High-efficiency and broadband on-chip electro-optic frequency comb generators

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Developments in integrated photonics have led to stable, compact and broadband comb generators that support a wide range of applications including communications, ranging, spectroscopy, frequency metrology, optical computing and quantum information. Broadband optical frequency combs can be generated in electro-optical cavities, where light passes through a phase modulator multiple times while circulating in an optical resonator. However, broadband electro-optic frequency combs are currently limited by low conversion efficiencies. Here we demonstrate an integrated electro-optic frequency comb with a conversion efficiency of 30% and an optical span of 132 nm, based on a coupled-resonator platform on thin-film lithium niobate. We further show that, enabled by the high efficiency, the device acts as an on-chip femtosecond pulse source (336 fs pulse duration), which is important for applications in nonlinear optics, sensing and computing. As an example, in the ultrafast and high-power regime, we demonstrate a frequency comb with simultaneous electro-optic and third-order nonlinearity effects. Our device paves the way for practical optical frequency comb generators and provides a platform to investigate new regimes of optical physics that simultaneously involve multiple nonlinearities.

On-chip optical frequency comb (OFC) generators provide opportunities for robust, compact, portable and scalable comb sources, enabling a wide range of applications. So far, the majority of on-chip OFCs originate from continuous-wave (pump) light driving resonantly enhanced third-order optical nonlinearities (χ(3)) in the anomalous group velocity dispersion (GVD) regime, producing Kerr frequency combs. Although these OFCs (typically referred to as bright-soliton Kerr combs) can feature attractive properties, such as octave-spanning bandwidths at terahertz-range comb line spacings, Kerr combs are limited by low pump-to-comb conversion efficiencies of a few percent, owing to the special mode-locking regime in which the pump is detuned far from the cavity resonance. Improving the efficiency of Kerr combs using a coupled-resonator structure has also been investigated recently. In contrast to bright-soliton Kerr combs, another approach for Kerr combs has recently emerged that relies on dark pulses. Dark-pulse Kerr combs are generated in the normal GVD regime and can increase the conversion efficiency to ~10–50%. However, this comes at the expense of broader temporal widths, which renders them unsuitable for ultrafast (for example, femtosecond) pulse generation. Finally, a characteristic of all Kerr frequency combs is the existence of a pump threshold that is determined by both the Kerr nonlinearity and the quality factor (Q) of the resonator. This results in a nonlinear dependence between the comb and pump powers, which leads to saturation effects and limits the absolute comb power.

Electro-optic (EO) modulation provides an attractive alternative to OFC generation. The electrical controllability of EO combs provides not only versatility but also excellent comb stability and phase coherence. EO combs based on conventional (travelling-wave) modulators feature a high pump-to-comb conversion efficiency, but their span is only a few nanometres due to the weak frequency mode interaction during a single pass through the modulator. Wider optical combs can be generated using cavity-based EO combs in which light passes through a phase modulator multiple times while circulating inside an optical microresonator. Recent progress on thin-film lithium niobate (TFLN) has enabled on-chip EO combs with a record-high optical span of ~80 nm (ref. 1). However, the comb conversion efficiency of this single-resonator EO comb generator is limited to only ~0.3%. Such a low conversion efficiency originates from a strongly under-coupled ‘hot’ cavity resonance (<1% extinction ratio) when the generator is driven using a strong microwave tone. As a result, most of the light is not coupled into the resonator and is transmitted through the bus waveguide without entering the cavity.

Here we address the low conversion efficiency of the cavity-based EO comb and experimentally demonstrate an on-chip EO comb with a line spacing of 30.925 GHz, a pump-to-comb conversion efficiency of 30% and a wide comb span of 132 nm. This is enabled by two mutually coupled resonators (Fig. 1d) realized in the TFLN platform. A small resonator (cavity 1) is used to over-couple only the pump mode of a racetrack cavity (cavity 2 for comb generation) while rejecting the other non-pump modes (Fig. 1e). This results in a critically coupled device when the microwave modulation is on (Fig. 1f) and increases the conversion efficiency as theoretically predicted. Here in this work, we use the tight-binding model, previously developed for frequency crystals, as well as the generalized critical coupling (GCC) condition, developed for EO frequency shifters and beam splitters, to model our coupled-resonator EO comb generator. Importantly, our theoretical approach enables the derivation of an analytical solution for the system and can be extended to multiple coupled-resonator devices that may provide additional novel functionalities. Our experimental demonstration, along with the previous investigation of coupled-resonator...
Kerr comb generation\(^6\), indicates that the coupled-resonator platform could be a general approach for power-efficient EO and Kerr comb sources.

