

Supplementary Information for

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

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Supplementary note 1: Waveguide amplifier design

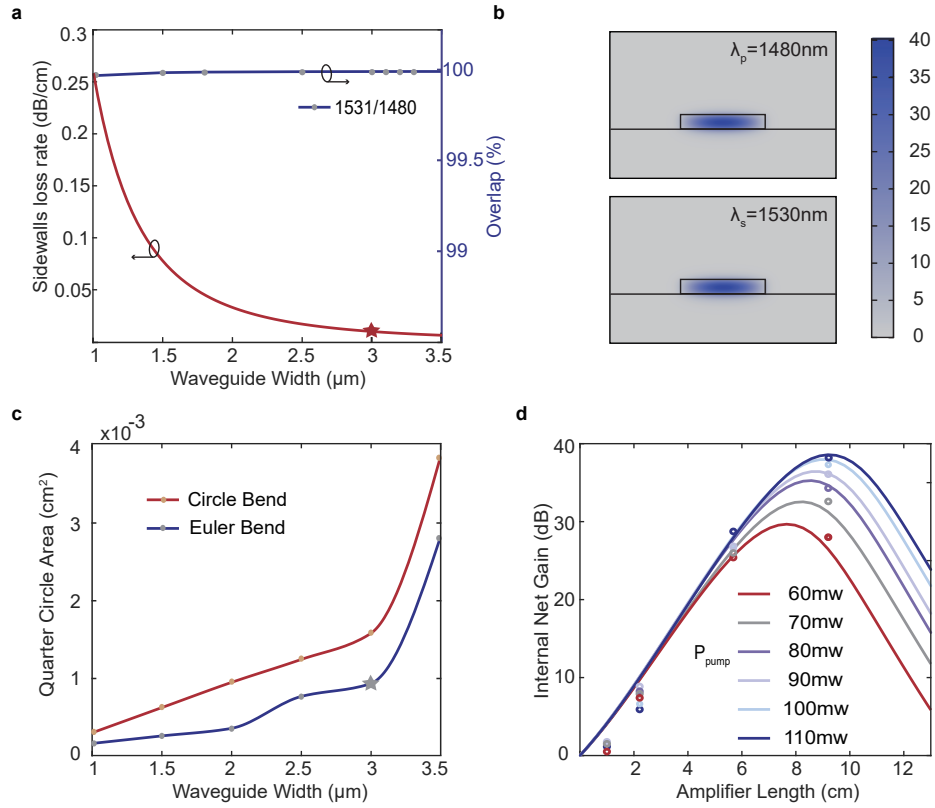


Fig. S1. Waveguide amplifiers design. **a**, Simulated scattering losses and mode overlaps under different waveguide widths. **b**, Simulated mode distributions of the signal light and the pump light. **c**, Areas of different bends under different waveguide widths. **d**, The relationships between internal net gains and amplifier lengths under different pump powers in simulation (curves) and experiment (dots)

A three-dimensional (3-D) analysis based on volume current method¹ is conducted to evaluate the scattering loss coefficient induced by sidewall roughness with the variations of waveguide widths, as shown in Fig. S1a. It is indicated that multimode waveguides demonstrate decreased sidewall losses in comparison to single-mode design, attributing to the reduced overlap between the optical field and the etched sidewalls. Particularly, with the waveguide getting wider, the sidewall loss coefficient first reduces then gradually levels off under multimode regime around 3 μm . The multimode waveguides with larger mode area feature higher optical power capacity, therefore provide higher gain and saturation power². Incidentally, this design also promises a high overlap between the signal at 1531 nm and the pump around 1480 nm. The blue curve depicted in Fig. S1a shows the variation of the mode overlap with the waveguide width. Theoretically, perfect mode overlap between 1531 nm (signal) and 1480 nm (pump) can be achieved regardless of waveguide width, where the overlap is ideally above 99.98 % (Fig. S1b) in a 3 μm waveguide. Considering the loss coefficient and the mode overlapping, the width of the waveguide amplifier is set to 3 μm .

Another loss factor is from the bending region. This issue is more severe in multimode waveguide bends, where a large bend radius is necessary to suppress the inter-mode crosstalk. Delicate adiabatic bend design is adopted, whose curvature changes gradually with the arc length. Common types of adiabatic bends include Euler bends³ and Archimedean bends. The curvature of an Euler bend changes linearly with its length, while in an Archimedean bend⁴, the radial distance increases linearly with the angle. 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 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.

Under certain waveguide structure, the optimal length also needs to be explored to maximize the gain. A two-level model⁵ is established, where the net gain with the relationship of the waveguide length (Fig. S1d) is obtained through the transmission equation:

$$\frac{dP_p(z)}{dz} = (\sigma_{21}N_2 - \sigma_{12}N_1 - \alpha)\Gamma_p P_p(z) \quad (1)$$

$$\frac{dP_s(z)}{dz} = (\sigma_{21}N_2\sigma_{12}N_1 - \alpha)\Gamma_s P_s(z) \quad (2)$$

$P_p(z)$ and $P_s(z)$ are the power of pump light and signal light. N_1 and N_2 represent the number of particles at each energy level of Er^{3+} ions in the steady state. α is the waveguide transmission loss, set to 0.4 dB/cm. Γ_p and Γ_s are the limiting factors of pump light and signal light in the gain material. Considering the side wall inclination angle possibly caused by processing, we set Γ_p and Γ_s as 98.5 % and 98 %, respectively, as the waveguide width is 3 μm and the waveguide height is 600 nm. The input optical power is set to -40 dBm.

