A power-efficient integrated lithium niobate electro-optic comb generator

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Integrated electro-optic (EO) frequency combs are essential components for future applications in optical communications, light detection and ranging, optical computation, sensing and spectroscopy. To date, broadband on-chip EO combs are typically generated in high-quality-factor micro-resonators, while the more straightforward and flexible non-resonant method, usually using single or cascaded EO phase modulators, often requires high driving power to realize a reasonably strong modulation index. Here, we show that the phase modulation efficiency of an integrated lithium niobate modulator could be enhanced by passing optical signals through the modulation electrodes for a total of 4 round trips, via multiple low-loss mode multiplexers and a waveguide crossing, reducing electrical power consumption by an experimentally measured factor of 15. Using devices fabricated from a wafer-scale stepper lithography process, we demonstrate a broadband optical frequency comb featuring 47 comb lines at a 25-GHz repetition rate, using a moderate radio frequency (RF) driving power of 28 dBm (0.63 W). Leveraging the tunability in repetition rate and operation wavelength, our power-efficient EO comb generator could serve as a compact low-cost solution for future high-speed data transmission, sensing and spectroscopy, as well as classical and quantum optical computation systems.
Optical frequency combs (OFCs), featuring discrete, equally spaced optical frequency components, are excellent building blocks for optical communication, light detection and ranging (LiDAR), optical computation, optical clocks, and spectroscopy. Chip-scale OFCs, taking advantage of recent developments in photonic integrated circuits (PICs), could further allow the above functions achieved in a compact and cost-effective manner. To date, most on-chip frequency comb generators are based on semiconductor mode-locked lasers or nonlinear Kerr effect (\(\chi^{(2)}\))\textsuperscript{16–18}. The former approach employs passive or active mode-locking schemes to directly achieve mode-locked lasing states in integrated III–V gain platforms, leading to smaller footprint and improved wall-plug efficiencies compared to traditional solid-state or fiber-based mode-locked lasers\textsuperscript{10–15}. The latter process originates from phase-locked cascaded four-wave-mixing (FWM) in ultra-high-quality microresonators\textsuperscript{14,15}, resulting in low-noise OFCs with broad spectral span achieved in various photonic platforms, such as silicon (Si)\textsuperscript{16}, silicon dioxide (SiO\textsubscript{2})\textsuperscript{17}, silicon nitride (SiN)\textsuperscript{18}, lithium niobate (LN)\textsuperscript{19}, silicon carbide (SiC)\textsuperscript{20}, aluminum nitride (AlN)\textsuperscript{21} and so on. Historically, there also exists a well-known and widely adopted alternative approach, namely electro-optic (EO) comb generation, to produce combs with high optical powers and widely tunable repetition rates via cascaded sideward generation processes in one or multiple EO modulators. Most EO combs to date, however, still rely on discrete LN modulators that are bulky and rather inefficient, leading to systems that are on table-top scales and consume substantial RF powers\textsuperscript{22,23}.

