High-speed tunable microwave-rate soliton microcomb

Several photonic technologies can produce coherent microwaves including optoelectronic oscillators1, dual-frequency lasers2, and Brillouin lasers. However, the highest frequency stability microwave signals generated by any technology (electronic or optical) are derived from frequency comb technology using the principle of optical frequency division1. Microcombs provide a powerful way to miniaturize this approach to the chip scale. The superior coherence of soliton microcombs has led to a variety of applications including optical communication6, spectroscopic sensing7, range measurement8–11, optical frequency synthesis12, and neuromorphic computing13–15. Recently, significant interest has been attracted to develop soliton microcombs with repetition rates in the radio and microwave frequency regimes15–31, with the potential of microwave synthesis on an integrated chip34.

High-speed frequency tuning and modulation are crucial for the applications of coherent microwaves. However, the repetition rates of current soliton microcombs are fundamentally determined by the physical sizes of the monolithic comb resonators, which are difficult to change after the devices are made. While the geometry of a comb resonator could potentially be deformed by piezoelectric actuation, its speed would be limited by the intrinsic slow mechanical response, which was recently shown with an operation bandwidth of ~0.6 MHz11. To date, the continuous tuning of the repetition rate of soliton combs primarily relies upon thermal or pump frequency control that is typically limited to audio bandwidths15–20,22,23,27. Here we demonstrate a soliton microcomb whose microwave repetition rate can be continuously tuned with a record bandwidth of 75 MHz and a frequency modulation (FM) rate > 5 × 10^14 Hz/s. Moreover, the device offers enormous bandwidth for direct locking of microwave frequency to an external reference source, free from the bandwidth constraint existing in current comb locking approaches15–20,22,23,27. Besides application to microwave photonics, this high-speed rate control will be useful in all microcomb applications including frequency synthesizers27 and optical clocks28,29.

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Results

Device design

The device is an on-chip high-Q lithium niobate (LN) microresonator whose dispersion is engineered for soliton comb generation. The lithium niobate platform has recently been shown to enable self-starting and bi-directional switching of soliton states with the assistance of the photorefractive effect. LN also exhibits a strong electro-optic Pockels effect, and here it is used for rapid tuning of the soliton repetition rate, by directly integrating electro-optic tuning and modulation elements into the comb resonator. Figure 1a shows the device concept wherein electro-optic tuning and modulation elements are integrated into the comb resonator. In essence, the LN resonator functions simultaneously as a soliton comb generator and a high-speed electro-optic (EO) modulator. As shown below, this fully integrated device not only enables high-speed tuning of the soliton repetition rate but also provides a way to tightly lock the repetition rate to an external microwave reference.

Figure 1b shows the LN chip, which was fabricated on a z-cut LN-on-insulator (LNOI) wafer platform. Figure 1c shows the detailed structure of a device that consists of a microring resonator, a pulley bus waveguide, and driving electrodes (Fig. 1a). The ring resonator is designed to have a waveguide width of 2.2 μm, which yields a group velocity dispersion of about $-0.035 \text{ ps}^2/\text{m}$ in the telecom band for the fundamental quasi-transverse-electric (quasi-TE) mode family that is suitable for soliton generation. The electrodes are placed along the ring resonator waveguide with an electrode-waveguide spacing of about 4 μm so as to optimize the electro-optic tuning/modulation efficiency without impacting the optical Q of the resonator. The electrodes are 525 nm thick and 5 μm wide in order to support high-speed modulation. The LN microring resonator exhibits an intrinsic optical Q of ~4 million. A similar optical Q is obtained for resonators ranging in radius up to 1.5 mm.

