteristic for an electro-optic (EO) modulator. **For directly characterizing the modulation efficiency of the phase modulator with an 8-mm-long electrode shown in Fig. 4b. We employ the carrier-to-first sideband (FSB) intensity equalization technique, where the RF voltage (V_m) is tuned until the intensities of the carrier and FSB are equal³³. The frequency of the applied RF signal is 50 MHz. A spectrometer (APEX AP2081A) with an ultra-high resolution of 0.04 pm is used to record the spectrum. As shown in Fig. 2f and Fig. S10, the carrier and FSB are equal in intensity when V_m is about 3.5 V, which leads to³³:**

$$V_m \approx 0.457 \cdot V_{\pi} \quad (4)$$

Therefore, the V_{π} is calculated to be 7.6 V. Considering a push-pull modulation, the $V_{\pi} \cdot L$ could reach 3.1 V·cm. A lower V_{π} can be achieved by using a longer RF electrode. Additionally, employing a slow-wave electrode can further decrease the half-wave voltage at high frequencies by minimizing microwave losses³⁴.

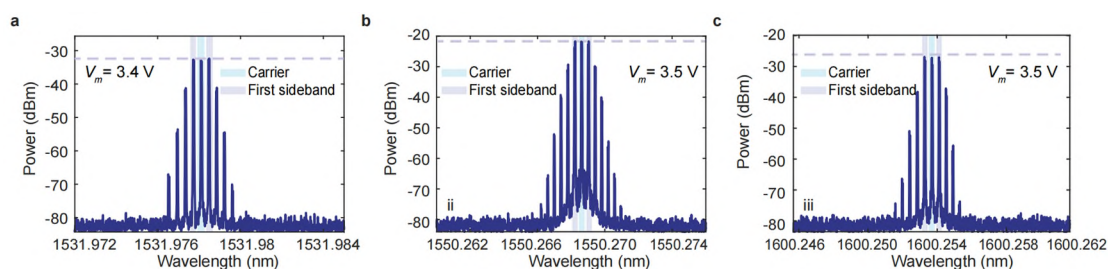


Fig. S10. Half-wave voltage characterization in different wavelengths.

(Results, Page 4) Figure.1b(iv) shows a photo of a **phase** modulator with **8-mm-long** electrode. The carrier-to-first sideband (FSB) intensity equalization technique⁴³ is used to determine the half-wave voltage. As depicted in Fig. 2f, when the peak-to-peak voltage V_m of the applied radio frequency field reaches 3.5 V, the modulated spectrum exhibits equal intensities between the carrier and the first sidebands. The modulation efficiency can be then estimated as $LV_m/0.457$, yielding **3.1 V-cm** push-pull modulation (See Supplementary Note IX).

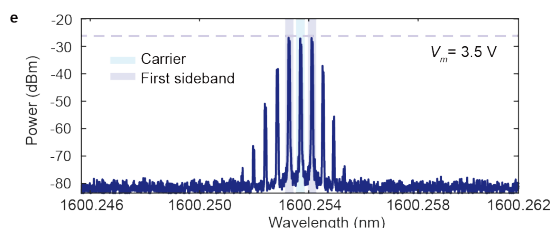


Fig.2.....e, Spectrum when a sine wave signal with an amplitude of 3.5 V is applied to the modulator.

Comment 11: " Page 3 paragraph 1: the lifetime was "calculated". However, this introduces too many unnecessary errors. It would be desirable to directly measure the lifetime. Please, add this experimental measurement to the manuscript.

Our reply: Our reply: We sincerely appreciate the questions raised by the reviewers. In our original manuscript, we reported a calculated lifetime of 9.4 ms derived from Judd-Ofelt (JO) theory. However, the JO framework assumes purely radiative transitions and neglects non-radiative decay pathways (e.g., multi-phonon relaxation, defect-mediated quenching). To address this limitation and validate the lifetime experimentally, we conducted direct time-resolved photoluminescence (TRPL) measurements using a transient fluorescence spectrometer (Edinburgh FLS980). The revised experimental lifetime is 5.8 ms. We acknowledge that the experimentally measured fluorescence lifetime of 5.8 ms is indeed shorter than typical values reported for commercial Er-doped silica fibers (~10 ms)[R6]. As the reviewer highlighted, lithium niobate's higher refractive index (~2.2 vs. silica's ~1.5) enhances spontaneous emission rates, theoretically reducing lifetimes.

We have updated the manuscript, replacing the initial calculated value with the experimentally determined lifetime and expanding the discussion in Supplementary Note V.

[R6]Taherunnisa, S. et al. Effect of up-conversion luminescence in Er³⁺ doped phosphate glasses for developing Erbium-doped fibre amplifiers (EDFA) and G-LED's. Optical Materials: X 3, 100034 (2019).

(Results, Page 3) According to the emission cross-section (See Supplementary Note V), The photo luminescence lifetime is ~~calculated~~ **measured** to be **5.8 ms** (See Supplementary Note V), which

indicates an ideal doping condition, comparable to the typical value in the commercial EDFA (@ 10 ms³⁹).

(Supplementary Note V, Page S8)

Supplementary Note V: Lifetime measurement

The photoluminescence lifetime of the sample was directly measured using a steady-state / transient fluorescence spectrometer (Edinburgh FLS980, UK) to ensure experimental accuracy and eliminate potential errors associated with indirect calculations. Fluorescence decay curves were recorded over a 0–80 ms time window. The decay profiles exhibited a biphasic behavior, characterized by an initial rapid decay followed by a slower exponential decay. To model this behavior, the data were fitted using a bi-exponential decay function, expressed as¹²:

$$I(t) = I_0 + B_1 * \exp\left(\frac{-t}{\tau_1}\right) + B_2 * \exp\left(\frac{-t}{\tau_2}\right) \quad (1)$$

where I_0 represents the photoluminescence intensity of the tested sample at $t=0$, τ_1 and τ_2 represent the short and long lifetime components, B_1 and B_2 are their respective amplitudes. The measured time-resolved fluorescence decay profile and the fitted profile are shown at Fig. S6. The fitted parameter values are shown as Table I. The measured fluorescence lifetime (τ) of the sample is given by:

$$\tau = \frac{B_1\tau_1^2 + B_2\tau_2^2}{B_1\tau_1 + B_2\tau_2} \quad (2)$$

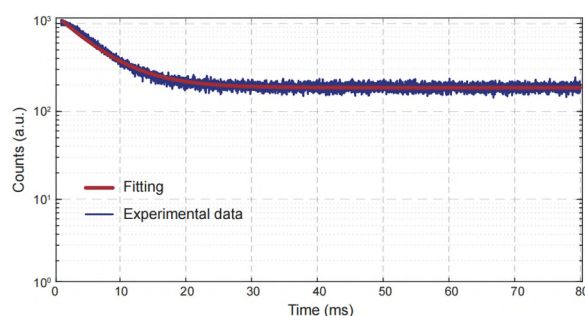


Fig. S6 Time-resolved fluorescence decay profile.

Table I. Biexponential decay fitting parameters for Er³⁺ photoluminescence lifetime

Parameter	Value
τ_1	5.4
τ_2	6.1
B_1	4.9
B_2	4.9

The lifetime is calculated as 5.8 ms, which indicates an ideal doping condition, close to the typical value in the commercial EDFA (@ 10 ms³⁹).

[12] Shrivastava R, Kaur J. Studies on long lasting optical properties of Eu²⁺ and Dy³⁺ doped di-barium

magnesium silicate phosphors[J]. Chinese Chemical Letters, 2015, 26(9): 1187-1190.

