

Supplementary Information

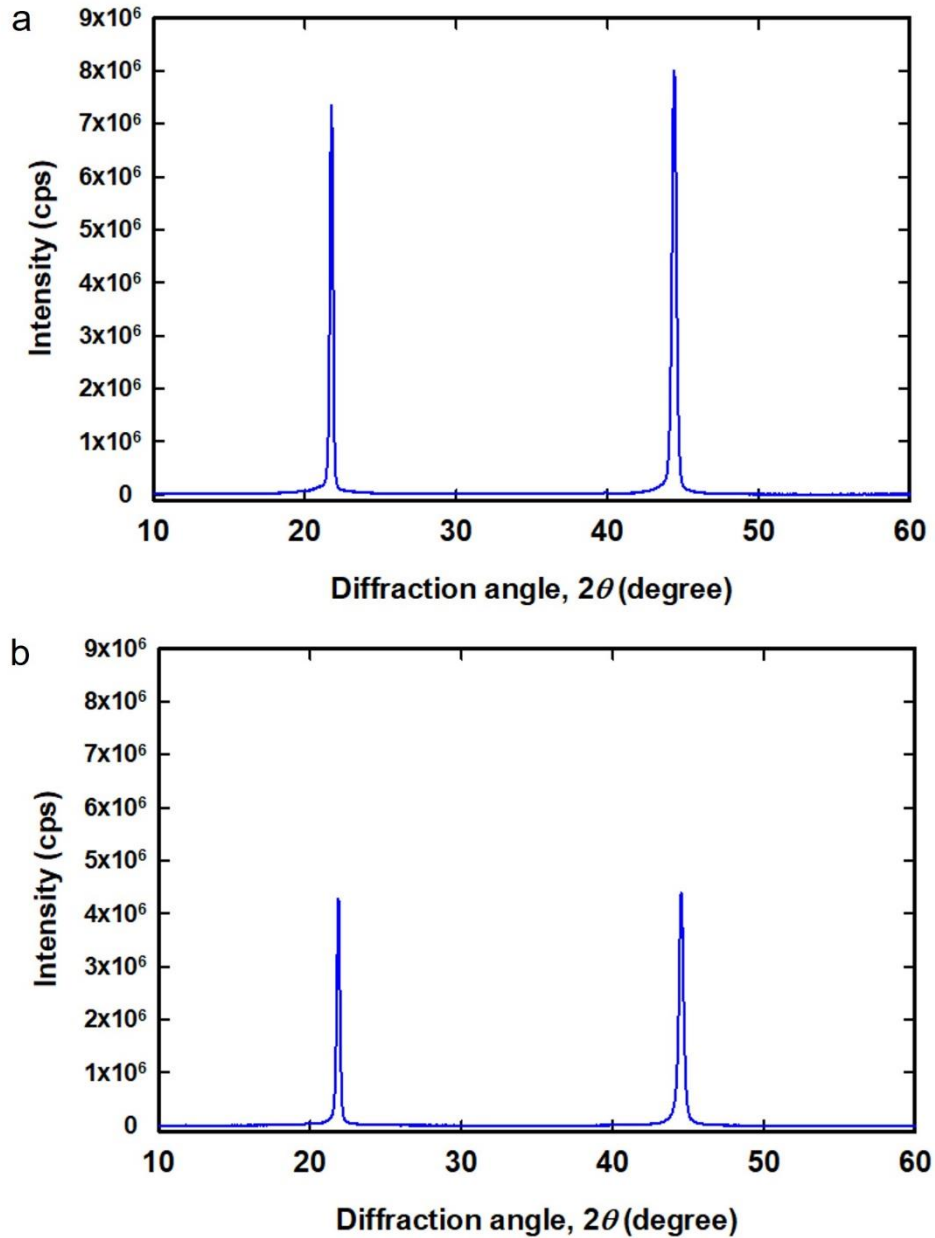
Ultra-fast perovskite electro-optic modulator and multi-band transmission up to 300 Gbit s⁻¹