The recent technological advances in the LN-on-insulator (LNOI) photonic platform have inspired a renaissance for EO combs to be achieved in chip-scale systems that are more efficient, more compact and lower cost\textsuperscript{24–30}. In the LNOI platform, a sub-micron-thick LN thin film is bonded on top of a SiO\textsubscript{2} dielectric substrate, resulting in much better light confinement, and substantially improved EO modulation efficiencies\textsuperscript{24–36}. As a result, breakthroughs have been made on LNOI-based on-chip EO comb generators in aspects of spectral breadth, light conversion efficiency, and comb line flatness\textsuperscript{24–30}. For example, EO combs generated using a single LN resonator can cover the entire telecom L band with over 900 lines\textsuperscript{24}, and light conversion efficiency can be further improved to 30% using a two-resonator system\textsuperscript{27}. Leveraging the high quality-factor (Q-factor), strong microwave-optic field overlap, and engineered dispersion, optical signals can pass through the EO modulation area many times, leading to a strong and cascaded sideward generation process, and in turn a broadband comb span. However, these high-Q-resonator-based EO combs usually suffer from limited tuning ranges in both the RF repetition rate and the optical operation wavelength due to the narrow resonance linewidths, hurdling their practical applications, e.g., in frequency-modulated LiDAR systems\textsuperscript{37,38}. On the contrary, the more conventional and straightforward non-resonant EO comb generation scheme offers much more flexibility in selecting and tuning the repetition rate and operation wavelength on demand. Cascading an amplitude and a phase modulator could further allow the generation of flat-top EO combs\textsuperscript{29,30}. Unfortunately, due to the non-resonant structure, light passes through the EO modulation area only once for each modulator, leading to a relatively weak EO modulation effect and high driving voltage (or RF power consumption) needed. Although longer metal electrodes can be utilized to induce a larger phase shift at low frequencies, the increased microwave loss and subsequently lowered EO bandwidth ultimately limit the maximally achievable modulation index at high frequencies (\(\approx\)20 GHz). For instance, EO combs featuring 40 comb lines can be generated using a single LNOI phase modulator, which however requires a high RF power of 3.1 W\textsuperscript{28}.

More recently, it has been demonstrated that, by recycling optical signals through both modulation areas of a typical ground-signal-ground (GSG) electrode structure, a double-pass EO phase modulator could provide a doubled phase modulation efficiency, leading to the generation of 67 comb lines spaced at 30 GHz using an RF power of 4.0 W\textsuperscript{29}. A mode-multiplexing-based phase modulator was also presented, where light is looped back twice but only passes through one of the two modulation areas, leading to 15 comb lines using an RF power of 25 dBm\textsuperscript{39}.

In this article, we demonstrate a power-efficient LNOI-based EO comb generator, where the phase modulation efficiency is increased by an experimentally measured factor of \(\approx 3.9\) using a multi-loop design, leading to a subsequent reduction of electrical power consumption by \(\approx 15\) times. This power-efficient characteristic benefits from passing optical signals through the modulation electrodes for a total of 4 round trips with the assistance of multiple low-loss mode conversion processes, leading to a substantially lowered RF phase-modulation voltage-length product \((V_{RF} \cdot L)\) of 1.90 V \cdot cm at 25 GHz. We show the generation of broadband optical frequency combs with 47 comb lines at a 25-GHz repetition rate using a moderate RF driving power of 28 dBm, while maintaining tunability in both the repetition rate and operation wavelength.