For a given pump power, the internal net gain first increases with the length of the waveguide and reaches the maximum due to the depletion of the pump light. With longer waveguide, the pump light is too weak to excite the Er^{3+} ions in the subsequent part, leading to the absorption of the signal. Thus, the gain factor decreases with increasing waveguide length. Also, as the pump power increases, the growth of the maximum gain slows down and gradually reaches saturation, limited by the concentration of Er^{3+} ions. Here, considering the transmission loss of pump light and signal light in the waveguide, as well as the risk of parasitic laser caused by excessive input pump light power, the length is set to around 9 cm.

Also, Figure. S1d 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.

Supplementary note 2: Materials and Fabrication process



Fig. S2. The Er:TFLN PIC fabrication process consisting of the ICP-RIE process

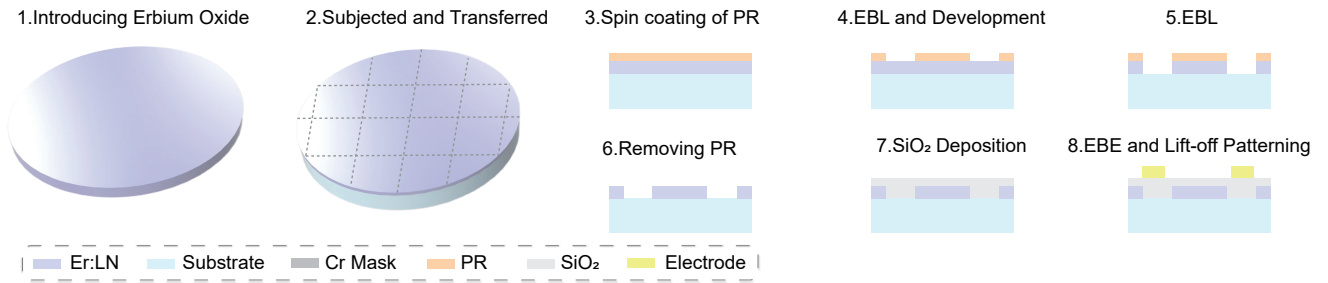


Fig. S3. The Er-doped thin-film lithium niobate (Er:TFLN) PIC fabrication process consisting of the EBL process

S2.1 Fabrication process of Er:TFLN waveguide amplifiers

Fig. S2 illustrates the fabrication process of the Er-doped thin-film lithium niobate (Er:TFLN) waveguide amplifier. 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:

$$n_{Er} = \frac{\text{mol}\%}{100} \times \frac{\rho}{M} \times N_A \quad (3)$$

where $\chi=0.5$ mol% is the Er^{3+} molar fraction, $\rho=4.64$ g/ cm^3 is the density of LiNbO_3 , $M=147.9$ g/mol is its molar mass, and $N_A=6.022 \times 10^{23}$ mol⁻¹ is Avogadro's constant. Substituting these values yields an Er^{3+} ion density of 10^{20} 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 undergone thin-film exfoliation and were transferred onto silicon dioxide substrates. The transferred Er:TFLN thin film was then sliced to regular shaped pieces. A 400-nm-thick Chromium (Cr) layer was deposited on the Er:TFLN surface as a hard mask by electron beam evaporation (EBE). After washing the chip to remove particles and organic impurities on the surface, the HSQ photoresist (PR) was spin coated on the Er:TFLN substrates of 600 nm. The waveguide patterns were defined in the PR using standard electron beam lithography (EBL). Then, inductively coupled plasma (ICP) was used to transfer the pattern from PR to the Cr layer. After removing the PR, the patterns were transferred into the waveguide layer by reactive ion etching (RIE)^{7,8}. Subsequently, cleaning was performed to remove the hard mask and small particles. Finally, a 5- μm -thick SiO_2 thin film was deposited on Er:TFLN as a protective layer by plasma-enhanced chemical vapor deposition (PECVD).

S2.2 Fabrication process of Er:TFLN with modulation

Fig. S3 illustrates the fabrication process of the Er:TFLN waveguide amplifier with modulation. The erbium-doped

wafer production, transfer and slicing are the same as S2.1. After washing the chip to remove particles and organic impurities on the surface, the PR was spin coated on the substrates. The waveguide patterns were defined in the PR using EBL. Then, cleaning was performed to remove the PR and small particles. Subsequently, 1- μm -thick SiO_2 thin film was deposited on Er:TFLN as a protective layer by PECVD. A 900-nm-thick gold (Au) layer was deposited on the SiO_2 surface by EBE. Finally, the electrodes were patterned using the lift-off method.