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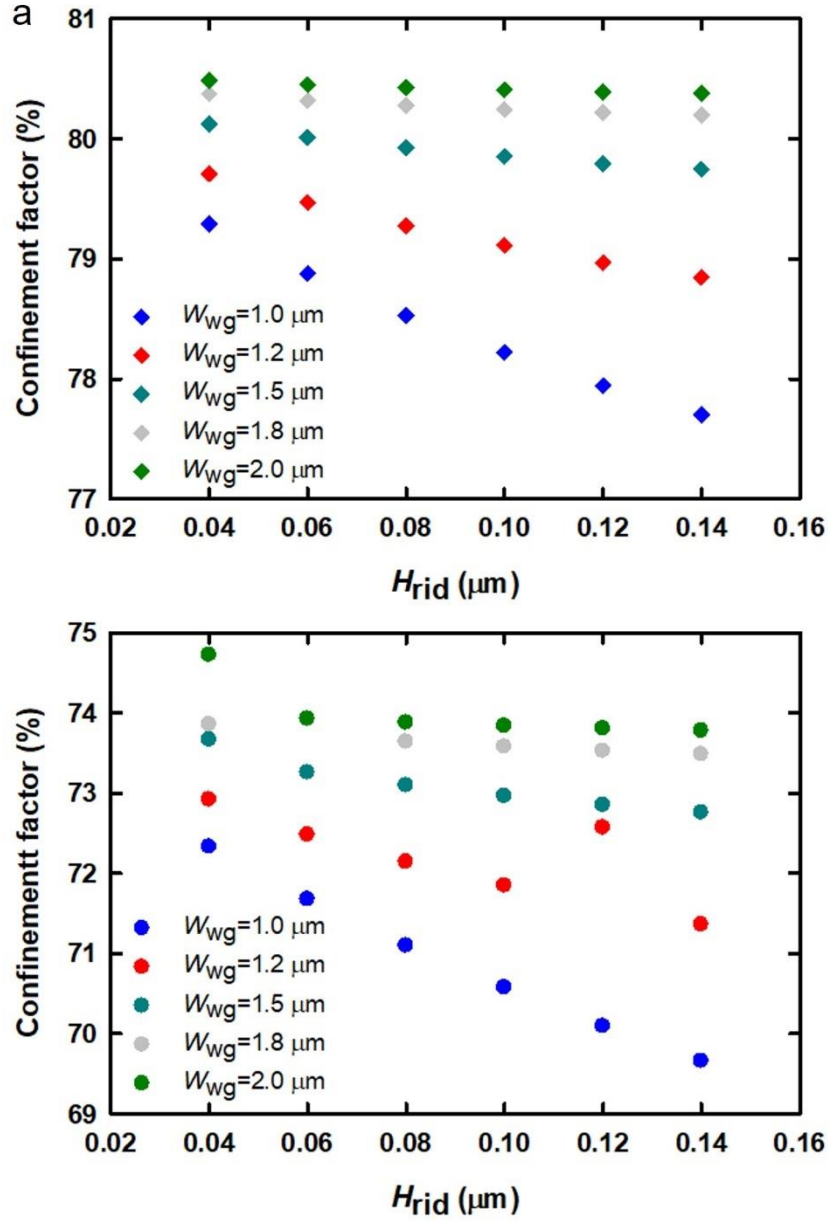
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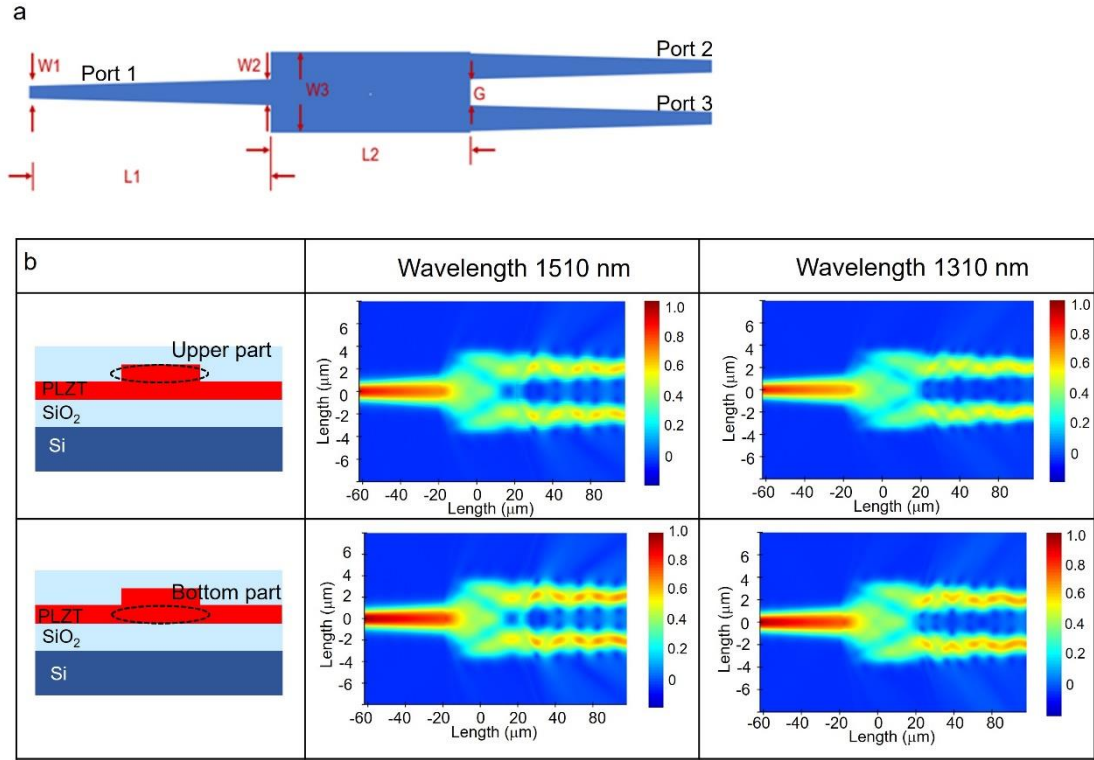
Supplementary Fig. 1. Preparation of PLZT films. **a** XRD pattern for PLZT film prepared under a flow of O_2 . **b** XRD pattern for PLZT film prepared under air.