Results

Overall design. Figure 1a shows the schematic of our EO comb generator, where continuous-wave (CW) pump light (fundamental transverse-electric mode, TE\textsubscript{0}) from the left-hand side travels through the phase modulation region (yellow electrode area) for the first EO modulation, then loops back and converts into a second-order transverse-electric mode (TE\textsubscript{1}) via an adiabatic TE\textsubscript{0}/TE\textsubscript{1} mode multiplexer (dashed arrow in Fig. 1b). This TE\textsubscript{1} mode light, which is orthogonal to the TE\textsubscript{0} mode in the first pass, subsequently goes through the phase modulation region for a second time, and is converted back to TE\textsubscript{0} mode in the lower output branch of a second TE\textsubscript{0}/TE\textsubscript{1} mode multiplexer (dashed arrow in Fig. 1c). The adiabatic mode multiplexer is designed such that TE\textsubscript{0} mode in the main branch stays in TE\textsubscript{0} mode throughout the mode evolution process (details to be discussed next). The twice-modulated optical signal is further guided back to the bottom modulation region of the GSG transmission line. Similar to the top part, light passes through the modulation area for a third and a fourth time, in TE\textsubscript{0} and TE\textsubscript{1} mode, respectively, ultimately reducing the drive voltage (power) of this comb generator by a factor of 4 (16) in theory. Importantly, the microwave-optic phase-matching condition needs to be satisfied in two aspects in our circulating waveguide design. First, similar to a normal EO modulator, the microwave phase velocity should be matched with the optical group velocity throughout the modulation region, which is achieved using a GSG traveling-wave electrode design and an engineered material stack (Fig. 1d), similar to those used in previous literature\textsuperscript{31,40} (see “Methods, Wafer-scale LNOI device design and fabrication”). The electrode length in our current device is 1 cm to avoid excessive RF losses at high frequencies (measured EO 3-dB bandwidth \(>40\) GHz). Second, the optical signals after each round trip should be precisely delayed, as shown in the microscope image of the full device (Fig. 1e), such that they experience the same RF phase in each modulation step for our target RF frequency of 25 GHz. The actual waveguide lengths for the 1\textsuperscript{st}, 2\textsuperscript{nd} and 3\textsuperscript{rd} loop are 26.67 mm, 28.99 mm and 20.89 mm respectively, while the corresponding optical propagation time for each loop is 5 \(\times\) \(\Delta T_{25\text{GHz}}\) 5.5 \(\times\) \(\Delta T_{25\text{GHz}}\) and 4 \(\times\) \(\Delta T_{25\text{GHz}}\) where \(\Delta T_{25\text{GHz}} = \frac{\Delta f}{25\text{GHz}}\) (see Supplementary Note 1). The second loop uses a half-integer multiple of \(\Delta T_{25\text{GHz}}\) to compensate for the \(\pi\)-phase difference
Adiabatic mode multiplexer. A key enabling component for our multi-loop EO comb generator is an efficient, low-crosstalk and low-loss TE₀/TE₁ mode multiplexer. This is achieved using a broadband and robust adiabatic coupler design as shown in Fig. 2a, where incoming TE₀ and TE₁ modes from the left-hand side are demultiplexed into the upper output branch (branch 1) and the lower output branch (branch 2), respectively, both in TE₀ mode. Insets of Fig. 2a show the simulated eigenmode profiles (|E₁|₁) at different positions of the adiabatic mode multiplexer. This mode-multiplexing function is achieved based on a 550-μm-long adiabatic coupling region, where branch 1 gradually narrows while branch 2 widens along the optical propagation direction, leading to a drop of the effective index (nₑᵣₑ) of TE₁ mode in branch 1 and an increase for TE₀ mode in branch 2 (Fig. 2b). When the two modes cross over each other in nₑᵣₑ a substantial avoided crossing (Δnₑᵣₑ = 0.01) is generated between the super-modes of the two-waveguide-coupled system, since the two optical modes share the same polarization and a finite field overlap over the coupling gap (500 nm) in our device. As a result, the optical energy of TE₁ mode in branch 1 is gradually transferred to and in the end totally converted to TE₀ mode in branch 2, following the red curve in Fig. 2b. Meanwhile, TE₀ mode in branch 1 stays the lowest-order mode of the coupled-waveguide system throughout the coupling region, and remains in TE₀ mode in branch 1 at the output end, shown as the green curve in Fig. 2b. To evaluate the performance of our adiabatic mode multiplexer, we design and fabricate a 2 × 2 cascaded structure using the same fabrication method as the actual comb generator, as schematically shown in the inset of Fig. 2c. Ideally, incoming light from port 1 (in TE₀ mode) will stay decoupled and output from port 3, whereas input light from port 2 will first be converted to TE₁ mode in the mode multiplexed middle section, and finally output from port 4. Figure 2(c) shows the measured optical S-parameters of this test structure, where Sᵢⱼ refers to the power ratio between the output optical power of port i and the input optical power of port j. The device shows low optical losses of <0.4 dB (S₃₁ and S₂₄) and high extinction ratios of >20 dB over a broad wavelength range from 1530 nm to 1630 nm, which is important to the wide operation wavelength window of our EO comb generator. Moreover, our simulation results (see Supplementary Note 3) suggest that the adiabatic multiplexer design is robust against variations in waveguide coupling gap, cladding material, waveguide width, and sidewall angle³³,³⁵.