Supplementary note 3: Low-loss characterization

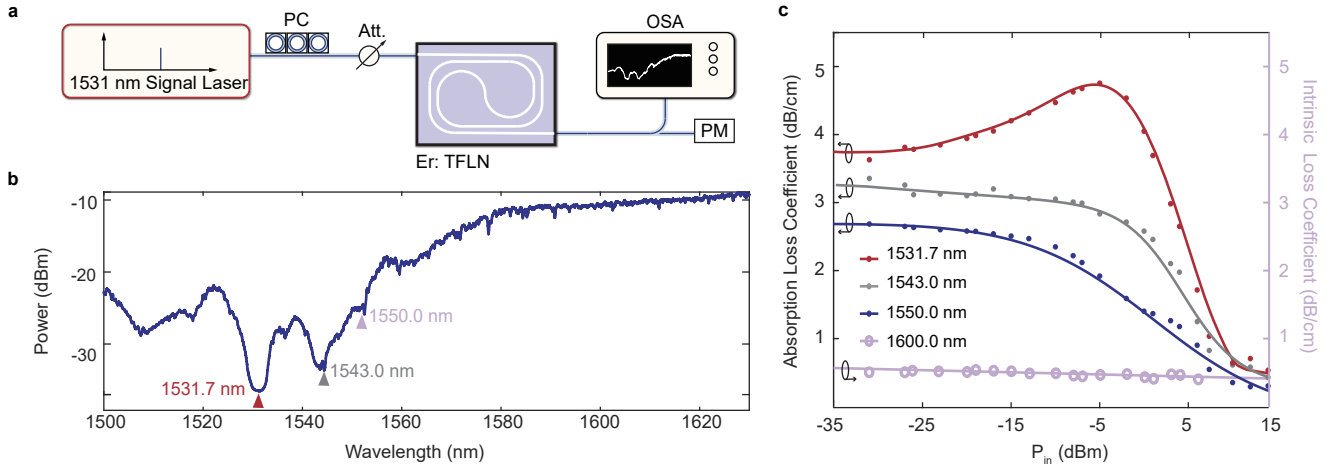


Fig. S4. Passive characteristics of Er:TFLN waveguide amplifier. **a**, Experimental setup; PC, Polarization controller; Att., Attenuator; OSA, Optical spectrometer analyzer. **b**, Measured transparent spectrum of the waveguide amplifier at low signal power; **c**, Measured loss factor of amplifiers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

Characterizing different loss factors can provide a better assessment of material absorption and fabrication quality. In this section, the transmission of the amplifiers without the pump light is measured to evaluate different losses, as depicted in Fig. S4a. Due to the absorption nature of Er^{3+} ions^{9–11}, the loss factor of the Er-doped materials may vary under different wavelengths. Fig. S4b shows the tested transmission spectrum of the amplifier. Three prominent absorption peaks are evident at 1531.7 nm, 1543 nm, and 1550 nm, indicating significant amplification at these wavelengths. Notably, the highest transmission occurs around 1600 nm, where the absorption of Er^{3+} ions is ignorable. Thus, the background loss rate can be estimated by linear fitting the total losses of different waveguide lengths at 1600 nm. 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. When the off-chip input signal power is 4 dBm, the scattering loss rate is found to be 0.4 dB/cm. The absorption loss at other wavelengths can be obtained by subtracting the background loss rate from the slope of fitted curves, which is 2.7 dB/cm (@ 1531.7 nm), 2.2 dB/cm (@ 1543 nm), and 1.5 dB/cm (@ 1550 nm), respectively.

Different from passive waveguides, where the insertion loss is independent of the optical power, the propagation loss of Er-doped waveguide is significantly related to the input power. The test results of the estimated propagation losses under different signal powers are depicted in Fig. S4c. It is worth noting that the waveguide absorption loss diminishes at high optical powers. The observed power-dependent losses are attributed to the saturable absorption. Under a weak injection power, the Er^{3+} ions are not excited, leading to a large absorption loss, corresponding to the small signal regime¹². With a strong signal light, most of the Er^{3+} ions are excited after absorbing portions of the injection light, and the rest of the signal could pass the amplifier with low absorption loss. The saturable absorption property suggests that assessing injection power by simply adding a fixed loss rate to the measured output power may lead to inaccuracies.

Supplementary note 4: 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:

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

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:

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

where k_B denotes the Boltzmann constant, T is the temperature (300 K for room temperature), λ_0 is the peak wavelength of the emission spectrum. The extracted absorption and emission cross-sections 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).

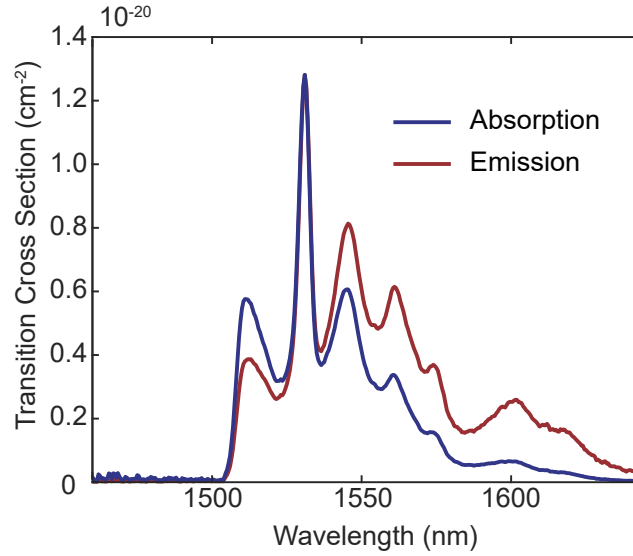


Fig. S5. Extracted emission and absorption cross sections.

Supplementary note 5: Lifetime measurement

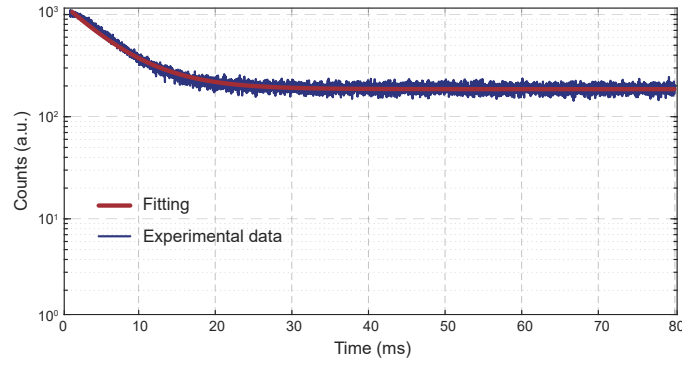


Fig. S6. Time-resolved fluorescence decay profile.