Comment 12: " The authors write: " For efficient amplifiers in the integrated Er:TFLN platform, the background loss, especially the scattering loss, is the most fatal blocks compared with their fiber-based competitor. ". The words: "fatal blocks" are not very understandable.

Our reply: Thanks for the suggestion. To improve clarity and technical precision, we have revised the sentence in the Results section (Page 3) as follows.

(Results, Page 3) For efficient amplifiers in the integrated Er:TFLN platform, the background loss, especially the scattering loss, ~~is the most fatal blocks~~ **emerges as the primary limiting factor** compared with their fiber-based competitor.

Comment 13: " Although the reviewer understands that larger cores will lead to higher gain, how is the multimode behavior handled in the rest of building blocks? Eg., MZI modulators? Mode conversion in the bends?"

Our reply: We sincerely thank the reviewer for highlighting this critical aspect of mode management. We only employ the multimode waveguide at the spiral parts as these count for the most length of the on-chip links. For other parts, such as the modulators and connections between different parts, single-mode waveguides are employed with a waveguide width of 1 μm . For the connection between the multimode waveguide and the single-mode waveguide, linear tapers are employed to avoid high-order modes, with the waveguide width changing linearly with the length.

For mode conversion in bends, the multimode waveguide amplifiers employ adiabatic bends with a R_{min} of 650 μm to suppress inter-mode crosstalk. The curvature of these bends follows a Euler profile (linear curvature variation with length) or Archimedean bends (linear radial scaling with angle), ensuring smooth mode evolution and minimal loss. This hybrid design strategy balances gain performance and mode purity across the integrated circuit. We have added these descriptions of the mode management in the revised Supplementary Note I:

(Supplementary Note I, Page S2) Taking Euler bending as an example (Fig. S1c), a comparison of the areas occupied by a single 90-degree Euler bend and a circular bend under quasi-single-mode conditions (where the fundamental mode transmission is more than 99.9 %) shows that the Euler bend offers a reduction in the area over 37 %. **This optimization enables compact spiral amplifiers without introducing modal interference. Besides, the multimode waveguide is only employed at the spiral parts as these count for the most length of the on-chip links. For other parts, such as the modulators and connection between different parts, single-mode waveguides are employed with a waveguide width of 1 μm . For the connection between the multimode waveguide and the single-mode waveguide, linear tapers are employed to avoid high-order modes, with the waveguide width changing linearly with the length.**

Comment 14: " Reference 40: " Gaafar, M. A. et al. Femtosecond pulse amplification on a chip. arXiv preprint arXiv:2311.04758 (2023)." Should be changed by the journal publication in Nature Communications."

Our reply: Thanks for reminding us. Reference 40 (Gaafar et al.) has now been updated which stands as a landmark work in integrated ultra-fast photonics.

(Reference, Page 9) [40] Gaafar, M. A. et al. Femtosecond pulse amplification on a chip. Nature communications 15, 8109 (2024).~~[40] Gaafar, M. A. et al. Femtosecond pulse amplification on a chip. arXiv preprint arXiv:2311.04758 (2023).~~

Comment 15: " The authors write: " Figure. 2b shows the measured loss of amplifiers with different lengths with the off-chip input signal power of 4 mW". The loss in erbium doped waveguides should be measured for very small launched signals, in the uW region, as otherwise variations in the ground state population will result in variation of the propagation losses. As the signal power increases, the losses should decrease till a saturable absorption. The same happens at the pump wavelength. It would be good to see the loss measured at very small signals and also the scan of the losses as a function of signal power and pump power till reaching saturation."

Our reply: In response to your feedback, we have modified the "Measured total loss of amplifiers of different lengths" in Fig. 2a to reflect the loss characterization under an input signal power of 30 μ W. Additionally, we have expanded our analysis in Supplementary Note III: Low-loss characterization.

As detailed in Fig. S4c, we systematically characterized the propagation loss of the Er-doped waveguide across a wide range of input signal powers, from -30 dBm to 10 dBm, at three key wavelengths (1531.7 nm, 1543 nm, and 1550 nm). At low signal powers, the absorption loss remains high, consistent with the unexcited state of Er^{3+} ions in the small-signal regime. As the input power increases, the absorption loss decreases due to saturable absorption, approaching the background loss floor of 0.4 dB/cm measured at 1600 nm (where Er^{3+} absorption is negligible). This background loss, labeled explicitly in Fig. S4c, serves as a baseline for isolating absorption-related losses at other wavelengths.

While pump light would further modify the absorption dynamics, such measurements fall outside the scope of this specific loss characterization. Instead, the impact of pump power on population inversion and gain is rigorously analyzed in the "High-gain optical amplification" section of the main text, where we discuss the amplifier's performance.

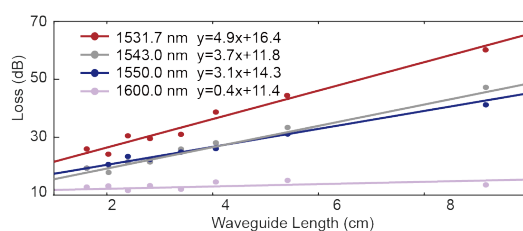


Fig.2. b. Measured total loss of amplifiers of different lengths under an input signal power of 30 μ W;

(Results, Page 3) Figure. 2b shows the measured loss of amplifiers with different lengths with the off-chip input signal power of ~~4 mW~~ 30 μ W.

(Supplementary Note III, Page S6)

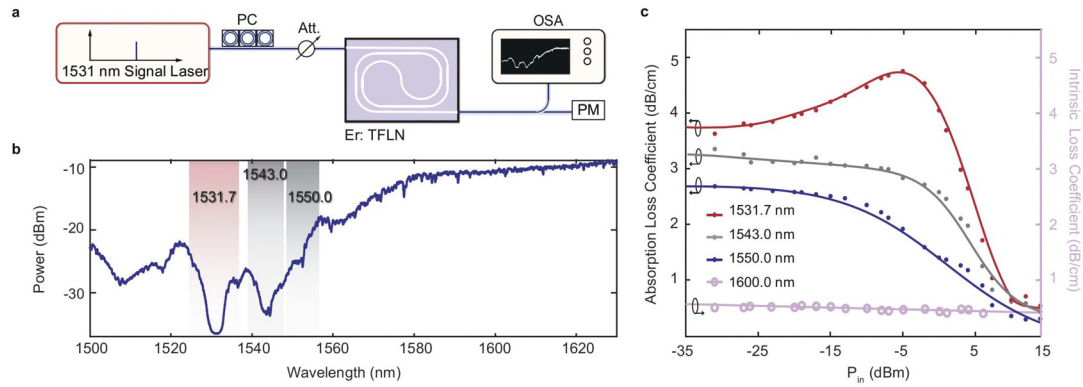


Fig. S4. Passive characteristics of Er:TFLN waveguide amplifier. a, Experimental setup; PC, Polarization controller; Att., Attenuator; OSA, Optical spectrometer analyzer. b, Measured transparent spectrum of the waveguide amplifier at low signal power; c, Measured loss factor of amplifiers under different input powers.

Comment 16: "In page 3 the authors write: "For moderate modulation efficiency, the electrode gap is set to 3.5 μm ." Why do they choose to go for "moderate" EO efficiency instead of "high"?"

Our reply: The electrode gap of 3.5 μm was selected to balance the trade-off between EO efficiency and optical propagation loss. Increased propagation loss from a smaller electrode gap (due to stronger metal absorption and scattering near the waveguide) would degrade the internal net gain, while a larger gap would reduce modulation efficiency. This choice of EO efficiency ensures that the waveguide amplifier achieves the expected performance under the laboratory's drive voltage constraints while maximizing the net signal gain. Therefore, we have replaced the term "moderate" with "trade-off-optimized" to more accurately describe the design choice that balances electro-optic efficiency and propagation loss.