The origin of the low conversion efficiency for single-resonator EO combs is the strong effective loss rate \(\kappa_{\text{eff}}\) for the pump mode, induced by the microwave modulation, which extracts power from the pump mode into other comb lines. The loss rate \(\kappa_{\text{eff}}\) is given in equation (1) (see the section ‘Theoretical analysis’ in the Methods):

\[
\kappa_{\text{MW}} = \kappa \left(1 + \frac{4\Omega^2}{\kappa^2} - 1\right)
\]

where \(\Omega\) is the mode-coupling rate between resonator modes separated by the free spectral range (FSR) and is proportional to the microwave voltage, and \(\kappa = \kappa_1 + \kappa_2\) is the cavity loss rate, with \(\kappa_1\) and \(\kappa_2\) being the intrinsic loss and coupling rate to the bus waveguide, respectively. Here \(\kappa_{\text{MW}}\) can be orders of magnitude higher than \(\kappa_1\) and \(\kappa_2\) (for example, \(\kappa_{\text{MW}} \approx 10\) GHz and \(\kappa_1 \approx \kappa_2 \approx 100\) MHz for TFLN). Broadband EO combs require a strong microwave driving power (large \(\Omega\)), which leads to a large \(\kappa_{\text{MW}}\). This, however, results in the cavity being strongly under-coupled (\(\kappa \ll \kappa_1 + \kappa_{\text{MW}}\)), reducing the comb efficiency. This trade-off between the EO comb span and the efficiency limits all single-resonator EO comb sources.

A coupled-resonator EO comb generator can overcome this trade-off and ensures efficient energy flow into the comb cavity (Fig. 1d). In this case, a critical coupling between the bus waveguide and the device can be achieved under the existence of the strong \(\kappa_{\text{MW}}\), if the following condition, referred to as the GCC condition, is met (Fig. 1e,f):

\[
\kappa_{e1} = \kappa_{e1} + \frac{4\mu^2}{\kappa_{e2} + \kappa_{e2} + \kappa_{\text{MW}}}
\]
where $\kappa_{i1}$ and $\kappa_{i2}$ are the waveguide coupling rates between the bus waveguide and cavity 1 and between the output waveguide and cavity 2, respectively. $\kappa_{i1}$ and $\kappa_{i2}$ are the intrinsic loss rates for cavities 1 and 2, respectively, and $\mu$ is the coupling rate between cavities 1 and 2. The term $-\frac{4\beta^2}{\kappa_{i1}+\kappa_{i2}+\kappa_{MW}} \equiv \kappa_{\text{eff}}$ can be interpreted as an effective loss rate of cavity 1 that is induced by cavity 2, the microwave modulation and the output waveguide (drop port). With the expression for $\kappa_{\text{MW}}$ (equation (1)), the coupled-resonator EO comb generator, which involves hundreds of frequency modes, can be simplified to a two-level system that can be solved for analytically. For the detailed discussion regarding the expression, and the maximum theoretical limitation, of efficiency in the ‘Theoretical analysis’ section.

To experimentally demonstrate the coupled-resonator EO comb generator, we fabricated TFLN-on-insulator devices (Fig. 2a). The small ring resonator and the long racetrack resonator are used as cavities 1 and 2, respectively. A microwave signal is sent to the electrode of cavity 2 to provide phase modulation. A thermal heater is used in cavity 1 for efficient resonance tuning.

We first demonstrate high-efficiency and broadband EO frequency comb generation. Continuous-wave light at 1,605 nm is fed into the device through the bus waveguide. A 30.925 GHz microwave signal, which matches the FSR of cavity 2, is used to drive the electrode. By applying microwave modulation, the transmission of the through port changes from over-coupled to nearly critically coupled (inset of Fig. 2c), indicating the efficient flow of pump power into the device. The frequency comb is collected at the drop port of the device (Fig. 1d) and measured using an optical spectrum analyser and photodetectors. The output comb power increases linearly with the pump power (Fig. 2b), indicating a pump-to-comb conversion efficiency of $\eta \equiv \frac{P_{\text{comb}}}{P_{\text{pump}}} = 30\%$, where $P_{\text{comb}}$ and $P_{\text{pump}}$ are the power values on the output and input waveguides, respectively. Using 2 mW of pump power (the same pump power as used in ref. 15), the comb spans 132 nm at a $-70\, \text{dBm}$ power level and features an efficiency $\eta = 30\%$ (Fig. 2c). Our device can be pumped at any of the resonances of cavity 2 by tuning the heater to overlap the resonance of cavities 1 and 2 (see Extended Data Fig. 1). The current pump wavelength is $-1,600\, \text{nm}$. It is chosen to avoid the polarization mode crossing at $-1,400\, \text{nm}$, which can be suppressed via dispersion engineering (see Extended Data Fig. 2). Compared with state-of-the-art integrated EO comb devices, our method yields a two-orders-of-magnitude improvement in the conversion efficiency and a 2.2 times wider span is measured at the $-70\, \text{dBm}$ power level with the same pump power (Fig. 2c). It should be noted that in the single-resonator TFLN EO comb generator, the pump intensity is 40 dB higher than the first comb line due to the low efficiency from the strong under-coupling of the resonator (purple trace in Fig. 2c). For our coupled-resonator device, the output spectrum in the through port (residual pump) is discussed later in Fig. 3.
To compare the performance between the existing frequency comb generators, we summarized the metrics of demonstrated EO and Kerr frequency combs in Table 1.