The PLZT films were prepared through thermal annealing at temperatures as high as 600 °C. Supplementary Figs. 1(a) and 1(b) show XRD patterns for the PLZT films annealed under flowing O_2 and under air, respectively. Diffraction peaks at 21.76° and 44.40° are attributed to (100) and (200) orientations in both films. Notably, the peak intensities are larger in the film annealed under O_2 flow, suggesting a higher degree of crystallization compared with that of the film annealed in air. To facilitate these comparisons, films were prepared under the same conditions, ensuring an almost identical thickness of 200 nm.



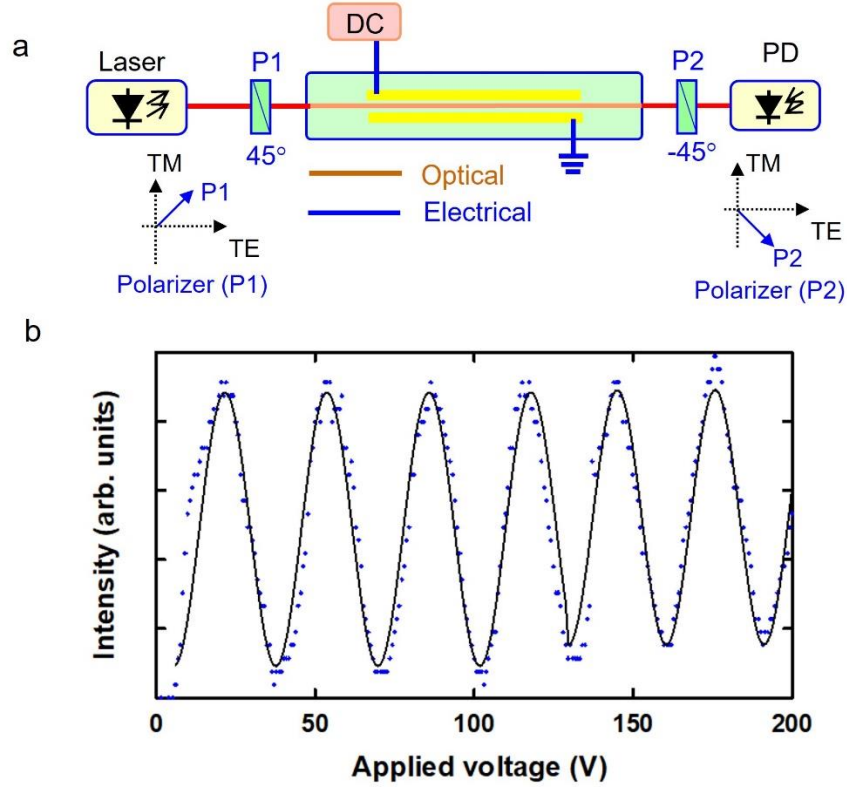
Supplementary Fig. 2. Calculated confinement factors for PLZT waveguides. a Confinement factors obtained at 1310 nm. **b** Confinement factors obtained at 1510 nm. The structural parameters (W_{wg} and H_{rid}) for the waveguides were varied.