(Results, Page 4) ~~For moderate modulation efficiency, the electrode gap is set to 3.5 μm . The electrode gap and oxide layer thickness are set to 3.5 μm and 1 μm , respectively, to optimize both optical and microwave losses while achieving improved modulation efficiency.~~

Comment 17: "The authors write: "Generally, the net gain dynamically changes under different pump powers". Does it not happen always? What case are the authors thinking about to say "Generally"? It would be good to explain in the manuscript."

Our reply: We appreciate the reviewer's feedback. The original sentence has been deleted.

(Results, Page 5) ~~Generally, the net gain dynamically changes under different pump powers. Here, to evaluate such relationship, To evaluate the amplification, the net gain with the varying pump power under a small input signal (off-chip -39.6 dBm)~~

Comment 18: "The authors write: "The internal net gain increases with the pump power, which is intuitive". I believe this is not "intuitive" but represents the physics of the device."

Our reply: The phrase "which is intuitive" has been removed, and the sentence has been revised to concisely describe the gain-pump power relationship observed in Fig. 4a.

(Results, Page 5) ~~The internal net gain gain factor increases much slower with the pump power, as the pump power > 80 mW compared with that in the low pump power region (0~20 mW). which is~~

intuitive, then gradually gets saturated when the off-chip pump power is over 20 dBm.

Comment 19: "Figure 4 (f): On-chip or off-chip?"

Our reply: Thanks for the careful attention to experimental details. In the original manuscript, Figure 4(f) presents **off-chip** measurements of the sideband modulation spectra, as stated in the figure caption: "f, Spectrum of sideband modulation with pump light and without pump light." The data were acquired using an external optical spectrum analyzer (OSA, Yokogawa AQ6370D) connected to the chip via polarization-maintaining fibers, consistent with the experimental setup described in Methods (Modulation measurement), Supplementary Note XI and Supplementary Fig. S12 and Fig. 13. To provide a more accurate description, the caption of Fig. 4f has been updated as follows.

(Fig. 4, Page 5) f, Spectrum of sideband modulation with pump light and without pump light **via off-chip measurement**.……

Comment 20: "The authors write: " Significantly, the highest on-chip net gain under 115 mW off-chip pump power is around 38 dB (with the consideration of 2.9 dB fiber link loss and 6.7 dB/facet coupling loss, as shown in Fig. 3b) in the 9.16 cm waveguide amplifier, corresponding to an average gain of 4.1 dB/cm": please, indicate that it is at 1531nm (it is in the figure, but it would be good for clarity and precision to also write it in the text."

Our reply: The relevant sentence in the main text has been revised to explicitly state the wavelength dependency of the reported gain.

(Results, Page 5) Significantly, the highest on-chip net gain under 115 mW off-chip pump power is around 38 dB **at 1531.7 nm** (with the consideration of 2.9 dB fiber link loss and 6.7 dB/facet coupling loss, as shown in Fig. 3b) in the 9.16 cm waveguide amplifier, corresponding to an average gain of 4.1 dB/cm.

Comment 21: "In figure 3(c), the gain saturates with pump power. However, in the text the authors mention that they can get more gain by pumping harder. It think it would be good to add an explanation."

Our reply: As suggested from Fig.3c, the curve still holds an increasing trend, which means the system approaches but does not fully enter saturation. However, in practice, attempts to operate beyond 115 mW trigger parasitic lasing. This instability prevents reliable gain measurement in the deep saturation regime. The current 38 dB net gain limit (Fig. 3b) is thus constrained by lasing thresholds rather than the intrinsic population inversion capacity of Er^{3+} ions. The original sentence has been revised.

(Results, Page 5) Higher pump power **of larger than 115 mW** could further increase the gain **before saturation**, while the measurement of such performance is presently affected by the parasitic lasing²⁴, resulting from the internal reflection between the chip facets.

Comment 22: "The authors write: " When the pump light is turned off, the on-chip loss decreases the output optical power to -27 dBm, resulting in a detected SNR of less than 5 dB, as depicted in Fig. 5b(i). The low SNR prevents the extraction of the instantaneous frequency. With the pump light, the output signal is boosted to -12 dBm, resulting in a SNR >15 dB. A clear FMCW signal is observed in Fig. 5c(ii). For comparison, the output signal without pump light is amplified to -12 dBm using a commercial EDFA" The reviewer is not sure whether this comparison makes sense: the SNR ratio increases when pumping.

When not pumped, the losses of the circuit are high. It makes sense that the performance improves with pumping. In the opinion of the reviewers the good comparison should be with an undoped modulator in TFLN amplifier by an EDFA. Can this comparison be made/ Otherwise, the reviewer is not sure whether the proposed comparison by the authors is relevant."

Our reply: We acknowledge that the previous comparative experiment setup was improper and have redesigned the experiment. The revised manuscript presents three sets of results under different experimental conditions. The first is conducted at 1600 nm band using the Er:TFLN chip without the pump. At 1600 nm, the large absorption loss of Er^{3+} ions is avoided. However, the long spiral waveguide introduces substantial background loss, resulting in an off-chip output power of -15.0 dBm with an off-chip input signal power of 5 dBm. And then the same test is performed at 1550 nm with the pump light. The input signal power remains the same as in the first one. Thanks to the amplification process, the off-chip output power is -4.2 dBm, achieving an internal net gain of 7.1 dB and a received SNR of 30 dB, with a 21 dB improvement over the first one. The third uses an undoped TFLN modulator and a commercial EDFA (Amonics AEDFA-PA-35-B-FA). The TFLN modulator exhibits a half-wave voltage V_π of 5.6 V, coupling loss of 8.9 dB/facet, and 3-dB EO bandwidth of 40 GHz. Despite a smaller EO bandwidth, the frequency response difference has a negligible impact due to the relatively low operating frequency range (8 – 12 GHz). The test link is similar to the second one while with the commercial EDFA inserted after the modulator. The input signal power and the received optical power are kept the same as the second one. Due to a lower input power to the optical amplifier with the insertion loss of the TFLN chip, the received SNR is 8 dB lower than in the second one.

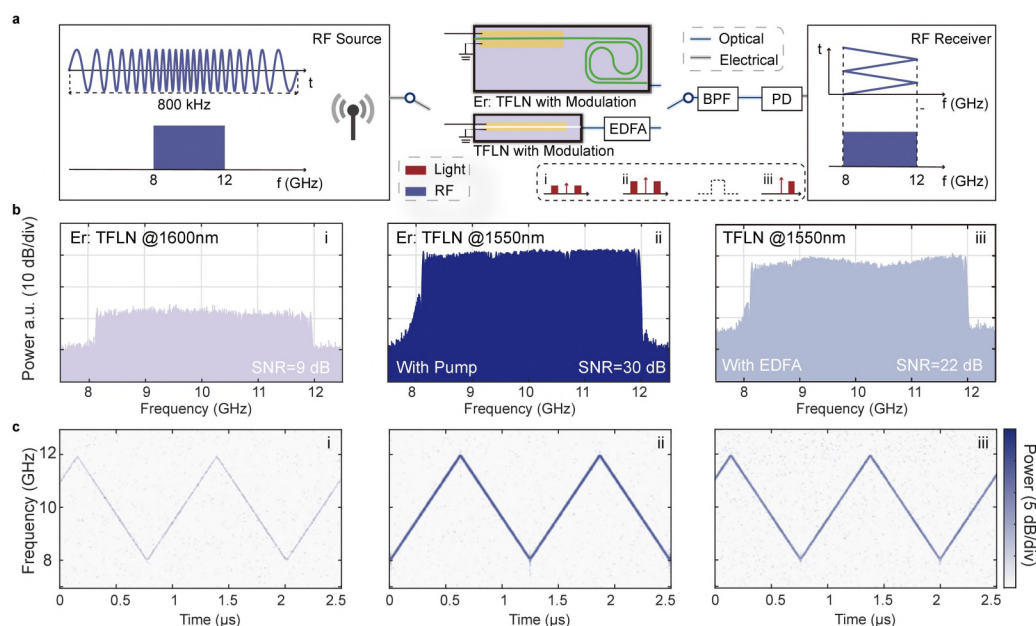


Fig. 5. On-chip signal modulation and amplification. a, Setup of frequency-modulated continuous wave (FMCW) signal modulation and amplification **chirped between 8 GHz and 12 GHz at a repetition rate of 800 kHz**. BPF, band pass filter. b-c, The received microwave signal and time-frequency spectra of the beatnote between the carrier and the sideband when the signal light is (i) **at 1600 nm** without pump light , (ii) **at 1550 nm** with pump light and (iii) **with the EDFA at 1550 nm by using a TFLN-based modulator and an EDFA**.