The conversion efficiency \( \eta \) can be understood by decomposing it into two components:

\[
\eta = \theta \times \xi
\]

where \( \theta = \frac{P_2}{P_{in}} \) is the ratio between the optical power \( P_2 \) that flows into cavity 2 and the input power \( P_{in} \), and \( \xi = \frac{k_{e2}}{k_{e2} + k_{i2}} \) with \( k_{e2} \) and \( k_{i2} \) being the waveguide–cavity 2 coupling rate and the intrinsic loss rate of cavity 2, respectively (see ‘Theoretical analysis’ section). The power ratio \( \theta \) is determined by the GCC condition. When the GCC condition is met and when \( k_{e1} \gg k_{i1} \), we have \( \theta \approx 1 \). The factor \( \xi \) describes how much power from cavity 2 is coupled into the output waveguide, which sets the theoretical upper limit for the conversion efficiency \( \eta_{\text{max}} \) for each device. It also generates a fundamental trade-off between the comb span and the conversion efficiency: for large \( \xi \) the comb generated inside cavity 2 can be efficiently coupled to the output waveguide, but at the same time the slope of the comb spectrum is increased due to the reduced lifetime of cavity 2, which leads to a lower loaded-quality factor of cavity 2. We theoretically obtained \( \eta_{\text{max}} \) and the slope of the comb for a range of \( k_{e2} \) and intrinsic quality factor \( Q_{i2} \) for cavity 2 (which corresponds to \( k_{i2} \)) to show this trade-off (Fig. 3a). Our comb (Fig. 2b) features a slope of \(-0.7\) dB nm\(^{-1}\) and a measured efficiency of 30\% (\( \eta = 28\% \) in theory and simulation), which is close to \( \eta_{\text{max}} = 38\% \) of our device. With an improved quality factor of \( 1 \times 10^7 \), it is possible to obtain \( \eta_{\text{max}} = 83\% \) with a slope of \(-0.27\) dB nm\(^{-1}\) or \( \eta_{\text{max}} = 50\% \) with a slope of \(-0.09\) dB nm\(^{-1}\). The difference between the achieved efficiency

![Diagram](image_url)
η and the theoretical efficiency $\eta_{\text{max}}$ is due to the imperfect GCC condition, the non-zero value of $k_i$ and the mode-crossing-induced loss due to cavity 1 (see below).

Cavity 1 has a large number of frequency modes that can lead to mode crossing with the modes of cavity 2, potentially causing comb power loss. To overcome this, we use an optimization algorithm to design the FSR values of cavities 1 and 2 so that they have overlapping resonances at the pump frequency only and misaligned resonances for most other frequencies (Vernier effect, Fig. 3a). To verify this, we collect the generated combs from both the through port and the drop port. The comb profile measured at the through port clearly shows the optimized Vernier effect (top third of Fig. 3b) and the drop port. The comb profile measured at the through port preserves the linear slope (bottom third of Fig. 3b) without cut-off, indicating that the mode-crossing-induced loss is minimized. The profile of the comb collected at the through port is the result of the comb generation inside cavity 2 followed by ‘cavity filtering’ in cavity 1. This signal can also be useful for, for example, heterodyne measurements, as local oscillators or clock references.

Next, enabled by the high-efficiency and wide comb span, we demonstrate that the device can serve as an on-chip ultrafast pulse source, which is important for nonlinear applications such as broadband parametric frequency conversion and optical atomic clocks. To characterize the time-domain signal of the output frequency comb, the optical output is sent to an erbium-doped fibre amplifier (EDFA) and dispersion-compensating fibre (DCF) followed by a second-harmonic generation-based intensity autocorrelator (see Fig. 4a for the setup). The full-width at half-maximum (FWHM) of the autocorrelator trace is 1.072 ps, which corresponds to a pulse FWHM of 36 fs (Fig. 4b). We infer that the pulse FWHM in the output facet of the chip is around 336 fs after extracting the total dispersion of the fibre output path of 36 fs nm$^{-1}$. The two sidelobes near the Lorentzian-shaped pulse are caused by the non-uniform gain coefficient of our EDFA (see the section ‘Pulse characterization’ in the Methods).