In designing the ridge-shaped waveguide for the PLZT modulator, we calculated the confinement factors for the optical electric field within the waveguides using modal calculation software (Lumerical). For the fabricated waveguide, which has $W_{eg} = 1.5 \mu m$ and $H_{rid} = 100 \mu m$, we achieved confinement factors of 79.9% and 73.0% at wavelengths of 1310 and 1550 nm, respectively.



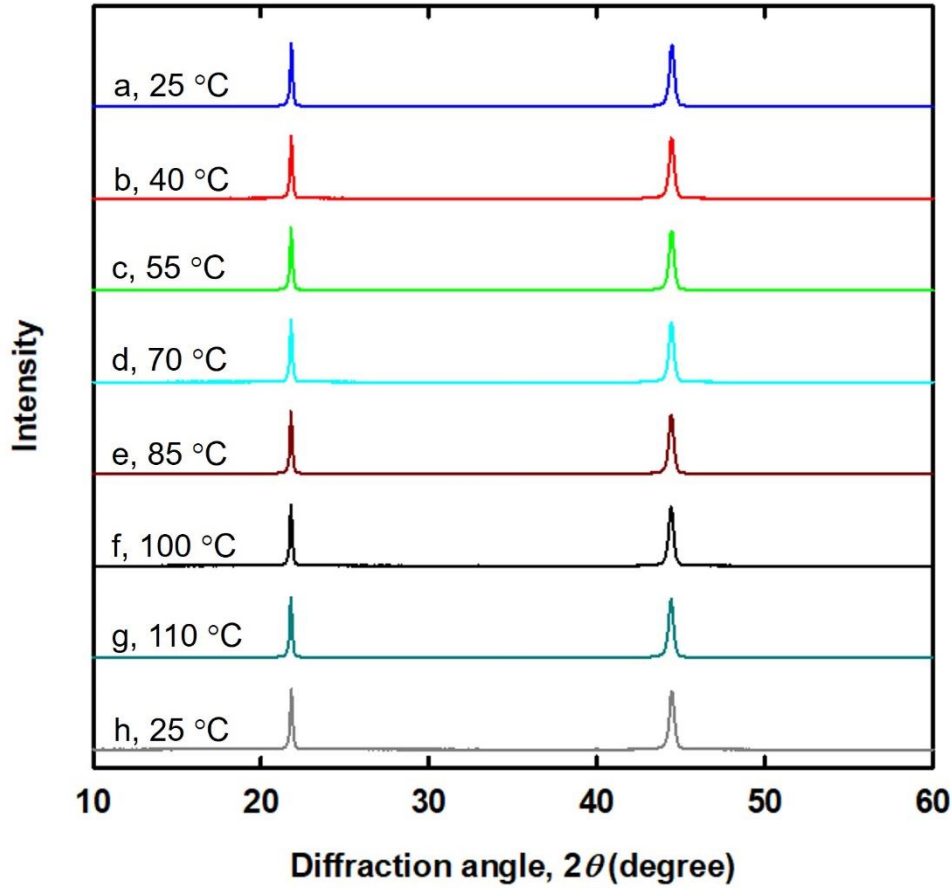
Supplementary Fig. 3. Design of MMI for PLZT modulator. **a** Schematic structure of the MMI ($W1 = 1.5 \mu\text{m}$, $W2 = 2.7 \mu\text{m}$, $W3 = 7.2 \mu\text{m}$, $G = 1.5 \mu\text{m}$, $L1 = 50 \mu\text{m}$, and $L2 = 41 \mu\text{m}$). **b** Calculated optical electric field distributions for the designed MMI. The calculated results at 1310 and 1550 nm are shown for the upper and bottom regions of the waveguide, respectively.