Broadband EO comb generation. We demonstrate broadband EO comb generation at moderate RF drive powers using our...
multi-loop on-chip EO comb generator. The corresponding experimental setup is shown in Fig. 3a (see "Methods, EO comb generation"). For better comparison and visualization of the enhanced comb generation process in our device, we fabricate and test four types of phase modulators (top row of Fig. 3b): (I) a single-pass phase modulator; (II) a double-pass phase modulator making use of both top and bottom modulation areas, both in fundamental TE₀ mode; (III) another type of double-pass phase modulator, with TE₀/TE₁ mode multiplexing but only going through the top modulation region; (IV) our quadra-pass phase modulator. Figure 3b shows the simulated (upper middle row) and measured (lower middle row) EO comb spectra using the above four types of comb generators driven at the same RF power of 28 dBm (630 mW) at 24.95 GHz, which corresponds to a peak voltage of \( V_F = 7.94 \text{ V} \) and a modulation index of \( -1.05\pi \) for a simple phase modulator [direct current (DC) half-wave voltage \( V_n = 6.29 \text{ V} \), RF \( V_n = 7.56 \text{ V} \) at 25 GHz]. A total of 15 comb lines are generated in the single-pass device, in line with the numerically simulated spectrum (Fig. 3b, Type I). The EO comb span is substantially broadened in the double-pass cases, to 25 lines in the type-II device and 27 lines in the type-III device, with increased effective modulation indices of \( -2.1\pi \). Finally, our quadra-pass EO comb generator (type-IV), a combination of type-II and type-III, shows a total of 47 measured comb lines (Fig. 3b, Type IV), corresponding to a 4× enhancement of the modulation index (~4.2π) in theory. To further verify the actual power reduction, we experimentally generate combs with similar span (bottom row of Fig. 3b) using the four EO comb generators at different RF driving powers. The same or similar comb span is obtained from our type-IV device using a much lower RF drive power, showing a measured power reduction of 11.7 dB (~15× in linear scale), or a modulation index enhancement factor of ~3.9, which agrees reasonably well with our theoretical prediction (16× power reduction). We also measure the generated comb spectra of our device at different RF driving power levels (Fig. 3c), showing 7, 16 and 47 comb lines at RF powers of 14 dBm, 23 dBm and 28 dBm, respectively. The profile differences between simulated and measured comb spectra for type-III and IV devices are likely caused by Fabry–Pérot fringes induced by non-ideal adiabatic mode multiplexers, where the un-coupled (or un-converted) optical mode, although quite small, will loop back and interfere with the new-coming light, adding a more linear roll-off envelope that is commonly seen in resonant EO comb to our spectra. This un-wanted resonance can be eliminated by further optimizing the design of the adiabatic mode multiplexer, such as the coupling length and gap. Our simulation results indicate that an even broader EO comb (purple spectrum in Fig. 3d) with 87 comb lines could be generated using our device if driven at 36 dBm (~10.5π equivalently), a similar power as that used in previous literature30 for a 30-GHz EO comb, spanning an optical bandwidth of close to 20 nm. Importantly, the dramatically reduced RF power consumption in our multi-pass EO comb generator does not come at the cost of substantially increased optical loss, as the measured optical transmission spectra of the four device types in Fig. 3d show. Although waveguides with a total of ~12 cm long and structures such as waveguide crossing and mode multiplexers (8 passes in total) are used, our EO comb generator (blue curve) only induces an optical loss of ~4 dB, benefiting from the low-loss and high-uniformity wafer-scale LN photonic platform used (see "Methods, Optical loss characterization"). Further improving the waveguide propagation loss to <0.1 dB/cm for both TE₀ and TE₁ modes33 could allow even lower total on-chip optical loss of <1 dB.