Finally, we demonstrate the observation of EO and $\chi^{(3)}$ combined high-power frequency combs in a single device, enabled by the formation of ultrafast pulses with a high circulating peak power inside the resonator. To demonstrate this effect, a 63 mW pump power (in the bus waveguide) is used to feed the device (see the setup in Fig. 4a) and the output frequency comb features a 32% conversion efficiency, a 20 mW on-chip comb power and a broadened span of 161 nm (Fig. 4d). As a result, we infer that an estimated ~85 W peak pulse power (~1 W average power) is circulating inside the comb resonator (cavity 2) (see the section ‘Frequency comb characterization’ in the Methods), large enough to stimulate the additional Raman29 and four-wave mixing effects14 (Fig. 4e). Optimizing the dispersion of the current device from normal dispersion to anomalous dispersion could further enhance the four-wave mixing effect, which could be useful for ultrabroad comb generation. Combining $\chi^{(2)}$ and $\chi^{(3)}$ nonlinearities also provides an intriguing opportunity for investigating new regimes of nonlinear optical dynamics such as the third of Fig. 3b) without cut-off, indicating that the mode-crossing-induced loss is minimized. The profile of the comb collected at the through port clearly shows the optimized Vernier effect (top third of Fig. 3b) and the drop port. The comb profile measured at the through port preserves the linear slope (bottom third of Fig. 3b) without cut-off, indicating that the mode-crossing-induced loss is minimized. The profile of the comb collected at the through port is the result of the comb generation inside cavity 2 followed by ‘cavity filtering’ in cavity 1. This signal can also be useful for, for example, heterodyne measurements, as local oscillators or clock references.

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### Table 1 | Comparison of EO and Kerr frequency comb generators

| Reference | Efficiency (%) | Pump power (mW) | Span (nm) | Repetition rate (GHz) | Number of comb lines* | Platform | Mechanism | Pump wavelength (nm) | Device size (mm²) |
|-----------|----------------|-----------------|-----------|----------------------|----------------------|---------|-----------|----------------------|------------------|
| This work | 32             | 63              | 161       | 650                  | 533                  | TFLN    | EO-Kerr   | 1,600                | 0.5              |
| Zhang et al. (2019) | -0.3 | 2 | 60 | 10.453 | 714 | TFLN | EO-SR | 1,600 | 1.2 |
| Yi et al. (2015) | -0.27 | 200 | 90 | 22 | 500 | Silica | Kerr | 1,550 | N/A |
| Marin-Palomino et al. (2017) | 0.1-0.6 | 1,000 | >250 | >96 | >325 | SiN | Kerr | 1,550 | 0.2 |
| Liu et al. (2018) | 1.5 | 50.6 | 120 | 86 | 174 | SiN | Kerr | 1,550 | 0.2 |
| Xue et al. (2019) | 0.0046 | 270 | -6.4 | 0.003 | -266,667 | Fibre | Kerr | 1,550 | N/A |
| Xue et al. (2017) | 31.8 | 656 | -250 | 231 | -135 | SiN | Kerr | 1,550 | 0.1 |
| Kim et al. (2019) | 41 | 180 | >120 | 201.6 | >75 | SiN | Kerr | 1,550 | N/A |
| Helgason et al. (2021) | 32-49 | 13-18 | -90 | 105 | -107 | SiN | Kerr | 1,550 | N/A |
| 36 | 2.5 | -70 | 227 | -39 | - | | | 0.5 |
| Kourogi et al. (1993) | N/A | N/A | 32 | 5.8 | 690 | Bulk | EO-SR | 1,550 | N/A |
| Xiao et al. (2008) | N/A | N/A | -38 | 10 | -475 | Bulk | EO-SR | 1,550 | N/A |
| Rueda et al. (2019) | N/A | N/A | 13 | 8.9 | 186 | WGM LN disk | EO-SR | 1,550 | N/A |

CR, coupled resonator; SR, single resonator; BS, bright soliton; SN, silicon nitride; DP, dark pulse; WGM, whispering gallery mode; LN, lithium niobate. The sequence of references is determined by the mechanism: EO comb, BS Kerr comb and DP Kerr comb. EO combs that are related but do not report efficiencies are listed at the end. *Number of comb lines calculated via the spanning/repetition rate. 