Table S 1. Biexponential decay fitting parameters for Er^{3+} photoluminescence lifetime

Parameter	Value
τ_1	5.4
τ_2	6.1
B_1	4.9
B_2	4.9

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 as¹⁶:

$$I(t) = I_0 + B_1 * \exp\left(\frac{-t}{\tau_1}\right) + B_2 * \exp\left(\frac{-t}{\tau_2}\right) \quad (6)$$

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. 1. The measured fluorescence lifetime (τ) of the sample is given by:

$$\tau = \frac{B_1\tau_1^2 + B_2\tau_2^2}{B_1\tau_1 + B_2\tau_2} \quad (7)$$

The lifetime is calculated as 5.8 ms, which indicates an ideal doping condition, close to the typical value in the commercial EDFA (@ 10 ms¹⁶).

Supplementary note 6: 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 an off-chip peak of 9.2 dBm at 1480 nm. Meanwhile, Fig. S7b reveals the Er:TFLN waveguide's broadband fluorescence under an off-chip pump power of 0 dBm. 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 panel in Fig. S7b). 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.

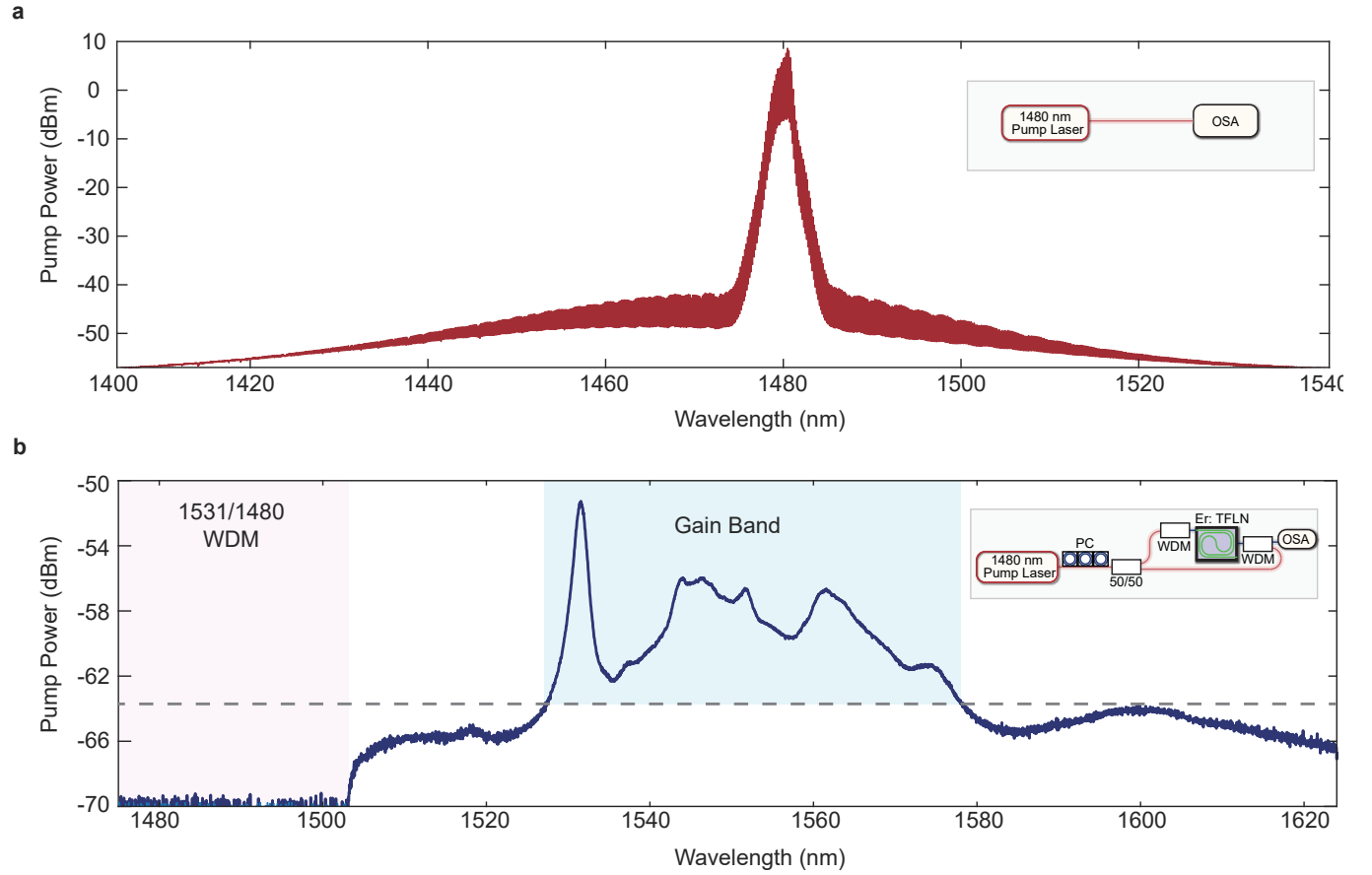


Fig. S7. Characterization of pump laser and Er:TFLN waveguide emission. **a**, Pump laser output spectrum, inside panel: experimental setup. **b**, Fluorescence emission spectrum from an Er:TFLN waveguide under an off-chip pump power of 0 dBm, inside panel: experimental setup.