![Device schematic, where input TE₀ and TE₁ modes are demultiplexed into TE₀ modes in the upper and lower output branches respectively (TE₀: fundamental transverse-electric mode, TE₁: second-order transverse-electric mode). Insets show the corresponding simulated eigenmode profiles of the coupled-waveguide system at different locations.](https://example.com/device_schematic.png)

**Fig. 2 Design and characterization of the broadband adiabatic mode multiplexer.** a Device schematic, where input TE₀ and TE₁ modes are demultiplexed into TE₀ modes in the upper and lower output branches respectively (TE₀: fundamental transverse-electric mode, TE₁: second-order transverse-electric mode). Insets show the corresponding simulated eigenmode profiles of the coupled-waveguide system at different locations. b Effective index \( n_{eff} \) evolution for the three lowest-order modes along our adiabatic mode multiplexer, at a wavelength of 1550 nm. c Measured optical transmission (S₁3 and S₂3) and crosstalk (S₃₂ and S₄₂) of a 2 × 2 cascaded multiplexer structure (inset), showing low optical losses of <0.4 dB and high extinction ratios of > 20 dB from 1530 nm to 1630 nm.
RF and optical tuning range. Thanks to the non-resonant configuration of our design, our power-efficient EO comb generator could efficiently operate within a broad range of RF and optical frequencies. To further characterize the frequency response of our EO comb generator at different RF frequencies, we specially design and fabricate a Mach–Zehnder interferometer (MZI) (Fig. 4a) formed by two identical multi-loop phase modulators on the two arms (see Supplementary Note 4). Electrical signals added to one of the two-phase modulators therefore are translated into amplitude modulation, allowing us to directly measure the EO response of our multi-loop phase modulator (red curve in Fig. 4b, see “Methods, EO response and RF $V_\pi$ characterizations”), which shows larger measurement uncertainties but also agrees reasonably well with the theoretically predicted trend and the responses measured from the MZI device. The maximally achievable EO $S_{21}$ values are bounded by a slowly rolling-off envelope (grey dash line) as a result of the intrinsic bandwidth limit of the phase modulator, which features a 3-dB bandwidth larger than 40 GHz in the current device. We further extract and plot the measured RF $V_\pi$ values of our device at various RF frequencies in Fig. 4c, showing a minimal RF $V_\pi$ value of 1.90 V at 24.95 GHz and a 3-dB tuning range of 1.4 GHz, from 24 GHz to 25.4 GHz (defined as the range within which RF $V_\pi$ is no more than $\sqrt{2}V_{\pi,\text{min}}$, Fig. 4d). The large RF frequency tuning...
range as compared with those of resonator-based EO combs are important for practical applications that require tunable repetition rates and/or are sensitive to environmental drifts. Apart from operating in the vicinity of 25 GHz, our EO comb generator can also efficiently function at other maximal-EO-response frequencies, e.g., near 20 GHz and 30 GHz (Fig. 4e). At all three phase-matched frequencies (i.e., near 20 GHz, 25 GHz, 30 GHz), our device is able to generate more than 45 comb lines, showing great flexibility in input RF frequency. Finally, we show that our power-efficient EO comb generator is wavelength insensitive by pumping the device at different laser wavelengths, from 1520 nm to 1610 nm. As shown in Fig. 4f, all measured comb spectra feature more than 45 lines, thanks to the broadband nature of our phase modulator, mode multiplexers and waveguide crossing, indicating a high degree of freedom in tuning the center wavelength of the generated EO combs. Our EO comb generator also shows temperature stability, supporting stable temperature-control-free operation throughout the duration of our experiments, thanks to the non-resonant configuration and the relatively small thermo-optic effect of LN.