Comment 23: "In Figure S1d the authors show results from the erbium model. However, it is necessary to show how the model fits the experimental data to ensure that it is correct. Can the authors add a graph showing how the model fits the experimental data? Ideally for different amplifier lengths, signal powers and erbium concentrations."

Our reply: We thank the reviewer for emphasizing the need to validate our erbium model against experimental data. To address this, we have expanded Supplementary Note I and incorporated experimentally measured net gain values (red dots) into Fig. S1d. This revised figure directly compares the modeled internal net gain (curves) with experimental measurements across amplifier lengths (1 – 9 cm) and pump powers (60 – 110 mW). The experimental data align closely with the simulated curves. The agreement across the full parameter space validates the model's ability to predict gain dynamics governed by erbium ion population inversion and pump power density. The discrepancies likely stem from fabrication-induced waveguide loss variations or slight deviations in erbium ion distribution uniformity.

Regarding erbium concentration, we acknowledge the reviewer's request for validation across doping levels. However, due to current fabrication limitations (all high-performance devices in this work are constrained to 0.5 mol% Er^{3+} concentration), we are unable to experimentally test other concentrations. Future studies will address this gap.

(Supplementary Note I, Page S2)

Figure. S1 directly compares the modeled internal net gain (curves) with experimental measurements across amplifier lengths (1-9 cm) and pump powers (60-110 mW). The experimental data align closely with the simulated curves. The agreement across the full parameter space validates the model's ability to predict gain dynamics governed by erbium ion population inversion and pump power density. The discrepancies likely stem from fabrication-induced waveguide loss variations or slight deviations in erbium ion distribution uniformity.

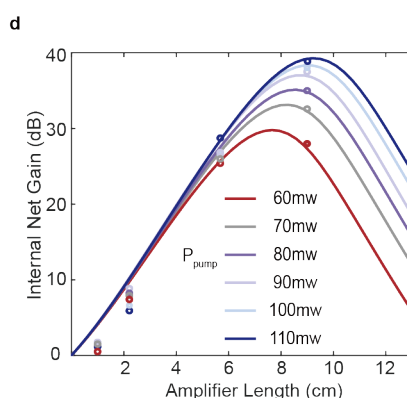


Fig. S1. The relationships between internal net gains and amplifier lengths under different pump powers in simulation (curves) and experiment (dots).

Comment 24: "In page 3 of the supplementary information, the authors mention parasitic lasing. Do they authors do anything to prevent it in the design?"

Our reply: We thank the reviewer for raising this important question regarding parasitic lasing suppression. To suppress parasitic lasing and minimize Fresnel reflections, an index-matching gel

(Norland Optical Adhesive 61) was carefully applied at the interface between the Er:TFLN chip and fiber (Supplementary Note VII: Parasitic Lasing and Mitigation Strategies). In future work, we plan to further mitigate parasitic lasing effects by exploring advanced suppression strategies, such as using angled end-face couplers to reduce back-reflections.

(Supplementary Note VII, Page S10)

Supplementary Note VII: Parasitic Lasing and Mitigation Strategies

Parasitic lasing in our Er:TFLN waveguide amplifier was experimentally observed under high pump powers. This phenomenon arises when amplified spontaneous emission experiences feedback from residual reflections at the waveguide facets (LN-air interfaces), forming an unintended Fabry-Pérot cavity. At first, we used lensed fibers, where the mode diameter is about 3 μm , for the coupling between the chip and the fiber links. Due to the large index mismatch between the integrated waveguide and air, parasitic lasing initiated at a pump power of approximately 40 mW with an input signal power of -39.6 dBm, corresponding to a net gain of ~25 dB. The FP-induced lasing and sudden power fluctuations were observed at this threshold, with the lasing wavelength (~1532 nm) aligning with the peak gain region of Er^{3+} ions in LiNbO_3 .

To suppress parasitic lasing and minimize Fresnel reflections at facets, an index-matching gel (Norland Optical Adhesive 61, refractive index $n = 1.56$ at 1550 nm) was applied at the interface between the Er:TFLN chip and fiber (Fig. S8). As the gel was added, the fiber tip would move and sometimes the tip would hit the chip facet, leading to the break of the fiber tip or the edge coupler. To avoid this, we adopted UHNA7 fibers with the same mode diameter of the lensed fiber for coupling between the fiber links and the chip. The end of such fiber is flat, which will not break itself or the edge coupler if hitting the chip edge as adding the gel. With the help of index-matching gel, we can achieve stable amplification up to a pump power of 115 mW with a net gain of 38 dB. With higher pump power, parasitic lasing is observed and makes the amplification process unstable. For future designs, angled end-facets can be implemented to further suppress feedback.

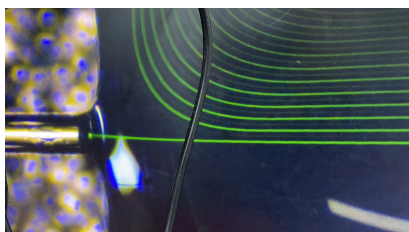


Fig. S8. The photo of the chip-fiber interface with the Index-matching gel applied.

Comment 25: "In Figure S2 a Cr mask is used. In Figure S3 a PR mask is used. Why?"

Our reply: We sincerely thank the reviewer for raising this critical question about our mask selection strategy. The distinction between chromium (Cr) and photoresist (PR) masks in Figs. S2 and S3 are driven by the unique requirements of the respective fabrication processes.

In the Er:TFLN waveguide amplifier fabrication (Fig. S2), the Cr hard mask, deposited via electron beam evaporation (EBE), plays a pivotal role during the inductively coupled plasma (ICP) and reactive ion

etching (RIE) steps. Cr's exceptional plasma resistance ensures precise pattern transfer from the resist to the Er:TFLN layer, enabling the formation of waveguides with near-vertical sidewalls and low surface roughness—critical for achieving low propagation loss. Following etching, the Cr mask is fully removed (Step 9 in Fig. S2) to prevent contamination during subsequent processing, such as the deposition of the SiO₂ protective layer.

In contrast, for the modulated Er:TFLN amplifier fabrication (Fig. S3), the PR mask is directly employed during electron beam lithography (EBL) to define both waveguide and electrode patterns. PR's ultrahigh resolution ensures precise patterning, while its compatibility with lift-off processes guarantees clean removal after metallization, preserving electrode integrity. The absence of Cr in this workflow eliminates compatibility issues with the Au electrode deposition and simplifies thermal management, as PR avoids high-temperature steps that could compromise Er³⁺ ion stability.