Supplementary note 7: Parasitic Lasing and Mitigation Strategies

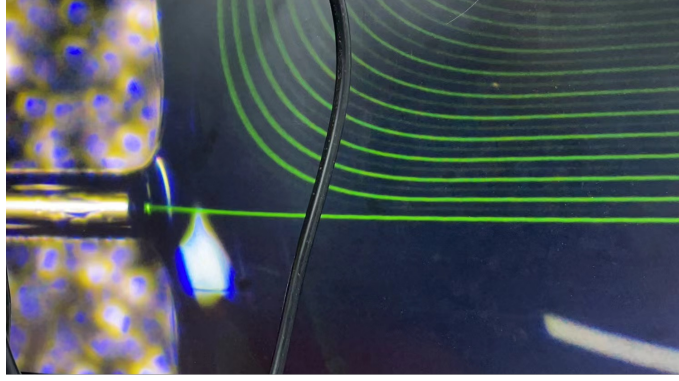


Fig. S8. The photo of the chip-fiber interface with the Index-matching gel applied.

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 as 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 it hits 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.

Supplementary note 8: Gain performance comparison with state-of-the-art on-chip amplifiers

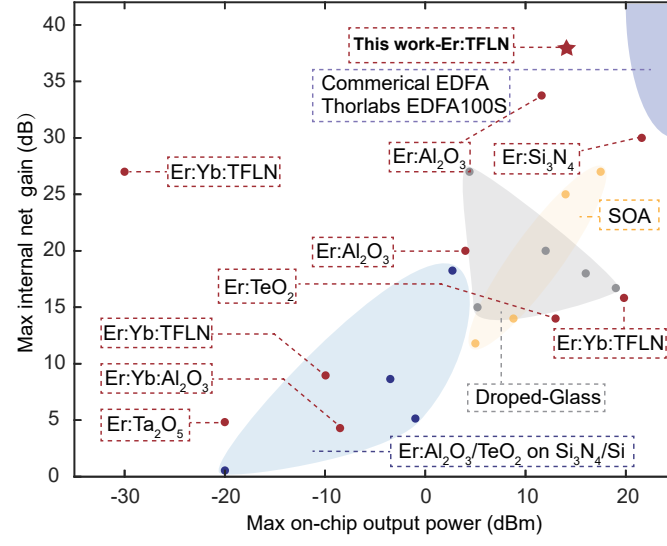


Fig. S9. Comparison with previously reported on-chip amplifiers and typical commercial EDFA.

The gain performance comparison with state-of-the-art on-chip amplifiers are shown in Table. 2 and Fig. S9.

Table S 2. 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 ¹⁷
Er:Al ₂ O ₃	Er:Al ₂ O ₃	13.2	33.5	1532	1480	12.9	Bonneville et al ¹⁸
Er:Al ₂ O ₃	Er:Al ₂ O ₃	4	20	1532	976	12.9	Vázquez et al ¹⁹
Er:TeO ₂	Er:TeO ₂	13	14	1530	1480	5	Vu and Madden ²⁰
Er:Ta ₂ O ₅	Er:Ta ₂ O ₅	<-20	4.83	1530	1480	2.3	Subramanian et al ²¹
Er:Yb:Al ₂ O ₃	Er:Yb:Al ₂ O ₃	<-8.5	4.3	1533	970	3	Bonneville et al ²²
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 ²³
Si ₃ N ₄	Er:Al ₂ O ₃	-3.5	8.5	1532	980	5.9	Chrysostomidis et al ²⁴
GeSbS	Er:Al ₂ O ₃	N/A	6.27	1533	1480	4.6	Wang et al ²⁵
Si ₃ N ₄	Er:Al ₂ O ₃	<-20	0.4	1533	1470	0.16	Rönn et al ²⁶
Low confinement waveguide based devices							
Er:phosphate glass	Er:phosphate glass	4.4	27	1530	1480	47.4	Hattori et al ²⁷
Er:Yb:phosphate glass	Er:phosphate glass	12	20	1550	980	4.1	Barbier et al ²⁸
Er:bismuthate glass	Er:bismuthate glass	≈ 16	18	1533	980	8.7	Thomson et al ²⁹
Er:Yb:phosphate glass	Er:Yb:phosphate glass	≈ 19	16.7	1534	980	3.1	Della Valle et al ³⁰
Er:soda-lime glass	Er:soda-lime glass	5.2	15	1550	980	4.5	Nykolak et al ³¹
Integrated semiconductor optical amplifier (SOA)							
Si	III-V material	17.5	27	1575	N/A	0.145	Van Gasse et al ³²
Si	III-V material	14	25	1550	N/A	N/A	Davenport et al ³³
Si ₃ N ₄	III-V material	8.8	14	1550	N/A	0.115	Op de Beeck et al ³⁴
LiNbO ₃	III-V material	<5	11.8	1537	N/A	N/A	Op de Beeck et al ³⁵

