

Integrated and DC-powered superconducting microcomb

Received: 28 December 2023

Accepted: 24 April 2024

Published online: 13 May 2024

 Check for updates

Chen-Guang Wang^{1,2,3}, Wuyue Xu^{1,2,3}, Chong Li^{1,2,3}, Lili Shi¹, Junliang Jiang¹, Tingting Guo¹, Wen-Cheng Yue^{1,2,3}, Tianyu Li^{1,2,3}, Ping Zhang¹, Yang-Yang Lyu^{1,2}, Jiazheng Pan², Xiuhaio Deng^{4,5}, Ying Dong⁶, Xuecou Tu^{1,5}, Sining Dong^{1,3}, Chunhai Cao¹, Labao Zhang^{1,5}, Xiaoqing Jia^{1,5}, Guozhu Sun^{1,5}, Lin Kang^{1,5}, Jian Chen^{1,2}, Yong-Lei Wang^{1,2,3}✉, Huabing Wang^{1,2}✉ & Peiheng Wu^{1,2}✉

Frequency combs, specialized laser sources emitting multiple equidistant frequency lines, have revolutionized science and technology with unprecedented precision and versatility. Recently, integrated frequency combs are emerging as scalable solutions for on-chip photonics. Here, we demonstrate a fully integrated superconducting microcomb that is easy to manufacture, simple to operate, and consumes ultra-low power. Our turnkey apparatus comprises a basic nonlinear superconducting device, a Josephson junction, directly coupled to a superconducting microstrip resonator. We showcase coherent comb generation through self-started mode-locking. Therefore, comb emission is initiated solely by activating a DC bias source, with power consumption as low as tens of picowatts. The resulting comb spectrum resides in the microwave domain and spans multiple octaves. The linewidths of all comb lines can be narrowed down to 1 Hz through a unique coherent injection-locking technique. Our work represents a critical step towards fully integrated microwave photonics and offers the potential for integrated quantum processors.

Frequency combs serve as high-precision rulers for frequency and time measurement, playing a pivotal role in a wide variety of modern science and technologies^{1–5}, including optical clocks, LIDAR, spectroscopy, arbitrary waveform generation, and optical neural networks. Over the past two decades, integrated combs have garnered significant research interests^{5–18}, leading to miniaturized and chip-based photonic systems⁷. However, most on-chip frequency combs, such as integrated semiconductor mode-locked lasers and microresonator-based Kerr combs, mainly operate in the optical frequency domain. A fully integrated frequency comb functioning in the microwave domain remains elusive, impeding the advancement of chip-based microwave

spectroscopy and integrated quantum circuits, which typically require precise microwave control. Here, we address these challenges by introducing an all-superconductor-based microcomb, featuring an elegantly simple structure, effortless operation, and ultra-low power consumption.

Our superconducting frequency comb is fully integrated, comprising two fundamental superconductor devices: a Josephson junction directly coupled to a superconducting coplanar waveguide (CPW) resonator, as illustrated in Fig. 1a (see Supplementary Fig. 1 for a photo of our device). Device fabrication is achieved through straightforward procedures utilizing standard photolithography and electron beam

¹Research Institute of Superconductor Electronics, School of Electronic Science and Engineering, Nanjing University, Nanjing, China. ²Purple Mountain Laboratories, Nanjing, China. ³National Key Laboratory of Spintronics, Nanjing University, Suzhou, China. ⁴Shenzhen Institute for Quantum Science and Engineering, Southern University of Science and Technology, Shenzhen, China. ⁵Hefei National Laboratory, Hefei, China. ⁶College of Metrology Measurement and Instrument, China Jiliang University, Hangzhou, China. ✉e-mail: yongleiwang@nju.edu.cn; hbwang@nju.edu.cn; phwu@nju.edu.cn