The strategic use of Cr and PR masks—tailored to their respective strengths in plasma resistance (Cr) and lithographic precision (PR)—optimizes material compatibility and process efficiency. This staged approach minimizes cross-contamination and maximizes yield, as evidenced by the high-performance devices reported in our work.

Comment 26: "In Figure S4c, please keep increasing the signal power, since it is supposed to go to saturate at the background loss and it did not happen yet in the figure."

Our reply: We appreciate the reviewer's insightful suggestion. In the revised Fig. S4c, we added new measurement results by further increasing the input signal power up to +15 dBm.

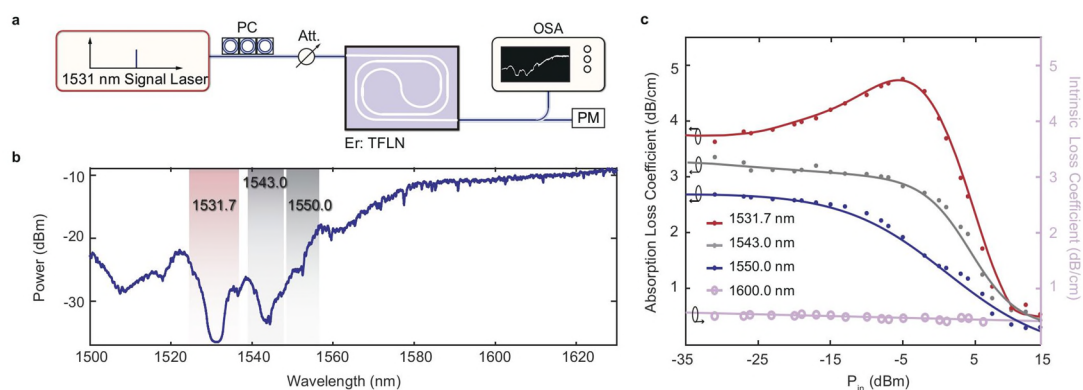


Fig. S4. Passive characteristics of Er:TFLN waveguide amplifier. a, Experimental setup; PC, Polarization controller; Att., Attenuator; OSA, Optical spectrometer analyzer. b, Measured transparent spectrum of the waveguide amplifier at low signal power; c, Measured loss factor of amplifiers under different input powers.

Comment 27: "In Figure S5, why is the absorption cross-section in the C-band higher than the emission? Also, it would be good to extend the wavelength range to cover the spectrum till both ends of the PL band. Finally, why does the PL spectrum do not resemble a typical erbium emission/absorption cross-section spectrum? Please, add an explanation in the paper."

Our reply: Thank you for raising these points. We acknowledge the initial mislabeling of absorption and emission cross-sections in Fig. S5, which has now been corrected in the revised manuscript.

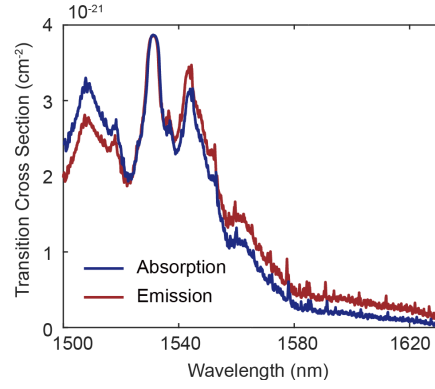


Fig. S5. Extracted emission and absorption cross sections of Er:TFLN waveguide amplifier

Additionally, we acknowledge the limitations of the original PL spectrum's wavelength range and spectral resolution. To address this, we re-measured the PL spectrum using a high-resolution spectrometer (MicroSpecIR), extending the range to 1460-1640 nm (now included in Fig. 2a). The atypical shape of the original PL spectrum arose from insufficient spectral resolution and background noise in our earlier measurements. Notably, the characterization of on-chip Er:TFLN photoluminescence remains limited in the literature, but our PL trends can be qualitatively compared to amplified spontaneous emission (ASE) intensity spectra reported in waveguide amplifiers[R12], further validating the consistency of our results.

[R12]Xu Q, Chen F, Chen Z X, et al. Er³⁺-Doped Lithium Niobate Thin Film: A Material Platform for Ultracompact, Highly Efficient Active Microphotonic Devices[J]. Advanced Photonics Research, 2021, 2(12): 2100081.

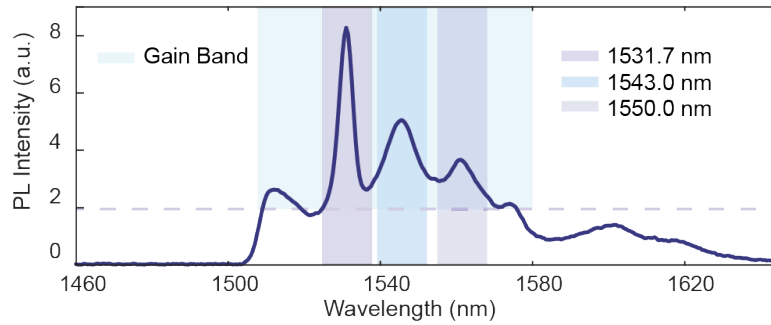


Fig.2 a, Photo luminescence (PL) spectrum of the Er:TFLN waveguide amplifier;.....

Title: Unifying Optical Gain and Electro-Optical Dynamics in Er-doped Thin-Film Lithium Niobate Platform

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Authors: Yimeng Wang, Bitao Shen, Bo Wang, Sijie Yang, Liyuan Yao, Ruixuan Chen, Yunhao Zhang, Haoyu Wang, Xuguang Zhang, Peiqi Zhou, Zihan Tao, Luwen Xing, Zhuliang Lin, Yichen Wu, Wencan Li, Dan Sun, Haowen Shu, & Xingjun Wang

Dear Editor and Reviewers,

We sincerely appreciate the careful review by the reviewers and have modified the manuscript in accordance with their suggestions. Here, we present a point-by-point reply (in blue) to the reviewers' comments (*in black*). All the changes have been highlighted (in red) with corresponding original text provided for comparison (in orange).

Sincerely,

Xingjun Wang

Response to the report from the Referee #1

General comments: "I have carefully reviewed the revised manuscript and response to reviewers. In my opinion, the authors have carried out a very careful and thoughtful revision of the manuscript and satisfactorily addressed almost all of my comments. However, there are still several remaining/additional comments for the revised manuscript and supplementary material that I believe are important to address before publication."

Our reply: We appreciate the reviewer's recognition of our revision efforts and are grateful for the constructive feedback. We have carefully addressed all remaining points below, with corresponding revisions highlighted in the manuscript (tracked changes) and supplementary materials.

Comment 1: "Perhaps I am missing it and it has been indicated somewhere, but for Fig. S7a, the pump power used to obtain that ASE spectrum should be indicated."

Our reply: Thanks for reminding. The pump power value has been added in the revised Supplementary Information.

(Supplementary Information, page S9) As shown in Fig. S7a, the pump laser exhibits an off-chip peak of 9.2 dBm at 1480 nm.

(Fig. S7, page S9)(b) Fluorescence emission spectrum from an Er:TFLN waveguide under an off-chip pump power of 0 dBm, ...

Comment 2: "Most important: The gain equation outlined in the Methods section and response doesn't seem to be correct."

Comment 2.1: "It mixes power units (dBm) and relative power units (dB) - it works out ok but it should be slightly revised."

Our reply: We thank the reviewer for raising this critical unit clarification. The subtraction of two dBm values $P_{out}^{(off-chip)} - P_{in}^{(off-chip)}$ intrinsically yields a dimensionless dB quantity, which represents the off-chip gain. Adding this off-chip gain to the facet coupling loss and waveguide propagation loss gives the internal net gain. To preclude any ambiguity, we have modified the original text as follows.