**Power conversion efficiency.** In a practical EO comb generator, the total power consumption comes from both the optical source and the electrical RF drive, the latter of which is usually more power-hungry. Our current device features an optical conversion efficiency of 39.8% on chip, larger than that of a double-microroring-based EO comb generator (~30%) specifically optimized for high optical power conversion. The total power conversion efficiency for our device is ~6.7% considering both optical and RF powers, which could be readily increased by applying a higher optical input power, thanks to the linear scaling law of EO comb systems, e.g., to 19.7% at an on-chip optical power of 630 mW (see Supplementary Note 5). The ultimate optical and electrical power consumptions are closely related to the optical insertion loss and the RF phase-modulation voltage-length product \( V_\pi \cdot L \), which we respectively plot in Fig. 5. Our current devices operate along the line of 7 V \( \cdot \) cm\( \cdot \)dB, offering a record-low \( V_\pi \cdot L \) of ~1.90 V \( \cdot \) cm at 25 GHz, not only more than an order of magnitude lower than that of commercial LN phase modulators (triangle mark, Thorlabs LN27S-FC), but also substantially lower than previous single-pass (circular mark) and double-pass phase modulators (square mark) in the LNOI platform. The current performance envelope of ~7 V \( \cdot \) cm\( \cdot \)dB could be further improved to around 2 V \( \cdot \) cm\( \cdot \)dB by reducing waveguide propagation loss to <0.1 dB/cm. We estimate the optical and total power (optical and electrical) conversion.
Figure 5 Performance comparison of non-resonant electro-optic (EO) comb generators on lithium niobate (LN) platform. The comparison includes the on-chip optical insertion losses and radio-frequency (RF) phase-modulation $V_N L$ values. Star marks correspond to devices in this work, which operate along the line of $7 \text{ V cm }^{-1} \text{ dB}$, leading to a low RF $V_N L$ of $1.9 \text{ V cm }^{-1}$ at 25 GHz. The horizontal axis is plotted in inverse scale to better visualize the device modulation efficiency, which is inversely proportional to the half-wave voltage.

**Discussions**

Our power-efficient broadband integrated EO comb generator is enabled by a combination of the multi-pass phase modulator design that increases the modulation efficiency by 4 folds, the low-loss and low-crosstalk TE$_0$/TE$_1$ mode multiplexers and waveguide crossing that allow for coherent phase accumulation between loops, as well as a reliable wafer-scale device fabrication platform that yields photonic devices and circuits with high uniformity, repeatability and low loss. The low RF $V_N$ of 1.90 V at 24.95 GHz in our current device could potentially be further reduced using even longer electrodes and/or scaling to more high-order modes. The 25-GHz-spaced, wavelength tunable EO comb could readily be matched with standard dense wavelength-division multiplexing (DWDM) grids (e.g., 50 GHz) in optical communications by filtering out half of the comb lines, using, e.g., a micro-ring resonator. Larger comb spacing could also be realized by directly driving the comb generators at higher RF frequencies, potentially using a capacitive-loaded electrode design with substantially lower RF losses. On the other hand, the highly scalable stepper-lithography fabrication process could allow for larger-scale comb-based PICs with advanced system functionalities. For example, the multipass phase modulator could be further integrated with an amplitude modulator to achieve flat-top broadband EO combs at low RF powers important for practical DWDM systems. Dispersion elements can also be added after our EO comb generator for ultrashort pulse generation. Our power-efficient EO comb generator could become a key building block in future chip-scale frequency comb systems for high-speed optical communications, LiDAR, sensing and spectroscopy applications.

**Methods**

Wafer-scale LNOI device design and fabrication. Our devices are fabricated from a commercially available x-cut LNOI wafer (NANOLN), which consists of a 500-nm LN thin film, a 2-μm buried SiO$_2$ layer, and a 500-μm silicon substrate. SiO$_2$ is first deposited on the surface of the 4-inch LNOI wafer using plasma-enhanced chemical vapor deposition (PECVD). Micro/nano-structures are then directly patterned on the entire wafer using an ASML UV Stepper lithography system die by die (1.5 cm × 1.5 cm) with a resolution of 500 nm. Next, a reactive ion etching (RIE) system is used to transfer patterns from photore sist layer to SiO$_2$ layer and subsequently to the LN device layer, leading to a 250-nm rib waveguide and a 250 nm LN slab. 1-cm-long metal electrodes are fabricated using a sequence of photolithography, thermal evaporation, and lift-off process, resulting in a 520-μm-thick metal layer with an electrode gap of 5.5 μm and a signal electrode width of 43 μm. 500-nm-thick SiO$_2$ is deposited by PECVD as cladding layer of the device. Our wafer-scale LNOI device, benefiting from a carefully designed GSG traveling-wave electrode and an engineered material stack, features a low microwave loss and an RF effective refractive index of ~2.30 at 40 GHz in simulation, which is close to the optical group refractive index (~2.27), leading to an efficient matching between microwave and optical velocity throughout the modulation region. Finally, chips are cleaved and the facets are carefully polished for end-fire coupling.