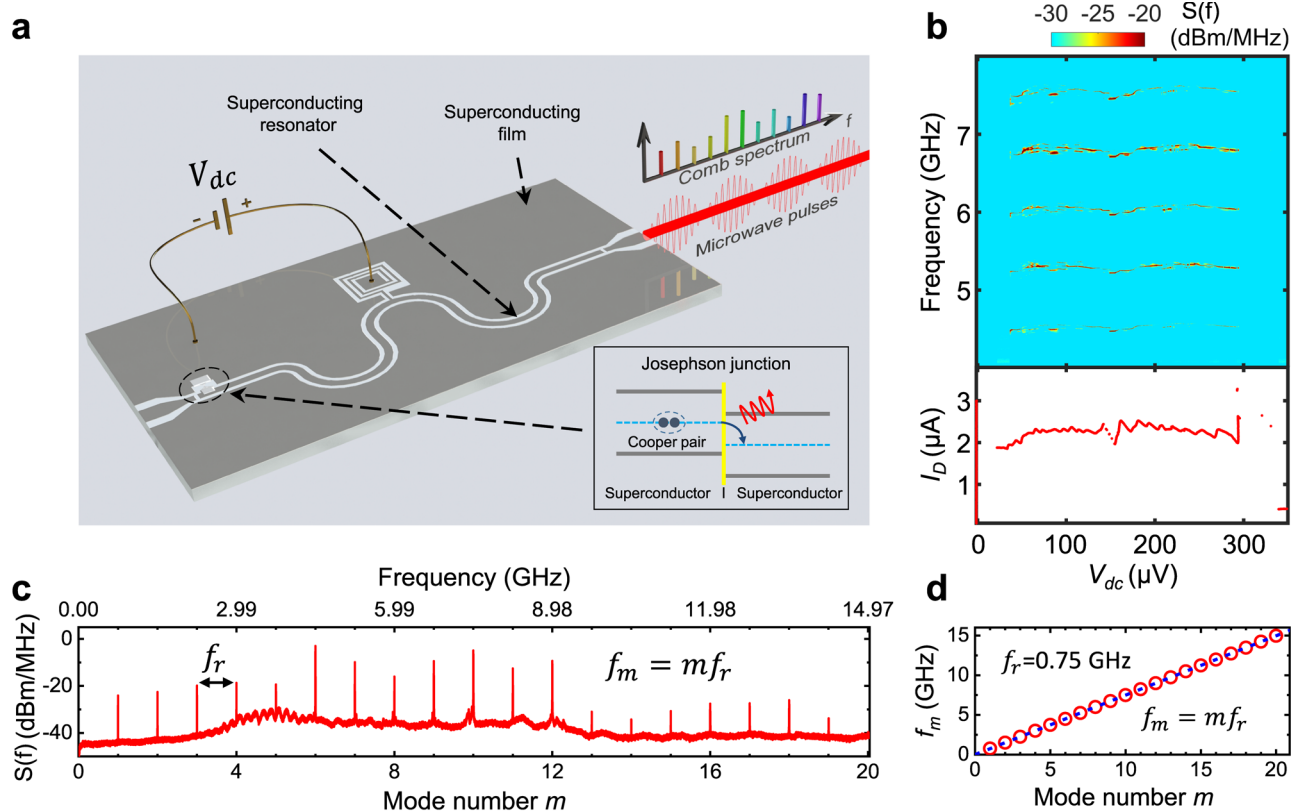


Fig. 1 | Integrated and DC-powered superconducting microcomb. **a** Illustration of the device. Frequency comb emission is generated when a DC voltage-biased (V_{dc}) Josephson junction is coupled to a superconducting CPW resonator. **b** The power spectral density (top) and flowing supercurrent through the Josephson

junction (bottom) as a function of DC bias voltage. **c** Frequency comb spectrum obtained at $V_{dc} = 43 \mu\text{V}$. **d** Extracted emission frequencies (open dots) from (c). The dashed line represents fitting to the comb formula $f_m = m f_r$.

evaporation techniques (See Methods). The Josephson junction consists of two superconductors connected by a weak link or a thin insulating barrier. It acts as an ideal voltage-to-frequency converter, emitting photons at the Josephson frequency $f_J = 2eV_{dc}/h$, where $2e$ is the charge of a Cooper pair, V_{dc} is the DC voltage bias across the junction, and h is Planck's constant. Meanwhile, the superconducting CPW resonator is another crucial superconductor device widely used in high-sensitive detectors and circuits for qubit control and read-out¹⁹. We demonstrate that the combination of these two fundamental superconducting elements can generate a coherent frequency comb (Fig. 1b, c). Its on-chip generation of pulse waves and inherent compatibility with production, operation, and integration into circuit quantum electrodynamics^{20–22} offers the potential for miniaturized, low-cost, and energy-efficient quantum processors.