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	SOA1117S

Supplementary note 9: Half-wave voltage characterization

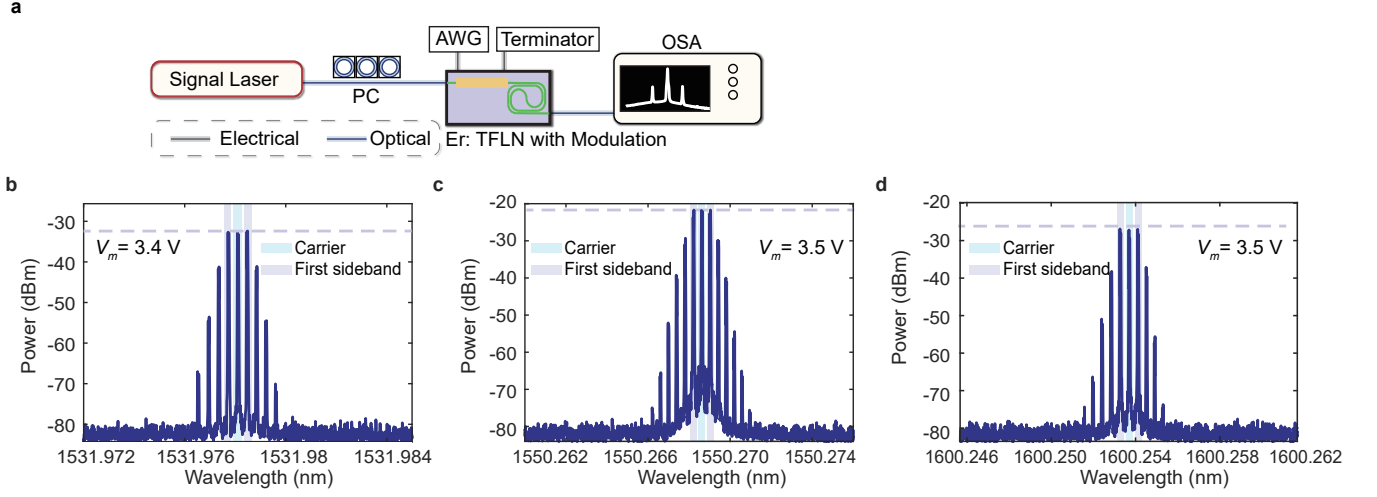


Fig. S10. Half-wave voltage characterization in different wavelengths. a, Half-wave voltage measurement setup. b-d, Spectrums when the carrier and FSB are equal.

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 equal³⁶. 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. 2e and Fig. S10, the carrier and FSB are equal in intensity when V_m is about 3.5 V, which leads to³⁶:

$$V_m \approx 0.457 \cdot V_\pi \quad (8)$$

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 losses³⁷.

Supplementary note 10: Bandwidth and high-speed data measurement setup

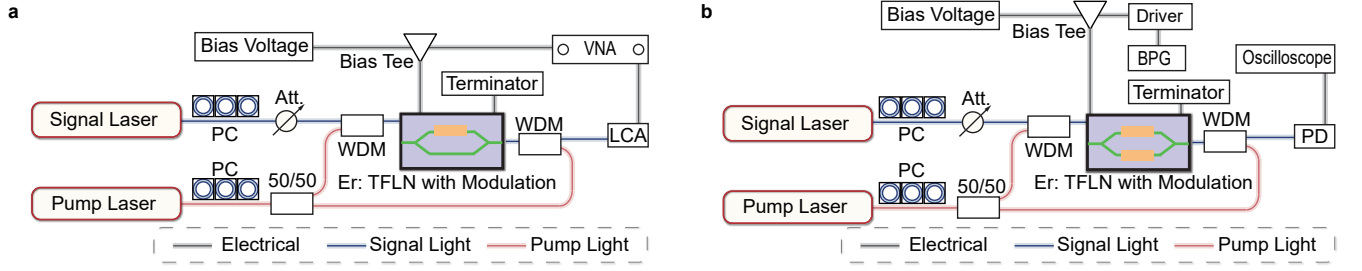


Fig. S11. High-speed measurement setup. a, Bandwidth measurement setup. **b,** Data transmission measurement setup. BPG, bit pattern generator.

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 was 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 S_{21} 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 analogue 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).