The MMI structure was designed using a modal calculation method. Because the MMI was prepared in the ridge-shaped waveguide, we conducted depth-dependent calculations to ascertain the modal distributions in both the upper and lower sections. The MMI size parameters ($W1$ – $W3$, G , $L1$, and $L2$) were optimized for the wavelength of 1550 nm. The relatively large $W2$ enables this MMI to also be used for the 1310 nm splitter. The calculated power divisions from port 1 to port 2 or 3 were -3.03 dB and -3.36 dB at 1550 and 1310 nm, respectively. In experiments, we prepared the MZI modulator having this MMI and used it for optical measurements for both wavelengths.



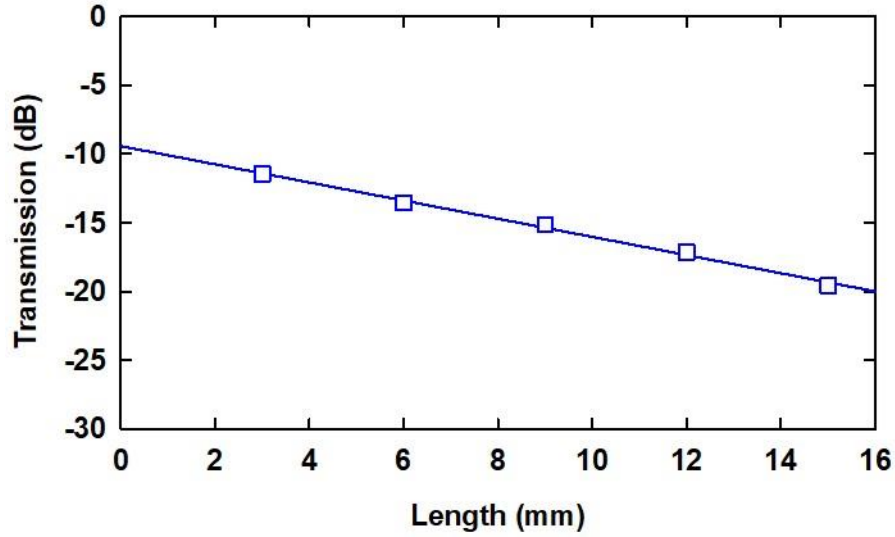
Supplementary Fig. 4. DC electric phase shifting of PLZT waveguide. **a** A diagram of the experimental setup. **b** The change of the optical intensity was measured at different applied DC voltages. The line curve was fit to the measured data (dots).

We characterized the electric poling of the PLZT modulator by observing its phase-shifting properties under various applied DC voltages. The single-arm PLZT waveguide with a 5 μm -gap electrode served as the polarization modulator. Incident light was polarized at 45° with respect to the direction of the applied drive voltage by aligning the polarization of the laser. Another polarizer was placed at the output of the waveguide and rotated 90° relative to the polarization of the incident light. Given that the input and output polarizations were cross-polarized, the device could be used to convert polarization modulation into intensity modulation. The output power of the light in the experiment, as shown in Fig. 4(a), varies according to the transfer function $I_{\text{out}} \propto I_{\text{in}} \times \sin^2(\pi V/2V_{\pi})$, where I_{out} and I_{in} represent the output and input optical power, respectively, V is the applied voltage, and V_{π} is the half-wave voltage. The PLZT was unpoled before the start of the experiment, thus the output power of the light from the waveguide was zero. By applying a DC voltage to the electrodes, the poled crystal orientation induced the phase retardation between fundamental TE and TM modes at the output of the waveguide. The measured transfer function is plotted in Fig. 4(b). The sinusoidal curve fitted to the measured light intensity could be obtained for applied voltages. The measured fringe-shaped pattern exhibited constant intensity magnification and intervals, indicating that the DC-induced polarization in the crystal was effectively completed at these electric fields. Consequently, we set the DC poling voltage for the PLZT modulator to be between 15 and 20 $\text{V } \mu\text{m}^{-1}$.