(Methods, page 10)

$$G_{net} = (P_{out}^{(off-chip)} - P_{in}^{(off-chip)}) + L_{coupling} + L_{link}$$

Comment 2.2: "Also the internal net gain should account for any on-chip loss. Therefore, as I understand it, the + L_{link} term should not be included in the G_{net} equation, and the reported internal net gain should be slightly (2.9 dB) lower (it doesn't affect the overall story, but the number should be correct). *But now as I read the corresponding description in the manuscript (page 5, bottom right), it seems to describe this as the fiber loss of the system, not the background loss as it seems to represent in the Methods description. It is important to clarify this."

Our reply: Thanks for scrutinizing the gain calculation methodology. In experiment, the gain factor is estimated by measuring the signal power before and after the gain chip. To avoid the influence of the strong pump power, the two power meters (PMs) are arranged before and after the WDMs at the input and the output side as shown in Fig.3a. The WDMs induce additional loss. The L_{link} term (2.9 dB) explicitly represents insertion loss from off-chip components (mainly from the two WDMs), not on-chip waveguide loss. This distinction is now clarified through the following revisions.

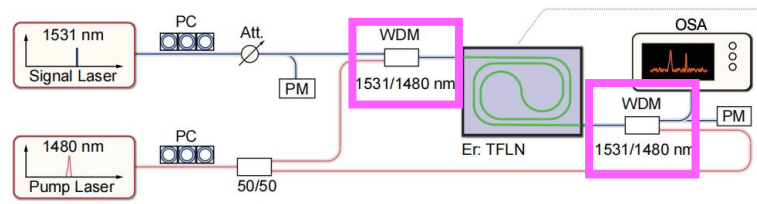


Fig. 3a Experimental setup of high-gain Er:TFLN waveguide amplifier. WDM, wavelength division multiplexer; PC, Polarization controller; Att., Attenuator; OSA, Optical spectrometer analyzer;

(Methods, page 10) $L_{link} = 2.9$ dB: Insertion loss of the fiber links and devices (mainly induced by the wavelength division multiplexers) in the unpumped waveguide.

Comment 2.3: "Also, I know it is a bit picky, but since the coupling might change slightly and the $L_{coupling}$ term is important in the gain calculation (effectively adding a lot of internal gain - $2 \times 6.7 \text{ dB} = 13.4 \text{ dB}$ - when you add it into the equation because of the relatively high coupling loss), somewhere it should be stated how it was verified to be consistent for pump on and off measurements. Perhaps there is already a statement, but a single sentence ensuring consistency of the $L_{coupling}$ term across gain measurements in the supplementary material would suffice."

Our reply: The coupling loss ($L_{coupling}$) does play a critical role in gain calculations. To address this concern, we conducted measurements in many times that confirmed the $L_{coupling}$ value remained stable across multiple pump on/off cycles. These results demonstrate the reliability of our $L_{coupling}$ correction in the gain calculation, where the $2 \times 6.7 \text{ dB}$ term properly accounts for the consistent fiber-chip coupling losses at both input and output facets. We have added a statement in the manuscript explicitly confirming the consistency of $L_{coupling}$ measurements during pump on/off cycling.

(Supplementary Information, page S9) The total losses are measured as the differences between the recorded signal powers before and after the amplifier, which include coupling loss, waveguide background loss, and waveguide absorption loss (See Methods). And the coupling loss remained stable across multiple pump on/off cycles and under different input power levels.

Comment 2.4: "Check the added text in Methods - $L_{coupling}$ is repeated"

Our reply: We thank the reviewer for their meticulous reading. The duplicate mention of $L_{coupling}$ in the Methods text was an error. We have rectified this error in the revised manuscript.

(Methods, page 10) L_{link} is the insertion loss of the fiber links and devices (mainly induced by the wavelength division multiplexers) amounting to 2.9 dB.

Comment 3: "Fig. 1 caption - "picture": should perhaps indicate they are SEMs (perhaps this is indicated in the text though...I can see that simplifying language for an overview panel is helpful, just double check what is typical for such overview pictures)"

Our reply: We have revised Fig. 1's caption and have checked all figures in the manuscript to ensure similar ambiguities are resolved.

(Fig. 1, page 1)(ii) False-color SEM picture of the waveguide amplifier, ...(iv) False-color SEM picture of the modulator.

Comment 4: "Response to Comment 18.10: The absorption cross-section for a given dopant ion and transition is an ion and host material property and can typically only be changed slightly by changing

the host material...if another method is suggested it should be indicated."

Our reply: We sincerely thank the reviewer for catching this critical terminology inaccuracy. Our original phrasing suggesting could be misleading. The revised manuscript is as follows:

(Results, Page 7) Further, **designing waveguides with larger mode areas elevates the saturated optical power. This enhancement stems from reduced optical intensity density within the waveguide cross-section, which mitigates gain saturation by distributing power over a broader effective area⁴².** ~~the increment of the absorption cross-section would help elevate the saturated optical power, which could be achieved by enlarging the mode area.~~

Comment 5: *"I believe it is important to clarify internal vs. external NF throughout because other recent works are referring to an external noise figure that accounts for fibre-chip coupling losses. The fiber-chip coupling loss is important for minimizing NF."*

Our reply: We thank the reviewer for highlighting this important detail. The NF of 4.7 dB in this paper adopts the EDFA's noise figure test method: Optical Source-Subtraction Method[R2]. All parameters used for the NF calculation are all directly measured in the test link (fiber-to-fiber) as given in the **Method: Noise figure extraction** section. Our measurement methodology inherently includes all fiber-chip coupling losses and waveguide propagation losses, aligning with the "external" NF definition. While the terminology of "internal" or "external" (fiber-to-fiber) NF is not strictly defined in EDFA literature. Therefore, we avoid using the terms "internal" or "external" when referring to the NF in this work. The same test method is also used in the NF characterization of other optical waveguide amplifiers[R2].

[R1] D. Derickson, Fiber Optic Test and Measurement, D. Derickson (Ed). (1998).

[R2] Liu, Y. et al. A photonic integrated circuit-based erbium-doped amplifier. Science 376, 1309–1313 (2022).

Comment 6: *"Is the ion concentration really exactly 10^{20} cm^{-3} , or is it missing a number in front? 1×10^{20} is relatively low for EDWAs and given the typical (actually slightly lower than silica) cross sections in Fig. S5 doesn't seem to match with the high gain."*

Our reply: We sincerely thank the reviewer for identifying these two critical issues.

We agree that achieving high gain is usually achieved with high doping density. However, it is not the case that higher doping density leads to higher gain. The observed gain performance cannot be explained by the concentration level alone.

We emphasize three contributing factors: First, compared to common poly-crystalline or amorphous host materials (e.g., poly-crystalline SiO_2 and Al_2O_3), single-crystal LiNbO_3 exhibits sharper emission lines with doping. This concentrates gain at the optimal 1531 nm wavelength, maximizing population inversion efficiency. In the future, to achieve dynamic gain equalization and broadband amplification, we could dope sensitizers like Yb^{3+} , Eu^{3+} , and Tm^{3+} to broaden the emission spectrum, monolithically integrate waveguide arrays with AWGs for real-time gain reshaping, and implement dual-wavelength pumping (980 nm + 1480 nm) to populate complementary energy levels of erbium ions — thus enabling flattened high gain across the full C-band. Second, crystalline LiNbO_3 achieves low 0.4 dB/cm background loss — below poly-crystalline Al_2O_3 and silica — extending the effective gain interaction

length. At last, the Er^{3+} concentration of 10^{20} cm^{-3} represents a carefully optimized level that balances gain performance while mitigating concentration quenching effects, which substantially degrade population inversion efficiency at higher densities in our material system.