**EO comb generation.** CW pump light from a tunable telecom laser (Santec TSL-550) first goes through a fiber polarization controller (FPC) to ensure TE mode excitation. Light is coupled into and out from our chip using lensed fibers. RF signals (Anritsu, MG2697C) are amplified using a medium power gallium arsenide (GaAs) amplifier (Pastersen, PE15A4021), before being delivered to the input port of the traveling-wave electrodes through a high-speed GSG probe. The output port of the electrodes is terminated with a 50-Ω load (Fig. 1a). Finally, the generated EO comb spectra are collected using an optical spectrum analyzer (OSA).

**Optical loss characterization.** Optical loss here is non-trivial due to our long and complex optical path design. The full device consists of 12-cm-long waveguides (10 cm in TE$_0$ mode and 2 cm in TE$_1$ mode), one waveguide crossing, and four mode multiplexers (8 passes in total), all of which contribute to the total on-chip optical loss. Based on the measured Q-factors of micro-resonators on the same chip, the waveguide loss is estimated to be ~0.2 dB cm$^{-1}$ for TE$_0$ mode, ~0.4 dB cm$^{-1}$ for TE$_1$ mode, leading to a total waveguide loss of ~2.8 dB at 1550-nm wavelength. The waveguide cross loss is evaluated by cut-back measurements of devices with different numbers of crossings (Supplementary Note 2), showing an average loss of 0.18 dB in y-crystal direction and 0.10 dB in z-crystal direction, leading to a total of 0.28 dB optical loss in the full device. The mode multiplexers exhibit high conversion efficiencies and low crosstalk (Fig. 2c), contributing to a total loss <1 dB. Therefore, the total on-chip optical loss is estimated to be ~4 dB near 1550 nm, which matches with our measured transmission spectrum (Fig. 3d). Except the on-chip optical loss, note that the end-fire coupling system also induces optical loss of ~5 dB per facet.

**EO response and RF $V_N$ characterizations.** A vector network analyzer (VNA) is used to measure the EO response of the MZI device, as shown in Fig. 4a. The MZI is biased at the quadrature point while RF signals from the VNA are delivered to one of the multi-loop phase modulators. The majority (90%) of output optical signal is then sent to a high-speed photodetector (Newport), which translates the signal back to electrical signals for EO $V_N$ response measurement using the VNA. The remaining 10% is delivered to a 125-MHz photodetector to monitor the intensity of output light. At higher RF frequencies, the RF $V_N$ of our EO comb generator is also directly measured by monitoring the power ratio between optical pump and sideband signals using an OSA. The device is driven by a small RF signal (<10 dBm) such that the system operates in the linear small-signal regime. RF frequency is swept from 18 GHz to 40 GHz, with a step of 200 MHz, to obtain the RF $V_N$ values at various frequencies.

**Data availability**

The data that support the plots of this paper and other findings within this study are available from the corresponding author upon reasonable request.

**Code availability**

No original algorithms or code have been developed for this article. The MATLAB program used for processing the data is nevertheless available from the corresponding author on reasonable request.

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**References**

1. Diddams, S. A. et al. Optical frequency combs: Coherently uniting the electromagnetic spectrum. *Science* **369**, 3676 (2020).
2. Marin-Palomo, P. et al. Microresonator-based solitons for massively parallel coherent optical communications. *Nature* **546**, 274 (2017).

3. Corcoran, R. et al. Ultra-dense optical data transmission over standard fibre with a single chip source. *Nat. Commun.* **11**, 2568 (2020).