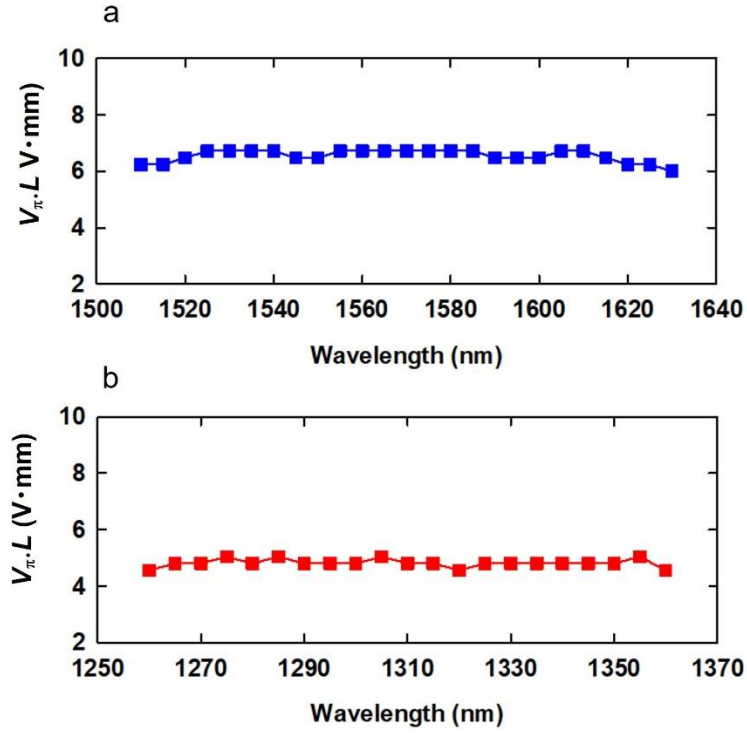
Supplementary Fig. 5. Temperature dependence of XRD patterns for PLZT film. **a–g** XRD patterns for PLZT films acquired at different temperatures from 25 to 110 °C. **h** XRD pattern after the sample was cooled from 110 to 25 °C.

To assess the thermal stability of the modulator with respect to the phase stability of the PLZT, we conducted XRD measurements at different temperatures from 25 to 110 °C. The resultant XRD patterns show no variation in either the 2θ angle or the intensity at any of the tested temperatures. This consistency in crystal orientation across different temperatures indicates that the PLZT modulator is thermally stable. This attribute is further corroborated by the material's high-temperature transmission and Curie temperatures. The PLZT crystal is expected to be stable at temperatures exceeding 300 °C according to reference values.



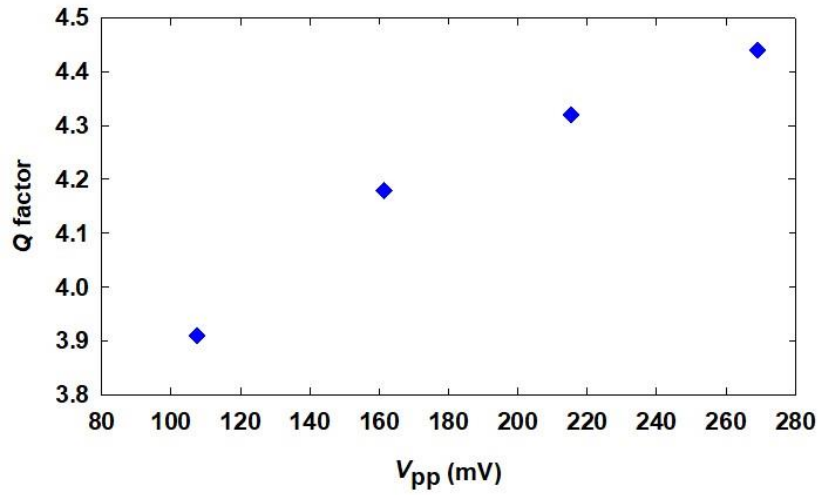
Supplementary Fig. 6. Transmission for PLZT waveguide for TE polarization. The blue line corresponds to a linear fit to measured values.