The observed high gain results from the synergy of optimized material processing and strategic exploitation of cross section transitions. The corrected concentrations are in good agreement with the gain performance achieved through these specific design choices.

Furthermore, we employed the Füchtbauer-Ladenburg equation to calculate the emission cross-section spectrum across the full fluorescence bandwidth, followed by deriving the absorption cross-section via the McCumber reciprocity relation. This method provides self-consistent cross-sections over an extended spectral range (1460-1630 nm), eliminating power-dependent errors inherent in conventional absorption measurements.

Based on experimentally determined parameters (emission cross-section of $1.28 \times 10^{-20} \text{ cm}^2$ and the Er^{3+} ion density of 10^{20} cm^{-3}), our two-level model simulations (Supplementary Note I) for a 9.16-cm waveguide demonstrate that an off-chip signal power of -39 dBm yields a simulated net gain of 38.84 dB, closely matching the measured gain of 38 dB. This agreement verifies both the accuracy of our cross-section determination and the intrinsic compatibility of Er:TFLN waveguides with high-gain amplification. We highlight our achieved larger cross section of $1.28 \times 10^{-20} \text{ cm}^2$ to promise a high gain, compared with other reported optical waveguide amplifiers ($1.01 \times 10^{-20} \text{ cm}^2$ @Er:TFLN[R3], $8 \times 10^{-21} \text{ cm}^2$ @Er:SiN[R2]).

(Supplementary Information, page S7) Supplementary note IV: The absorption and emission cross-sections calculation

The absorption and emission cross-sections are the most fundamental indices of gain materials. **The emission cross section can be calculated from the Fuchtbauer-Ladenburg equation, a rigorously established method for determining emission cross-sections. This approach exploits the relationship between the measured fluorescence intensity $I(\lambda)$ and the intrinsic radiative properties of the gain medium. The wavelength-dependent emission cross-section is obtained by¹³:**

$$\sigma_{21}(\lambda) = \frac{\bar{\lambda}^4}{8\pi n_{\text{eff}}^2 \tau_{\text{rad}}} \frac{I(\lambda)}{\int I(\lambda) d\lambda} \quad (4)$$

Where $\bar{\lambda}$ donates the mean emission wavelength of the transition, c is the speed of light in vacuum, n_{eff} is the effective refractive index of the host material, τ_{rad} is the radiative lifetime and $I(\lambda)$ is the absolute fluorescence intensity at wavelength λ . While the absorption cross-section $\sigma_{12}(\lambda)$ is obtained by the McCumber theory¹⁴:

$$\sigma_{12} = \sigma_{21} e^{\hbar(\frac{2\pi c}{\lambda} - \frac{2\pi c}{\lambda_0})/k_B T} \quad (5)$$

where k_B denotes the Boltzmann constant, T is the temperature (300 K for room temperature), and λ_0 is the peak wavelength of the emission spectrum. The extracted absorption and emission crosssections under different wavelengths are shown in Fig. S5. **The achieved larger cross-section of $1.28 \times 10^{-20} \text{ cm}^2$ could promise a high gain, compared with other reported optical waveguide amplifiers ($1.01 \times 10^{-20} \text{ cm}^2$ @Er:TFLN¹⁵, $8 \times 10^{-21} \text{ cm}^2$ @Er:SiN⁹).**

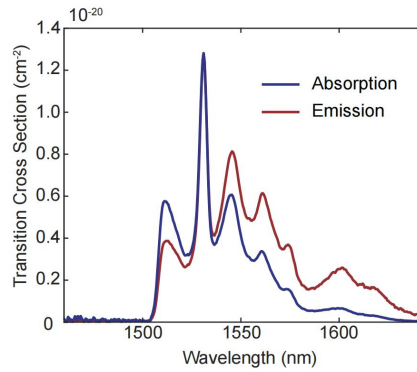


Fig. S5. Extracted emission and absorption cross sections

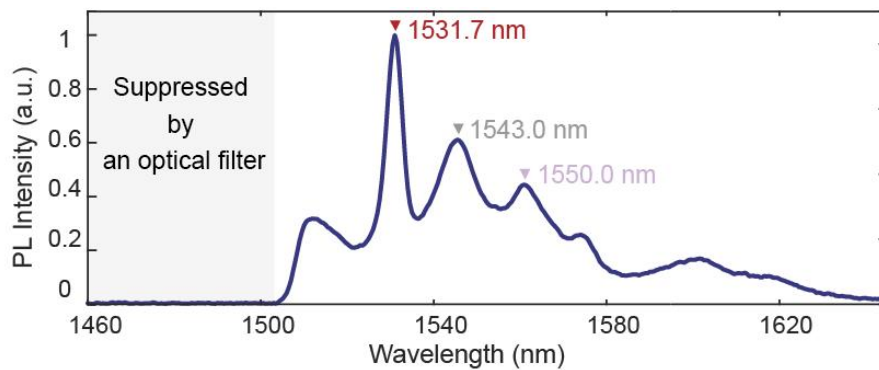
[R3]Cai M, Li T, Zhang X, et al. Gain dynamics in integrated waveguide amplifier based on erbium-doped thin-film lithium niobate[J]. ACS Photonics, 2024, 11(11): 4923-4932.

[R2] Liu, Y. et al. A photonic integrated circuit-based erbium-doped amplifier. Science 376, 1309–1313 (2022).

Comment 7: "Why are there thick bars for individual wavelengths in the PL spectrum in Fig. 2a? Also photo luminescence -> photoluminescence. And why does the spectrum cut off sharply before 1500nm - is this a setup artifact or truly the shape of the PL spectrum??? It does not seem to match the emission cross-sections in Fig. S5. This should be clarified. Furthermore, a statement with comparison to literature erbium-doped lithium niobate cross-sections should be included."

Our reply: The horizontal bars explicitly highlight the primary emission peaks corresponding to the transition wavelengths (1531.7 nm, 1543 nm, 1550 nm). In the revised manuscript, we have now included clearer labels on the corresponding figures and added corresponding descriptions.

(Fig.2, page 3)



.....a, **Photoluminescence (PL)** spectrum of the Er:TFLN waveguide amplifier;.....

(Results, page 3) ... Figure. 2a depicts the **photoluminescence (PL)** spectrum of the Er:TFLN, exhibiting amplified photon emission via stimulated emission from Er^{3+} ions across 1520 - 1570 nm and a notable peak emerges around 1531.7 nm, with two minor peaks observed at 1543 nm and 1550 nm.

The spelling of 'photoluminescence' has been corrected throughout the manuscript as indicated

below.

(Results, page 3) Figure. 2a depicts the **photoluminescence** (PL) spectrum of the Er:TFLN, ...

(Results, page 3) The **photoluminescence** lifetime is measured to be 5.8 ms (See Supplementary Note V),.....

(Fig.2, page 3).....a, **Photoluminescence** (PL) spectrum of the Er:TFLN waveguide amplifier;.....

The observed spectral attenuation below 1500 nm stems from a long pass optical filter (Thorlabs FELH1500, cut-on wavelength: 1500 nm) deliberately incorporated into the fluorescence spectrometer (MicroSpecIR). This configuration specifically suppresses residual pump scattering at the 1480 nm excitation wavelength. We will supplement the corresponding explanations in Methods.

(Methods, page 10) **Photoluminescence spectrum measurement**

The **photoluminescence** (PL) spectrum was acquired using a fluorescence spectrometer (MicroSpecIR) equipped with a long-pass optical filter (Thorlabs FELH1500; cut-on wavelength: 1500 nm). The sample was pumped by a 1480 nm laser source (PSU-III-LED1480). The added optical filter suppressed residual pump scattering at 1480 nm, ensuring signal fidelity below 1500 nm.