Supplementary note 11: Amplification with full-band modulation test

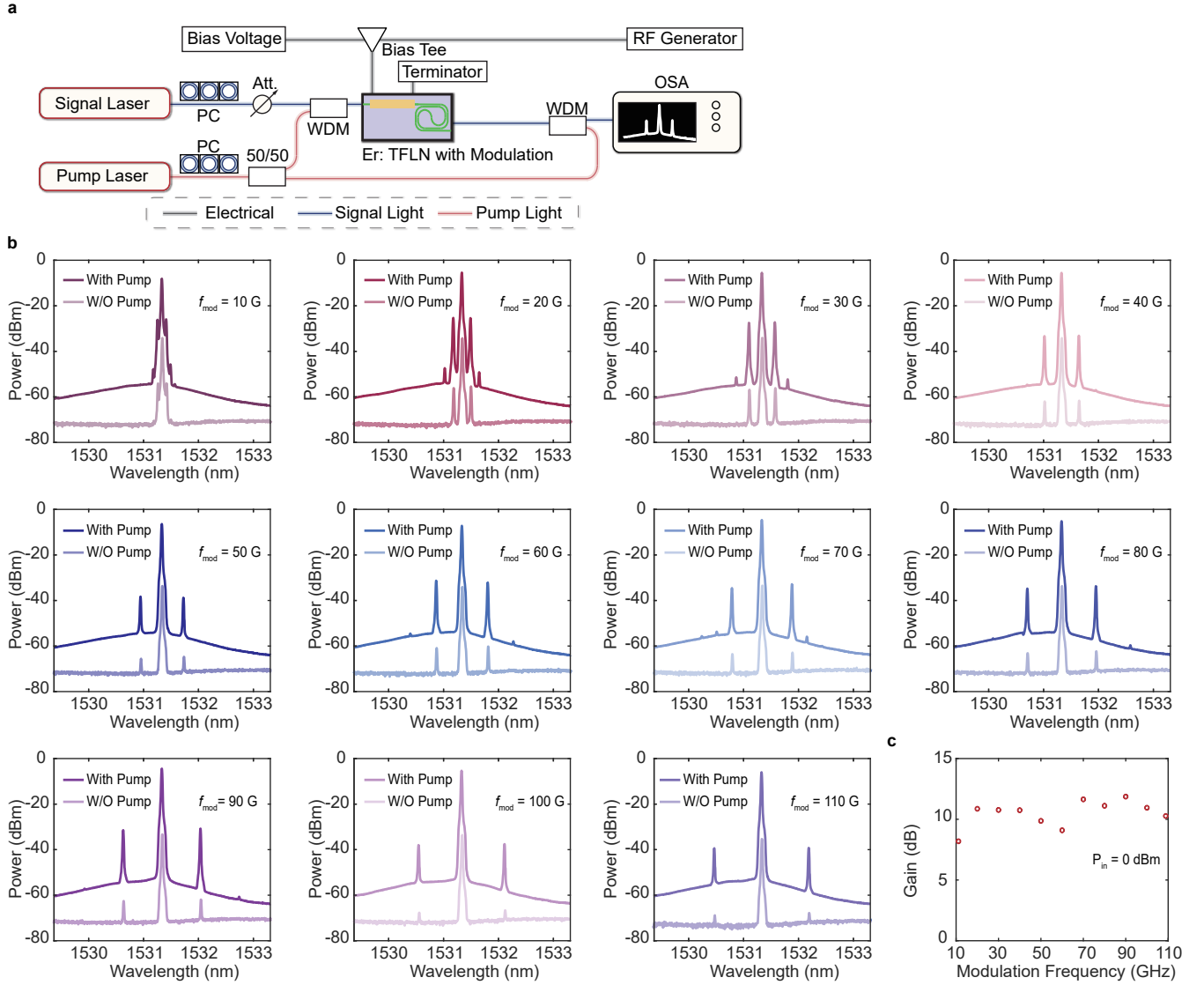


Fig. S12. Amplification experiment of 10 GHz - 110 GHz modulated signals. **a**, Experimental setup, f_{mod} , Modulation frequency. **b**, Spectrum of the modulated signal. **c**, Measured internal net gain under different modulation frequencies.

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 110 GHz to 170 GHz 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.

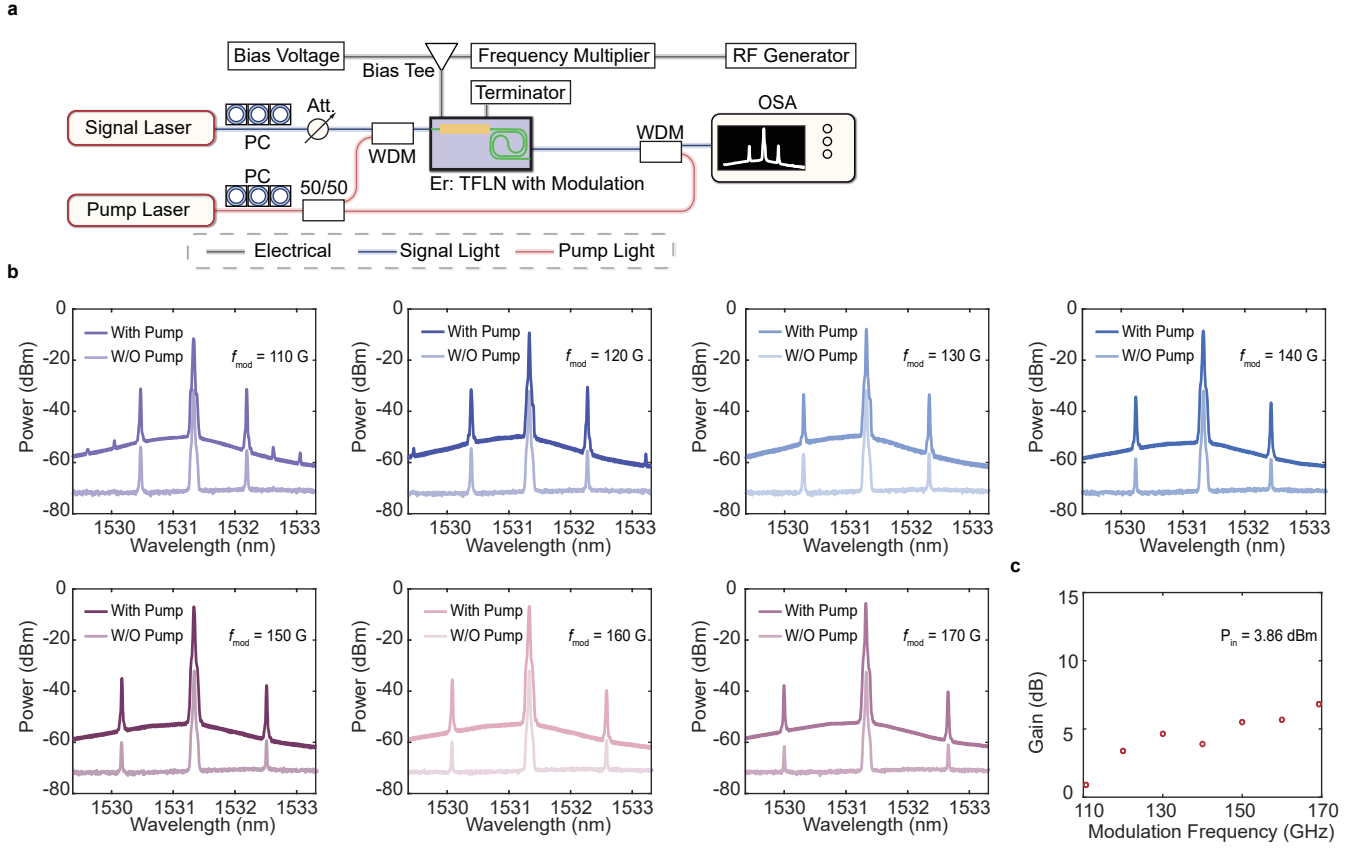


Fig. S13. Amplification experiment of 110 GHz - 170 GHz modulated signals. a, Experimental setup. **b**, Spectrum of the modulated signal. **c**, Measured internal net gain under different modulation frequencies.