The propagation loss for the PLZT waveguide was determined using the cut-back technique. Transmission measurements were conducted on fabricated straight waveguides of various lengths. A propagation loss of 0.66 dB mm^{-1} was obtained from the slope of the blue line in Supplementary Fig. 6. The inset in this figure shows the fiber-to-waveguide coupling loss. The propagation loss could be further reduced by improving the dry etching conditions to mitigate the side-wall roughness of the waveguide. In addition, the coupling loss is attributable to the absence of a suitable spot size converter for coupling to the single-mode fiber.



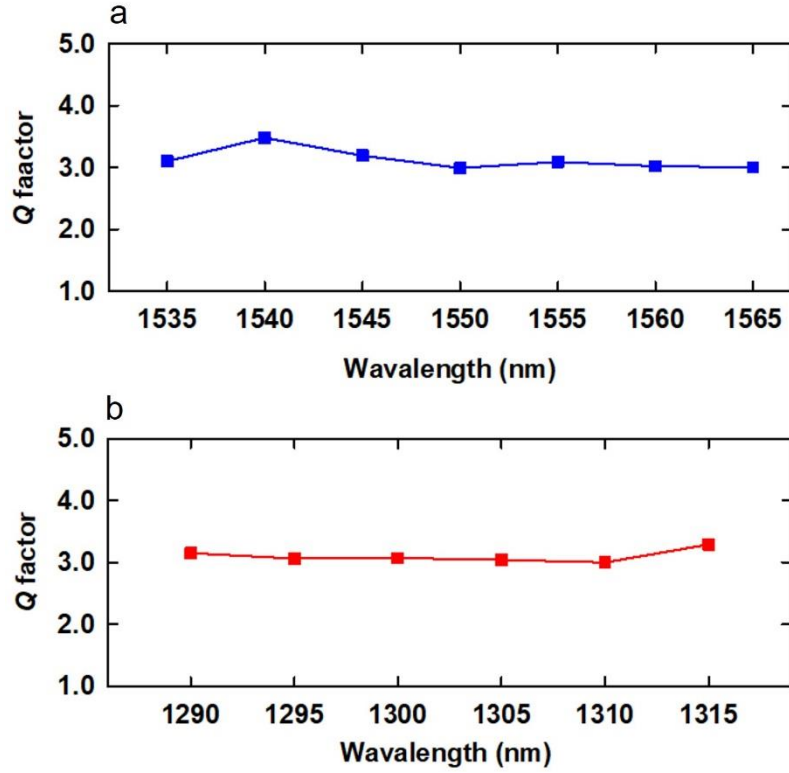
Supplementary Fig. 7. Half-wave voltage length products of PLZT modulator at various wavelengths. Measured $V_{\pi} \cdot L$ values from $\lambda = 1505$ to 1630 nm (a) and 1310 to 1360 nm (b).

The half-wave voltage length products ($V_{\pi} \cdot L$) were measured at various wavelengths using wavelength-tunable lasers; V_{π} values were measured across different wavelengths while keeping other experimental parameters constant during scanning of the wavelengths.



Supplementary Fig. 8. Driving voltage for PLZT modulator. The measured Q factors from 152 Gbit s⁻¹ OOK transmissions with different drive voltages.

The high-speed drive voltage of the PLZT modulator was evaluated on the basis of the measured Q factors for the 152 Gbit s⁻¹ OOK signals. The AWG, in conjunction with the RF driver amplifier, cables and connectors, produced a maximum voltage swing of 270 mV under our experimental conditions. We observed an increase in the measured Q factor with increasing drive voltage. The limited voltage swing is mainly attributed to the bandwidth and electric linearity of the available testing equipment. Although the Q factor did not reach a constant value within the tested voltage range, further improvements in modulation performances are anticipated for higher-fidelity and more efficient signaling.



Supplementary Fig. 9. 172 Gbit s⁻¹ OOK signal fidelity of PLZT modulator at various wavelengths. The measured Q factors for the synthesized OOK signals from $\lambda = 1535$ to 1565 nm (a) and 1290 to 1315 nm (b).

The PLZT modular was first driven as an OOK transmitter at a line rate of 172 Gbit s⁻¹. The corresponding Q factors of eye patterns for the synthesized signal were determined at various wavelengths. Wavelength-tunable lasers were employed to scan these wavelengths, with the scan ranges confined to the optical windows of optical fiber amplifiers (EDFA and PDFA).