4. Riemensberger, J. et al. Massively parallel coherent laser ranging using a soliton microcomb. *Nature* **581**, 164 (2020).

5. Feldmann, J. et al. Parallel convolutional processing using an integrated photonic tensor. *Nat. Photonics* **52**, 52 (2021).

6. Boulder Atomic Clock Optical Network (BACON) Collaboration. Frequency ratio measurements at 18-digit accuracy using an optical clock network. *Nature* **591**, 564 (2021).

7. Papp, S. B. et al. Microresonator frequency comb optical clock. *Optica* **1**, 10 (2014).

8. Myoung-gyun, S. et al. Microresonator soliton dual-comb spectroscopy. *Nat. Photonics* **10**, 27 (2015).

9. Levy, J. S. et al. Coherent terabit communications with microresonator Kerr frequency combs. *Nat. Photonics* **8**, 375 (2014).

10. Huang, X. et al. Passive mode-locking in 1.3 μm two-section InAs quantum dot lasers. *Appl. Phys. Lett.* **78**, 2825 (2001).

11. Meng, B. et al. Mid-infrared spectrum from a ring quantum cascade laser. *Optica* **7**, 162 (2020).

12. Corcoran, B. et al. Ultra-dense optical data transmission over standard fibre with a single chip source. *Nat. Commun.* **11**, 2568 (2020).

13. Riemensberger, J. et al. Massively parallel coherent laser ranging using a soliton microcomb. *Nature* **581**, 164 (2020).

14. Feldmann, J. et al. Parallel convolutional processing using an integrated photonic tensor. *Nat. Photonics* **52**, 52 (2021).

15. Pfeiffer, J. et al. Coherent terabit communications with microresonator Kerr frequency combs. *Nat. Photonics* **8**, 375 (2014).

16. Griffith, A. G. et al. Silicon-chip mid-infrared frequency comb generation. *Nat. Photonics* **10**, 6299 (2015).

17. Li, J. et al. Low-pump-power, low-phase-noise, and microwave to millimeter-wave repetition rate operation in microcombs. *Phys. Rev. Lett.* **109**, 233901 (2012).

18. Kuse, N. et al. Broadband adiabatic polarization rotator-splitter based on a lithium niobate microring resonator. *Chin. Opt. Lett.* **10**, 567 (2018).

19. Zhang, K. et al. High-Q lithium niobate microring resonators using lift-off metallic masks [Invited]. *Chin. Opt. Lett.* **19**, 6 (2021).

20. Chen, Z. et al. Broadband adiabatic polarization rotator-splitter based on a lithium niobate on insulator platform. *Photonics Res.* **9**, 6 (2021).

21. Poulton, C. V. et al. Coherent solid-state LiDAR with silicon photonics optical phased arrays. *Opt. Lett.* **42**, 4091 (2017).

22. Kuse, N. et al. Frequency-modulated comb LiDAR. *APL Photonics* **4**, 106105 (2019).

23. Huang, H. et al. Non-resonant recirculating light phase modulator. *APL Photonics* **7**, 106102 (2022).

24. Zhang, Y. et al. Systematic investigation of millimeter-wave optic modulation performance in thin-film lithium niobate. *Photonics Res.* **10**, 2380 (2022).

25. Kharel, P. et al. Breaking voltage–bandwidth limits in integrated lithium niobate modulators using micro-structured electrodes. *Optica* **8**, 357 (2021).

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**Author contributions**

K.Z. and C.W. conceived the idea in collaboration with the other co-authors. K.Z. designed the full device layout. K.Z., W.S., H.F. and Z.C. fabricated the device. K.Z. and Y.C. performed numerical simulations. K.Z., Y.C. and Y.Z. carried out the device characterization. K.Z. wrote the manuscript in discussion with all authors. C.W. supervised the project. All authors reviewed and approved the final manuscript.

**Competing interests**

The authors declare no competing interests.

**Additional information**

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