Supplementary note 12: Frequency modulated continuous wave (FMCW) signal modulation and amplification test

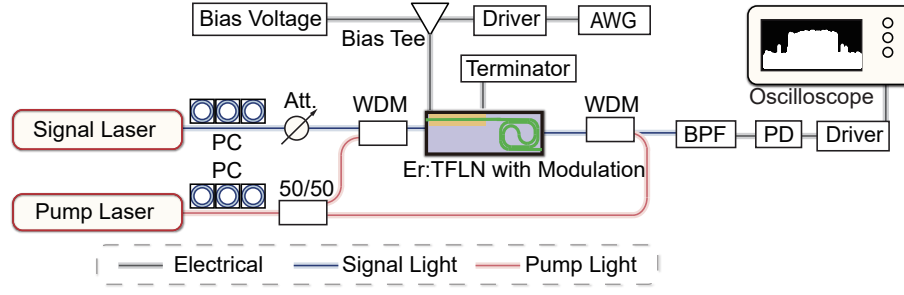


Fig. S14. Setup of on-chip signal modulation and amplification based on Er:TFLN platform. BPF, bandpass filter.

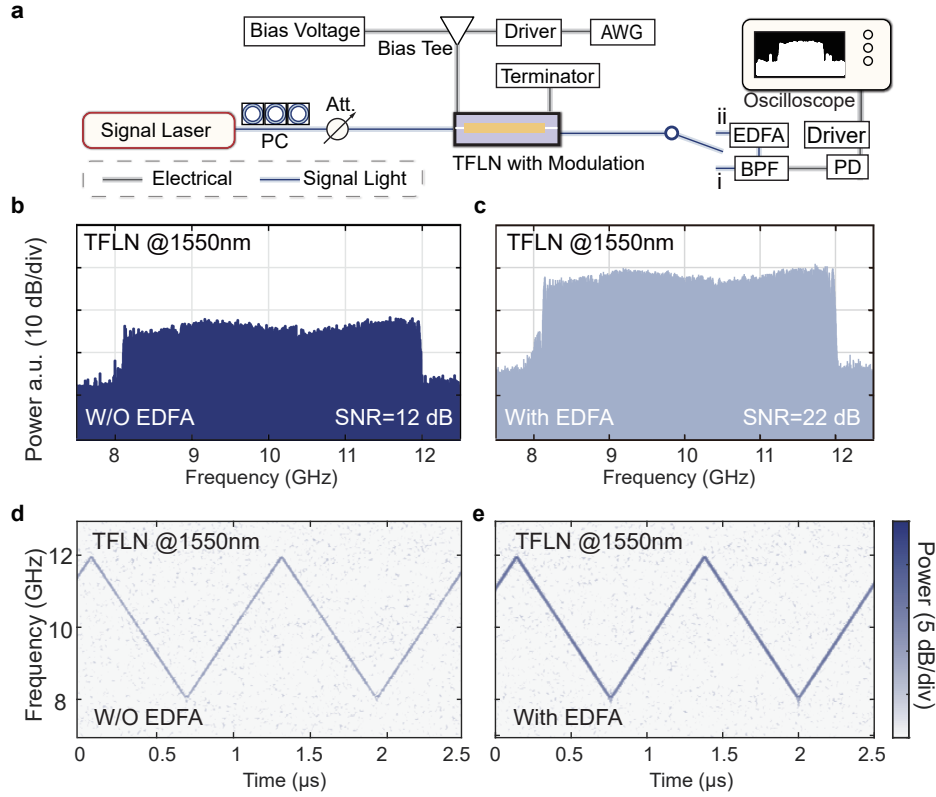


Fig. S15. Signal modulation and amplification based on TFLN platform. **a**, Experimental setup. **b-e**, The received microwave signal and time-frequency spectra of the beatnote between the carrier and the sideband without EDFA (**b,d**) and with pump light (**c,e**).

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 with a 200 mV amplitude was generated using an arbitrary waveform generator (AWG, Micram Instruments 10002). One of the sidebands was then filtered using a bandpass filter (BPF EDFO XTM-50) with an insertion loss of 5.5-6 dB. At 1600 nm, the large absorption loss of Er^{3+} ions can be avoided, 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 one at 1600 nm (Fig.

5b,c).

To completely avoid the influence of Er^{3+} ions, we conducted comparative experiments with an undoped TFLN modulator and a commercial EDFA (Amonics AEDFA-PA-35-B-FA), as shown in Fig. S15a. The TFLN phase modulator exhibits a half-wave voltage V_π of 5.6 V, close to that on Er:TFLN, 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 previous one while with the commercial EDFA inserted after the TFLN chip, amplifying the optical power to -4.2 dBm. The input signal power and the received optical power are kept the same as in the previous. 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 the one on Er:TFLN platform with pump at 1550 nm.(Fig. S15c) This indicates that the waveguide amplifier in this work has a lower noise level compared to the commercial EDFA.

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