$\eta$: efficiency, $\eta_{\text{max}}$: maximum efficiency, $k_i$: non-zero value of the gain coefficient of our EDFA (see the section ‘Pulse characterization’ in the Methods).
as the proposed "band soliton" and might enable superior OFCs, owing to the ability to reach both the ultrafast and high-power regimes in the same resonator under EO modulation.

In summary, we demonstrate high-efficiency and broadband EO frequency combs using a coupled-resonator structure. We show that it can be used as an integrated femtosecond pulse source and can...
stimulate combined second- and third-order nonlinear processes in the ultrafast high-power regime. In addition, we provide a theoretical model that simplifies the coupled-resonator system supporting hundreds of energy levels as a two-level system. Simultaneously achieving a high-efficiency and wide span can enable a broad range of applications. For example, an already demonstrated 100-fold improvement in comb efficiency can lead to a 20 dB increase in the signal-to-noise ratio of frequency-multiplexed applications such as optical communications. These advances can also reduce the optical pump power needed for the realization of optical neural networks. In addition, the microwave-power consumption could be reduced by integrating on-chip microwave resonators with our comb source. Furthermore, the ability to generate on-chip femtosecond pulses is important for nonlinear photonics, optical atomic clocks, optical sensing and time-bin-encoded optical computing. Finally, the high conversion efficiency of our device opens the door for a generation of broad EO combs for entangled photons, broadly enabling frequency-domain quantum information processing.

Online content
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Methods

Device fabrication. Our devices are fabricated from a commercial X-cut lithium niobate on insulator wafer (NanoLN), with a 600 nm LN layer, 2 μm buried oxide (thermally grown), on a 500 μm silicon handle. Electron-beam lithography with a hydrogen silsesquioxane resist followed by argon-ion-based reactive ion etching (350 nm etch depth) are used to pattern the optical layer of the devices, including the rib waveguides and micro-ring resonators. The devices are cleaned and the microwave electrodes (15 nm of titanium, 300 nm of gold) are defined using photolithography followed by electron-beam evaporation and a bilayer lift-off process. One layer of silica (SiO2) (800nm) using plasma-enhanced chemical vapour deposition is used to clad the devices. The heater (15 nm of titanium and 200 nm platinum) for cavity 1 is defined by photolithography followed by electron-beam evaporation and lift-off. The heater is designed as a short metal strip (5 μm wide) that is placed 3 μm away from the resonator on top of the SiO2 cladding. The resistance of the heater is ~140Ω (including parasitic resistance from routing strips). Tuning of the ring resonance via the FSR is achieved using a current of ~50 mA.

Frequency comb characterization. The measurement setup is illustrated in Extended Data Fig. 3. Telecommunication-wavelength light from a fibre-coupled tunable laser (TSL-510, SANTEC) passes through a polarization controller and is coupled to the LN chip using a lensed fibre. The output is collected using a lensed fibre and then sent to an optical spectrum analyser with a spectral resolution of 0.02 nm for characterization of the frequency comb. The microwave signal is generated from a synthesiser followed by a microwave amplifier and delivered to the electrodes on a device using an electric probe. The microwave driving power is 2.2 W.

The circulating power in Fig. 4d is inferred from the comb power $P_{\text{circ}} = 20 \text{ mW}$ in the bus waveguide, which for cavity 2 gives an intra-cavity power of $P_{\text{intra}} = \frac{20 \text{ mW}}{2}$. The Finesse is calculated using

$$\text{Finesse} = \frac{C}{\Delta \lambda_{\text{FWHM}}} = \frac{2 \times 2 \times 10^8}{0.02 \text{ nm}} = 139.3.$$ Therefore $P_{\text{intra}} = 0.9 \text{ W}$ and the peak power of the pulse can be inferred via $P_{\text{peak}} = \frac{C}{2 \pi} P_{\text{intra}} = 85 \text{ W}$ in which $C = 32 \text{ ps}$ and $\tau = 336 \text{ fs}$ are the roundtrip time of cavity 2 and the pulse duration, respectively.

The device parameters are extracted based on measurement on the transmission spectra (Extended Data Fig. 4 and Extended Data Table 1). The parameters of cavity 1 ($\kappa_1$ and $\kappa_c$) and cavity 2 ($\kappa_2$ and $\kappa_c$) are obtained from the linewidths and extinction ratio of the resonances. The coupling $\kappa$ between the two cavities is extracted by tuning the two resonances of the cavities to a degenerate point and measuring the mode splitting, which gives $\mu = \sqrt{\left(\frac{\kappa_1}{\kappa_2}\right)^2 + \left(\frac{\kappa_c}{\kappa_c}\right)^2}$ for degeneracy point.