Microwave rate solitons and phase noise performance

By increasing the radius of the ring resonator from 100 to 450 μm, we are able to vary the soliton repetition rate $f_r$ from 200 to 44.84 GHz, as shown in Fig. 2a and b. Further increase of resonator size is non-trivial due to the interference of stimulated Raman scattering. LN exhibits rich Raman scattering characteristics that were recently shown to introduce self-frequency shift (SFS) on the Kerr solitons. However, Raman lasing is also possible when a Stokes frequency matches a cavity resonance. For a resonator with a radius $\geq$1 mm, the free-spectral range is small enough ($\leq$20 GHz) that Raman lasing becomes unavoidable, and this perturbs soliton generation. For the z-cut resonators used here, the most significant interference comes from the Stokes wave with a Raman frequency shift of $-19 \text{ THz} (E(L0))$ phonon mode of LN. To resolve this issue, the pulley bus waveguide is designed to be critically coupled at the pump wavelength around 1550 nm and over-coupled at the Raman Stokes wavelength around 1720 nm (Supplementary Information (SI), part A). As a result, Raman lasing can be suppressed.

Figure 2c and f show two examples of soliton microcombs with $f_r$ of 19.82 and 13.5 GHz, respectively. The slight spectral distortion around 1580 nm is a side effect of the bus waveguide which is designed to be under-coupled at this wavelength (see SI, part A). This side effect, however, does not impact the integrity of the Kerr solitons and their coherence is evident in the detected microwave signal shown in Fig. 2d and g. Here, both microwave signals at 19.82 and 13.5 GHz exhibit a signal-to-noise ratio $>70 \text{ dB}$. As shown in Fig. 2e and h, the phase noise of the microwaves is about $-40 \text{ dBc/Hz}$ at 1 kHz, reaches $-100 \text{ dBc/Hz}$ at 10 kHz, and goes below $-130 \text{ dBc/Hz}$ at 3 MHz. These phase noise levels are comparable to those demonstrated recently in other on-chip soliton platforms. The spectral bump around 4 kHz is likely due to the impact of the frequency noise of the pump laser (New Focus, TLB-6328).

![Fig. 1 | Concept of the high-speed tunable microwave-rate soliton source.](https://doi.org/10.1038/s41467-023-39229-3)
High-speed modulation of soliton repetition rate

In order to dynamically tune and modulate the microwave-rate solitons, we integrate EO tuning/modulating components directly onto the comb resonator as shown in Fig. 1a. For the z-cut resonator, we utilize the $r_{22}$ electro-optic tensor element of LN to tune the fundamental quasi-TE modes. For a circularly shaped ring resonator, our analysis shows that the EO tuning efficiency can be maximized with three groups of driving electrodes, each of which contains two pairs of signal-ground electrodes and spans an angle of 60° (see SI, part B for details). A detailed device layout is shown in Fig. 1c, in which only two groups of electrodes are fabricated so as to avoid interference with the coupling bus waveguide (see also Fig. 1a). To simplify experimental testing, we utilized only one group of electrodes for EO tuning and modulation. Nonetheless, the integrated EO tuning still achieves good efficiency, whose details are provided in the SI (part D). As such an FM efficiency drops, however, with further increases in modulation frequency (160 MHz) of the spectrum analyzer (Tektronics, RSA5126B) used for the time-dependent frequency characterization. For the same reason, the time-dependent frequency analysis likely underestimates the FM efficiency, whose details are provided in the SI (part E).

The broadband EO response of the device implies that high-speed tuning control of the soliton microcomb is possible. To show this feature, we applied a sinusoidal electric signal to the 19.81 GHz comb resonator and monitored the frequency of the detected microwave signal. As shown in Fig. 3b–e, the sinusoidal EO-drive produces a sinusoidal frequency modulation (FM) of the microwave signal. At a modulation frequency of 1 MHz (Fig. 3b), a peak driving voltage of $V_p = 0.76$ V produces an FM amplitude of 41.8 kHz which corresponds to an FM efficiency of 53 kHz/V. The FM efficiency increases considerably with the modulation frequency, reaching a value of 463 and 824 kHz/V at the modulation frequency of 10 and 50 MHz, respectively (Fig. 3c and d). As shown in Fig. 3e, we are able to modulate the microwave signal at a frequency as high as 75 MHz, where a driving voltage of $V_p = 3.0$ V produces an FM amplitude of 3.45 MHz, corresponding to an FM efficiency of 1.15 MHz/V. Here, the blurring of the time–frequency spectrum is due to the limited bandwidth (160 MHz) of the spectrum analyzer (Tektronics, RSA5126B) used for the time-dependent frequency characterization. For the same reason, the time-dependent frequency analysis likely underestimates the FM efficiency since it only captures the first-order modulation sidebands at such a high modulation frequency. Indeed, the microwave spectrum shown in Fig. 3e implies a considerably higher FM amplitude and phase noise of the detected 19.82 GHz microwave signal produced by the soliton comb shown in (c). The soliton comb was boosted by an optical amplifier before it is detected by a high-speed detector. g and h Same as d and e but for the 13.3 GHz soliton comb shown in (f). In d and g, the RBW of the RF spectrum is 200 Hz. In all figures, the devices are free running without active feedback, and the pump-laser-cavity detuning is self-stabilized by the photorefractive effect.