The Josephson junction-coupled superconducting resonator has drawn significant research interest due to its capability not only to operate as ultrasensitive sensors, such as for single photon detection²³ and/or thermometry²⁴, but also to function as a coherent photon source^{25–34}. Particularly, in the strong coupling regime, the device generates stable microwave lasing²⁵ and demonstrates remarkably low noise²⁶. However, in previous investigations, the coupled devices were all operated in single mode, resulting in continuous-wave emissions. Their properties under a multimode operation have not been explored.

Results

Coherent comb generation

We demonstrate that a Josephson junction coupled to a superconducting resonator can generate a self-phase-locked coherent

frequency comb under multimode operation. The coupling between a Josephson junction and a resonator is proportional to the Josephson energy $E_J h I_c / 2e$, where I_c is superconducting critical current^{25,28}. To directly ensure strong coupling, we employ a Josephson junction with a large I_c . This is achieved by fabricating a sizable Josephson junction (approximately $4 \mu\text{m}^2$), resulting in a relatively large supercurrent of $I_D \approx 2 \mu\text{A}$ in the lasing state (Fig. 1b), which surpasses by more than two orders of magnitude compared to that in the continuous-wave Josephson laser²⁵. To achieve multimode operation within the frequency range of interest (typically 1–10 GHz), we fabricate a superconducting resonator with a low free spectrum range of 0.75 GHz. The strong coupling allows stable microwave lasing when a dc voltage bias $V_{dc} 20 \mu\text{V}$ is applied to the Josephson junction (Fig. 1b).

Figure 1c shows the comb spectrum measured at $V_{dc} = 43 \mu\text{V}$. First, we will prove that the observed spectrum in Fig. 1c indeed represents a coherent frequency comb. The raised background between 3–10 GHz in Fig. 1c is a consequence of the limited bandwidth of amplifiers. Therefore, our subsequent investigations will focus on the frequency range in the detection bandwidth. The frequencies of a comb are given by the formula: $f_m = f_0 + m f_r$, where f_0 denotes the carrier offset frequency, f_r represents the repetition frequency, and m stands for the mode number^{1–5}. The extracted mode frequencies are shown in Fig. 1d, align perfectly with fitting to the comb formula. The result indicates a negligible offset frequency ($f_0 \approx 0$ GHz). Consequently, our superconducting microcomb can be expressed by a simplified comb formula:

$$f_m = m f_r \quad (1)$$

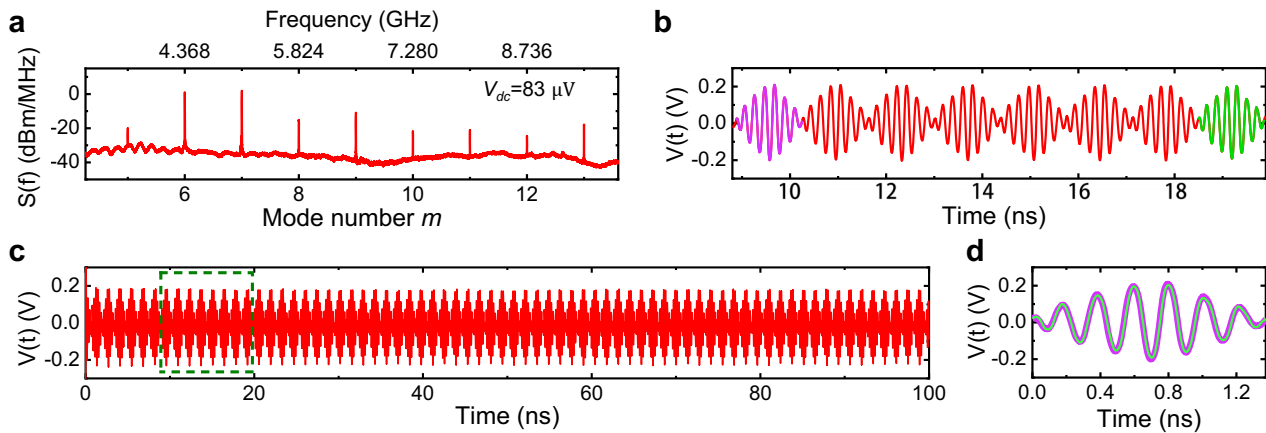


Fig. 2 | Coherent pulse-wave. **a** Comb spectrum obtained at $V_{dc} = 83 \mu\text{V}$. **b–d** Pulse waveforms corresponding to the spectrum in **(a)**. The zoom-in waveform **(b)** of the region enclosed by the green-dashed box in **(c)** displays two highlighted pulse waves with purple and green, which overlap perfectly in **(d)**.