Pulse characterization. The output frequency comb is sent to an EDFA and a DCF followed by a second-harmonic generation-based intensity autocorrelator. Pulse characterization.

Theoretical analysis. Effective loss rate induced by microwaves for the EO comb. To obtain the effective loss rate that is induced by microwave modulation, $\kappa_{\text{microw}}$ we consider the case that our cavity 2 (the comb cavity) is driven by a continuous microwave signal without the existence of the cavity 1. Then, the Hamiltonian of the system follows a single-resonator EO comb model (we set $h=1$ in which $h$ is the Planck constant):

$$H = \sum_{j=1}^{N} a_j a_j^\dagger + \cos \omega_{\text{microw}} t \left( a_j a_j^\dagger + \text{h.c.} \right)$$

in which $a_j$ (or $a_j^\dagger$) is the annihilation (creation) operator of each optical mode $j$, $t$ is time, $\omega$ represents the frequency of each frequency mode, $\Omega$ is the coupling rate due to microwave modulation and $\omega_{\text{microw}}$ is the frequency of the microwave signal. We also assume that the frequency modes range from $j=1$ to $j=N$. Implementing the Heisenberg–Langevin equation gives a set of equations of motion for each mode $a_j$:

$$\dot{a}_j = \left( -i \omega_j - \frac{\delta}{2} \right) a_j - i \Omega a_j a_{j+1} + i \sqrt{2 \kappa_{\text{microw}}} a_{j+1}$$

in which $i$ is the imaginary unit, $\kappa_{\text{microw}}$, $\kappa_1$ and $\kappa_2$ are the coupling rate between cavity 2 and the output waveguide, the intrinsic loss rate of cavity 2, and total loss rate of $a_j$, respectively. The pump power and frequency are denoted by $\omega_{\text{microw}}$ and $\omega$, respectively. We use the Kroenke delta function $\delta_j$ to indicate that only the zeroth mode is pumped. Therefore, we write $a_0$ as $a_0 = a_0 + \text{h.c.}$ in which $a_0$ is the resonance frequency of the zeroth mode. By changing rotating frames for each mode $a_j \rightarrow e^{-i \omega_{\text{microw}} t} a_j$, we obtain the simplified equations of motion:

$$\dot{a}_j = \left( i \Delta - \frac{\delta}{2} \right) a_j - i \Omega a_j a_{j-1} - i \sqrt{2 \kappa_{\text{microw}}} a_{j+1}$$

in which $\Delta = \omega - \omega_0$ and $\delta = \omega_{\text{microw}} - \text{FSR}$ are the laser detuning and the microwave detuning, respectively.

The steady state of such a system can be analytically solved. Considering the case that $\Delta = \delta = 0$, the equations of motion become

$$0 = \left( \frac{\kappa_1}{2} a_0 - \frac{\kappa_2}{2} a_{N-1} \right) a_0 - \frac{\Omega}{2} a_j a_{j-1}$$

which gives a relation $a_0 = -i \frac{\Omega}{\kappa_1} a_{N-1}$. As a result, the equation for $a_j$, becomes

$$0 = \left( \frac{\kappa_1}{2} a_{j-1} - \frac{\kappa_2}{2} a_j \right) a_j - \frac{\Omega}{2} a_j a_{j-1} - \frac{\Omega}{2} a_j a_{j-1} - \frac{\Omega}{2} a_j a_{j-1}$$

which leads to another relation $a_{j-1} = i \left( \frac{\Omega}{\kappa_1} + \frac{\kappa_2}{2} \right) a_j$. By iterating the above steps, we obtain the relation for an arbitrary mode $a_j$ with $l$ representing an arbitrary mode number.

$$a_l = -i \frac{\kappa_1}{2} a_l - i \frac{\kappa_2}{2} a_l - i \frac{\kappa_2}{2} a_l - i \frac{\kappa_2}{2} a_l - i \frac{\kappa_2}{2} a_l - i \frac{\kappa_2}{2} a_l$$

where the total number of the factor $2^l$ is $N-l$. As a result, the equation of motion for the zeroth mode is

$$0 = \left( \frac{\kappa_1}{2} a_0 - i \frac{\kappa_2}{2} a_0 \right) a_0 - \frac{\kappa_{\text{microw}}}{2} a_0$$