One mechanism responsible for the observed FM of the microwave signal is the Raman-induced SFS of the solitons whose magnitude depends on the laser-cavity detuning. EO modulation of the comb resonator modulates the laser-cavity detuning of the pump wave which in turn changes the magnitude of SFS and thus shifts the carrier frequency of the Kerr solitons. Due to the group-velocity dispersion of the resonator, such a shift of soliton carrier frequency translates into a...
Rate at a modulation frequency of 1 GHz essentially as a pure electro-optic modulator. To obtain the no comb or other nonlinear effect was produced, and the device functioned electro-optic tuning performance, the pump laser power was reduced to a low level such that the actual EO response of the device is much larger than the cavity. Direct injection locking and feedback locking mechanism accounts for an FM effect change in the repetition rate. As shown in the SI (part C), this mechanism accounts for an FM efficiency of ~100000-200000 kHz/V, which explains well the observed phenomena at low modulation frequencies. However, the FM efficiencies observed at higher modulation frequencies of 50 and 75 MHz are considerably larger than this value. The underlying reason is likely related to the speed of EO modulation which becomes comparable to the photon lifetime in the resonator so that the cavity resonances cannot adiabatically follow the EO modulation anymore. However, the exact physical mechanism is not clear at this moment and will require further exploration. On the other hand, the same mechanism of Raman-induced SFS leads to a certain extent of underlying reason is likely related to the speed of EO modulation which becomes comparable to the photon lifetime in the resonator so that the cavity resonances cannot adiabatically follow the EO modulation anymore. However, the exact physical mechanism is not clear at this moment and will require further exploration. On the other hand, the same mechanism of Raman-induced SFS leads to a certain extent of underlying reason is likely related to the speed of EO modulation which becomes comparable to the photon lifetime in the resonator so that the cavity resonances cannot adiabatically follow the EO modulation anymore. However, the exact physical mechanism is not clear at this moment and will require further exploration. 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Direct injection locking and feedback locking

The actual EO response of the device is much larger than the cavity bandwidth as evidenced in Fig. 4b. In this measurement, the resonantly enhanced EO response is apparent at the modulation frequencies of 19.81 and 39.62 GHz corresponding to one and two free-spectral ranges of the cavity. Comb-like sidebands can be produced by driving the comb resonator at a frequency of 19.81 GHz (Fig. 4b, inset). Apparently, the device offers an EO bandwidth of up to tens of gigahertz. With this broadband modulation response of the comb resonator, we are able to lock the soliton repetition rate in two ways. On one hand, we can apply the 19.81 GHz reference microwave directly to the comb resonator during the soliton generation (Fig. 4a, yellow box). The produced EO comb then seeds the soliton generation. This approach is similar to the injection locking approach, but the reference microwave is now fed directly to the comb resonator itself rather than through external modulation on the pump laser. As shown in the yellow curve in Fig. 4c, such a direct locking approach is able to suppress the phase noise by about 40 dB over the frequency range of 1–10 Hz. On the other hand, we can also compare the detected microwave with the reference oscillator and apply the error signal to

![Image](https://via.placeholder.com/150)
Soliton Resonator substantially reduced in the future with the packaging of the chip\textsuperscript{19,22}. On the other hand, the photorefractive effect of LN could have a potential impact on the phase noise at low frequencies, whose exact behavior is difficult to characterize at this moment and will require further exploration in the future.