The apparent spectral differences between the photoluminescence (PL) spectrum in Fig. 2a and emission cross-sections in Fig. S5 stem fundamentally from distinct measurement methodologies: while the emission cross-sections were rigorously derived via the McCumber method applied to waveguide absorption spectra, inherently incorporating waveguide mode confinement effects and potential facet reflections, the PL spectra were obtained through normal-incidence excitation / detection—avoiding waveguide-coupling reflections but sensitive to surface alignment variations. Nevertheless, both datasets exhibit strong qualitative consistency, with precise wavelength alignment across the three primary Er^{3+} emission peaks (1531.7 nm, 1543.0 nm, 1550.0 nm), complemented by their identical intensity trend hierarchy to amplified spontaneous emission (ASE) spectra in Er^{3+} :FLN waveguide amplifiers[R4].

And as mentioned in our reply to Comment 6, we employed the Füchtbauer-Ladenburg equation to calculate the emission cross-section spectrum across the full fluorescence bandwidth instead, followed by deriving the absorption cross-section via the McCumber reciprocity relation. This method provides self-consistent cross-sections over an extended spectral range (1460-1630 nm), eliminating power-dependent errors inherent in conventional absorption measurements. Now the PL spectrum is match the emission cross-sections in Fig. S5.

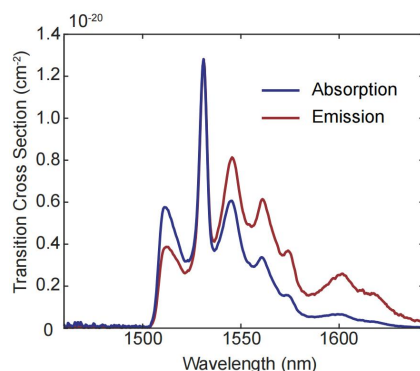


Fig. S5. Extracted emission and absorption cross sections

As requested, we provide a direct comparison to literature values for erbium-doped waveguide amplifiers: Our emission cross-section of $1.28 \times 10^{-20} \text{ cm}^2$ in Er:TFLN waveguides (this work) versus the reported Er:TFLN platforms ($1.01 \times 10^{-20} \text{ cm}^2$ [R3]). The revised manuscript is as follows:

(Supplementary Information, page S7) **The achieved larger cross section of $1.28 \times 10^{-20} \text{ cm}^2$ could promise a high gain, compared with other reported optical waveguide amplifiers ($1.01 \times 10^{-20} \text{ cm}^2$ @Er:TFLN¹⁵, $8 \times 10^{-21} \text{ cm}^2$ @Er:SiN⁹).**

[R3]Cai M, Li T, Zhang X, et al. Gain dynamics in integrated waveguide amplifier based on erbium-doped thin-film lithium niobate[J]. ACS Photonics, 2024, 11(11): 4923-4932.

[R4]Xu Q, Chen F, Chen Z X, et al. Er³⁺-Doped Lithium Niobate Thin Film: A Material Platform for Ultracompact, Highly Efficient Active Microphotonic Devices[J]. Advanced Photonics Research, 2021, 2(12): 2100081.

Comment 8: *"Supplementary note 12: chirp -> chirped; and what is the spiral waveguide length and why does it introduce significant loss if the background loss is only 0.4 dB/cm?"*

Our reply: We appreciate the reviewer's attention to loss characterization details and acknowledge that describing the 0.4 dB/cm background loss as "significant" was imprecise. We have implemented the following revisions in response to your comments:

(Supplementary Information, page S18) For the FMCW signal modulation and amplification experiment on Er:TFLN platform(Fig. S14), a **chirped** microwave signal ranging from 8 GHz to 12 GHz at a repetition rate of 800 kHz

(Supplementary Information, page S18) At 1600 nm, the large absorption loss of Er³⁺ ions can be avoided. ~~However, the long spiral waveguide introduces substantial background loss, resulting in an off-chip output power of -15.0 dBm with an off-chip input signal power of 5 dBm.~~

Response to the report from the Referee #2

General comments: "Dear authors and editor, I have carefully reviewed the updated manuscript, supplementary information and response to the comments of the reviewers. My concerns have been addressed by the authors and I find the manuscript almost ready for publication. I especially appreciate that the authors extended the supplementary information with detailed setup and power level descriptions of the relevant experiments clarifying conditions for the readers of the paper. It is my opinion that the paper represents an a very relevant and detailed technical work with interesting experiments and photonic integrated circuit design.

Pending this minor correction and any associated updates, I recommend the manuscript for publication."

Our reply: We sincerely thank Referee #2 for their thorough review and positive assessment of our revised manuscript. As requested, we have carefully implemented the minor correction noted in the report and ensured all associated updates are reflected in the manuscript.

Comment 1: "However, I do have a concern that the manuscript needs a final in depth review by the authors themselves to assure quality. For example in the supplementary information on page 4 the authors calculate the density of the ions which they find to be 10^{23} per cm^3 : "... is the Er^{3+} molar fraction, $\rho=4.64 \text{ g/cm}^3$ is the density of LiNbO_3 , $M=147.9 \text{ g/mol}$ is its molar mass, and $N_A=6.022\times 10^{23} \text{ mol}^{-1}$ is Avogadro's constant. Substituting these values yields an Er^{3+} ion density of $10^{23} \text{ ions/cm}^3$." This is clearly not correct and a quick calculation yields approximately $9 \times 10^{19} \text{ cm}^{-3}$ for the ion density. Please assure that this error is not propagated into the other parts of the manuscript, where the value for N_{Er} is not explicitly given."

Our reply: We sincerely thank the reviewer for identifying this critical calculation error in the supplementary material. The Er^{3+} ion density is $9.5\times 10^{19} \text{ cm}^{-3}$, which rounds to approximately 10^{20} cm^{-3} . As documented in the response letter, **our Reply to Comment 18.10 (Reviewer #3)**, the originally reported value is indeed 10^{20} cm^{-3} . The erroneous value of 10^{23} cm^{-3} in the Supplementary Note II (Page S4) resulted from a typographical error during manuscript preparation. All instances of this value have been updated.

(Supplementary Note II, Page S4) The erbium oxide is introduced during the growth and preparation process of the lithium niobate crystal⁶. Erbium ions were introduced into the lithium niobate (LiNbO_3) crystal lattice via a controlled solid-state reaction. High-purity Li_2CO_3 , Nb_2O_5 , and Er_2O_3 powders were stoichiometrically mixed according to the target composition of LiNbO_3 : 0.5 mol% Er^{3+} . The homogeneous distribution of Er^{3+} ions was ensured by iterative grinding and re-sintering steps prior to single-crystal growth via the Czochralski method.

The Er^{3+} concentration in ions per cubic centimeter (ions/cm^3) was derived from the molar percentage (mol%) using the following relationship:

$$n_{\text{Er}} = \frac{\text{mol}\%}{100} \times \frac{\rho}{M} \times N_A$$

Where $\chi=0.5 \text{ mol}\%$ is the Er^{3+} molar fraction, $\rho=4.64 \text{ g/cm}^3$ is the density of LiNbO_3 , $M=147.9 \text{ g/mol}$ is its molar mass, and $N_A=6.022\times 10^{23} \text{ mol}^{-1}$ is Avogadro's constant. Substituting these values yields an Er^{3+} ion density of **$10^{20} \text{ ions/cm}^3$** . This approach ensures a more uniform distribution of Er^{3+} ions within the crystal, thereby enhancing the effective concentration of erbium doping.