Simplifying this equation gives

$$0 = \left( \frac{\kappa_1}{2} - \frac{\kappa_{\text{microw}}}{2} \right) a_0 - \frac{\sqrt{2 \kappa_{\text{microw}}}}{2}$$

in which $\kappa_{\text{microw}} = \frac{\kappa_1}{2} \times 2(l,-1)$ with
\[ f_0 = 1 + \frac{\kappa^2_{1eff}}{1 + \kappa^2_{int} + \frac{\mu^2}{\kappa^2_{1eff}} - \kappa^2_{0} - \alpha^2} = \kappa^2 + \frac{4\mu^2}{\kappa^2_{1eff} - \alpha^2}. \]

In the limit of \( N \) is a very large number, and we can use the limit of \( f_0 \) with \( f \) defined as \( f \equiv \lim_{n \to \infty} f_n \) and \( f = 1 + \frac{\mu^2}{\kappa^2_{1eff}} \) to solve the final expression for \( \kappa_{1eff} \) as

\[ \kappa_{1eff} = \kappa_2 \left( 1 + \frac{4\mu^2}{\kappa^2_{1eff} - 1} \right). \]

Conversion efficiency analysis using the generalized critical coupling condition. With the expression for \( \kappa_{1eff} \), the single-resonator EO comb system can be simplified to a single mode, which has three loss rates \( \kappa_{1eff} \), \( \kappa_2 \) and \( \kappa_{1in} \). Therefore, the steady-state equations for a coupled-resonator EO comb are

\[ 0 = -\frac{\kappa_2 + \kappa_{1in}}{2} i\mu d \]
\[ 0 = -\frac{\kappa_2}{2} i\mu d - \frac{\kappa_2 + \kappa_{1in}}{2} i\mu a_0 \]

in which \( d \) is the pump mode of cavity 1, \( \mu \) is the evanescent coupling rate between cavities 1 and 2, and \( \kappa_{1in}, \kappa_2 \), and \( \kappa_1 (= \kappa_{1eff} + \kappa_{1in}) \) are the coupling rate between cavity 1 and input waveguide, the intrinsic loss rate of the cavity 1, and the total loss rate of \( d \), respectively. Note that in the above equation, cavity 1 is pumped instead of cavity 2. Hence, the effective loss rate \( \kappa_{1eff} \) for cavity 1 that is induced by cavity 2 and the output waveguide of cavity 2 is

\[ \kappa_{1eff} = \frac{4\mu^2}{\kappa_2^2 + \kappa_{1in}^2} \]

and a critical coupling condition occurs when \( \kappa_1 = \kappa_3 = \frac{\mu^2}{\kappa_{1eff} + \kappa_{1in}} \). The output in the through-port waveguide is \( d_{out} = d_{in} + \sqrt{\kappa_{1eff}} d_{in} = d_{in} \left( \frac{\kappa_{1eff} + \kappa_{1in}}{\kappa_{1eff} + \kappa_{1in}} \right) \).

The amplitude that is lost in the intrinsic loss of cavity 1 is

\[ d_l = \sqrt{\kappa_{1in}^2} d_{in} = d_{in} \frac{\sqrt{\kappa_{1eff} + \kappa_{1in}}}{\kappa_{1eff} + \kappa_{1in}}. \]

Therefore, the parameter \( \xi \) sets the fundamental limit of the conversion efficiency. For example, in this work, cavity 2 is nearly critically coupled to the output comb waveguide, leading to a ~50% theoretical limit of the conversion efficiency. With the expression for \( P_2 \), we obtain the final efficiency:

\[ \eta = \frac{P_{comb}}{P_{in}} = P_2 \times \xi. \]

Data availability

The datasets generated and analysed during this study are available from the corresponding authors upon reasonable request.

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Author contributions

Y.H. and B.B. conceived the idea. Y.H. developed the theory and fabricated the devices. M.Y. and J.M.K. carried out the measurements. B.B. and Y.H. performed the numerical simulations. Y.H. wrote the manuscript with contributions from all authors. N.S., D.Z., R.C., A.S.-A., L.S. and M.Z. helped with the project. M.L. and J.M.K. supervised the project.

Competing interests

M.Z. and M.L. are involved in developing lithium niobate technologies at HyperLight Corporation. The remaining authors declare no competing interests.