It was shown recently\textsuperscript{10} that soliton microcombs exhibit a certain quiet point around which the phase noise of the microwave can be significantly suppressed due to the recoil effect between soliton SFS and dispersive wave produced via mode crossing. This approach was not implemented in our current experiments which focus on the basic phase-noise performance offered by an LN soliton microcomb and the high-speed tunability of the soliton repetition rate. The use of the quiet-point method could further improve the phase-noise performance of the LN soliton microcombs.

**Discussion**

In summary, we have demonstrated the microwave-rate soliton microcomb whose repetition rate can be tuned at a high speed. By taking advantage of the strong electro-optic Pockels effect of LN and by integrating electro-optic tuning and modulation components directly into the LN comb resonator, we are able to achieve a continuous frequency modulation speed up to 75 MHz and a frequency modulation rate up to $>5 \times 10^{14}$ Hz/s, several orders-of-magnitude faster than existing microcomb technology\textsuperscript{11,15,16,33}. The device exhibits a modulation efficiency of $>1$ MHz/V, which could be further increased if all three groups of driving electrodes are employed. The device offers a significant bandwidth (up to tens of gigahertz) for feedback locking of the repetition rate to an external reference source, enabling the realization of both direct injection locking (via intracavity EO modulation) and feedback locking (via fast repetition-rate control), to the comb resonator itself without involving external modulation.

The broadband locking offered by the device would enable comb-based self-sustained coherent microwave oscillation, by self-injecting the detected microwave to feedback lock to the comb resonator. Such a self-sustained approach not only could improve the coherence of microwave but also would potentially eliminate the need for an external reference microwave source that is required in current comb-based microwave synthesis. In addition to the microwave applications, the flexible and high-speed temporal modulation of soliton microcomb may offer a new path for sensing applications such as dual-comb spectroscopy, where the soliton comb with a time-varying repetition rate naturally provides soliton subsets with different repetition rates for the sensing and reference paths (with an appropriate time delay). Such an approach would enable dual-comb or even multi-comb spectroscopy with only a single and repetition-rate-tunable soliton comb that could considerably simplify the sensing architecture. Development of these applications will be left for future exploration in the next step. Overall, the demonstrated device brings high-speed modulation to soliton microcombs, providing a new approach to electro-optic processing of coherent microwaves and opening up a continuous frequency modulation speed.
great avenue towards high-speed control of soliton comb lines that is crucial for many applications including frequency metrology, frequency synthesis, RADAR/LiDAR, sensing, and communication.

**Methods**

**Device fabrication**
The devices were fabricated on a 610-nm z-cut LN-on-insulator (LNOI) wafer. Ring resonators and waveguides structures were defined by electron-beam lithography with ZEP520a as a resist, followed by etching to about 410 nm depth with Ar ion milling. After removing the ZEP520a residue, 525 nm-thick Au electrodes were patterned by electron-beam lithography with PMMA as a resist, followed by deposition using an electron beam evaporator. An overnight lift-off process was applied to remove PMMA and residual Au.

**Reporting summary**
Further information on research design is available in the Nature Portfolio Reporting Summary linked to this article.

**Data availability**
All data are available in the main text or the supplementary materials.

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Author contributions
Y.H. designed and fabricated the sample. Y.H. designed and performed the experiments. Y.H., R.L.-R., and U.A.J. did the numerical simulations. Y.H. and R.L.-R. analyzed the data. U.A.J., J.L., R.L.-R., and M.L. assisted in the experiments. S.X. assisted in device fabrication. Y.H. and Q.L. analyzed the data. U.A.J., J.L., R.L.-R., and M.L. assisted in the experiments. S.X. assisted in device fabrication. Y.H., R.L.-R., K.V., and Q.L. wrote the manuscript. K.V. and Q.L. supervised the project. Q.L. conceived the device concept.

Competing interests
The authors declare no competing interests.

Additional information
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