Additional information

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| Parameters                                      | Values          |
|------------------------------------------------|-----------------|
| Waveguide-cavity 1 coupling $\kappa_1$        | $2\pi \times 1.37 \text{ GHz}$ |
| Intrinsic loss rate $\kappa_i$                 | $2\pi \times 152 \text{ MHz}$  |
| Intrinsic quality factor $Q_1$                  | $1.2 \times 10^6$         |
| Waveguide-cavity 2 coupling $\kappa_2$        | $2\pi \times 85 \text{ MHz}$ |
| Intrinsic loss rate $\kappa_2$                 | $2\pi \times 137 \text{ MHz}$ |
| Intrinsic quality factor $Q_2$                  | $1.4 \times 10^6$         |
| Cavity 1-cavity 2 coupling $\mu_2$             | $2\pi \times 1.47 \text{ GHz}$ |
| Mode-coupling rate $\Omega$                    | $2\pi \times 7.40 \text{ GHz}$ |
| Modulation index $\beta$                       | $0.48\pi$         |
Extended Data Fig. 1 | Tunability of pump frequency and turning on-off using the heater. Spectra of the device pumped at 1530 nm (purple trace) and 1603 nm (blue trace and red trace). By tuning the resonances of cavity 1 to match the resonances of cavity 2, the device can be pumped at different wavelengths. The cut-off at wavelengths that are far blue-detuned (purple trace) is due to TE-TM (transverse electric-transverse magnetic) polarization crossing, which affects the TE-designed cavity 2, and can be minimized by additional dispersion engineering. The comb can also be turned off simply by tuning the resonance of cavity 1 to be mis-aligned from cavity 2. The blue and red traces show the on and off comb states by changing the heater voltages without changing the laser or microwave drive, showing an excellent extinction ratio.
Extended Data Fig. 2 | Minimizing the TE-TM crossing via dispersion engineering. The cut-off of the comb spectrum around 1400 nm originates from the TE-TM polarization crossing. Due to birefringence of lithium niobate, the TE modes that propagate along the y- and z-direction of the thin-film lithium niobate crystal axes have different indices $n_{y,\text{TE}}$ and $n_{z,\text{TE}}$, respectively, while the indices of TM modes are $n_{y,\text{TM}}$ and $n_{z,\text{TM}}$ for both directions. When the TE mode circulates inside the micro-resonator, it experiences different averaged TE indices ranging from $n_{y,\text{TE}}$ to $n_{z,\text{TE}}$ at different bending points of the resonator. As a result, in our current geometry ($w = 1.2 \, \mu m$, $h = 350 \, nm$, and $t = 250 \, nm$), the TM mode has an index that is between the value of $n_{y,\text{TE}}$ and $n_{z,\text{TE}}$ at wavelengths below ~1450 nm (Left panel), leading to a degeneracy between the TM index and averaged TE indices. This index degeneracy can cause polarization-crossing, which can be pushed toward lower wavelength via dispersion engineering. For example, for a geometry with $w = 1.2 \, \mu m$, $h = 350 \, nm$, and $t = 150 \, nm$, the range that $n_{y,\text{TM}}$ is in between the $n_{y,\text{TE}}$ and $n_{z,\text{TE}}$ is pushed to ~1250 nm.
Extended Data Fig. 3 | Measurement setup for Figs. 2 and 3. The coupled-resonator device is characterized using the above setup. In the experiment of Fig. 2b, an EDFA is used to obtain higher pump power. In the experiment of Figs. 2c and 3b, the EDFA is not used. PC, polarization controller; DUT, device under test; EDFA, Erbium-doped fiber amplifier; OSA, optical spectrum analyzer; PD, photodetector.
Extended Data Fig. 4 | Device parameter analysis. a, b, Transmission spectrum of a single cavity 1 (a) and 2 (b) with the same fabrication parameters as the coupled-resonator device. c, Transmission spectrum of a coupled-resonator device on the through port. d, Transmission spectrum of a coupled-resonator device when microwave is on. (c) and (d) are measured on two different coupled-resonator devices with the same fabrication parameters. The background oscillation is due to the Fabry-Perot resonance formed in the bus waveguide due to the reflection at the two facets of the chip. The extracted parameters give a theoretical conversion efficiency of 28%.
Extended Data Fig. 5 | Frequency spectrum before and after passing the EDFA. The spectrum shows the frequency comb before (top panel) and after (bottom panel) amplification by the EDFA in the time-domain pulse measurement of Fig. 4b.
**Extended Data Fig. 6 | Tuning the dual-pulse in one roundtrip time.** The high conversion-efficiency allows us to measure the signal in the time-domain under varied optical detuning. Unlike dark-pulse Kerr combs or platicons in a coupled-resonator Kerr frequency comb generator, which exhibits a completely different mechanism in both spectral and temporal domains compared to their single-resonator counterparts, our coupled-resonator structure preserves the time-domain features of the single-resonator EO combs. The output signal shows that there are two pulses in one round-trip time and the delay between the two pulses can be tuned by changing the optical detuning, which is identical to the conventional single-resonator EO comb.