Additionally, Fig. 1c, d demonstrate that the repetition frequency f_r nicely aligns with the free spectrum range (0.75 GHz) of the half-wave resonator.

The evenly spaced spectral lines alone are not sufficient for correlations among the comb teeth. To examine the coherence state of the emitted signal, we first proved that each individual mode has a stable phase using the heterodyne detection technique (Supplementary Fig. 2). One direct consequence of phase-coherent comb is the generation of pulses in the time domain^{1–5}. Figure 2a displays a comb spectrum, and its corresponding time-dependent waveform is shown in Fig. 2b, c. The waveform reveals a sequence of microwave pulses, indicating that all spectrum modes are phase-locked and maintain a stable phase relationship. Moreover, every pulse displays identical features, as seen in Fig. 2d by the perfect overlap of two pulse waves. This indicates that all pulses are in-phase, and also suggests a carrier offset frequency of 0 Hz, thus confirming that all the spectral lines share a uniform phase. The coherence of the comb modes can be further validated through a unique coherent injection-locking effect, as demonstrated below.

The emission power of each individual comb line, ranging up to subpicowatt (see Supplementary Fig. 3), is consistent with that of the continuous-wave (or single-mode) source²⁵. The microcomb's performance could be further enhanced by refining the structures and parameters of the Josephson junction-coupled resonators²⁶. The stability of the frequency comb is determined by the linewidth of the spectral lines (see Supplementary Fig. 4). In general, the overall linewidth is influenced by the quality factor of the resonator, the stability of the DC bias voltage, and environmental electromagnetic and thermal noise. Moreover, our experiments demonstrate that the linewidth of our comb increases quadratically with the mode number (or frequency), as illustrated in Supplementary Fig. 5. This finding is consistent with the observations in quantum-limited optical combs^{35,36}.

Coherent injection-locking effect

Injection-locking is a widely used technique for effectively narrowing the linewidth of a laser source^{25,26,37,38}. In optical frequency combs, it has been demonstrated only in a few cases in quantum cascade lasers by injecting a radio-frequency (RF) modulation at the cavity roundtrip frequency^{39–42}. In our superconducting microcomb, we showcase a distinct coherent injection-locking effect that can be achieved by injecting an external microwave at any arbitrary comb mode. For instance, we select an arbitrary mode, such as $m_{inj} = 7$, as the injection tone (Fig. 3a). Then, an injection signal f_{inj} is applied and swept around $f_7 = 5.26$ GHz. We measure the spectra at frequencies f_{sen} around various sensing modes m_{sen} (Fig. 3a). The resulting spectra maps are illustrated in Fig. 3b–d (additional results in Supplementary Fig. 6).

We find that all modes are simultaneously locked within the same injection frequency range $\Delta f_{inj} = 8.08$ MHz (see Fig. 3b, d for definition and Fig. 3k for extracted values). This reaffirms that all spectral lines are coherently phase-locked.

This unique coherent injection-locking effect results in an ultra-high-resolution comb, with the linewidth of all comb teeth significantly narrowed down to ≤ 1 Hz, as shown in Fig. 3e–g and their insets. It's worth noting that the observed linewidth of 1 Hz is constrained by the resolution bandwidth of the spectrum analyzer used in the experiments²⁶, implying the potential for even narrower linewidths.

The injection-locking range Δf_{inj} of our microcomb widens with the injection power P_{inj} (Supplementary Fig. 7). Specifically, when $m_{sen} = m_{inj}$ (Fig. 3c, f, i), the injection-locking phenomena replicate those observed in the continuous-wave source^{25,26}, and can therefore be explained by the Adler's theory⁴³. However, the results for the comb modes with $m_{sen} \neq m_{inj}$ cannot be described by Adler's equation (see Supplementary Fig. 8a, b). We find that the locked sensing frequency range Δf_{sen} (see Fig. 3b–d for definition) is proportional to m (Fig. 3l). This implies that the radiation frequencies of the injection-locked comb satisfy the comb formula (1) over the entire locked frequency range. Consequently, this introduces an in-situ tunable superconducting microcomb, allowing for adjustable f_r within the range of $\Delta f_{inj}/m_{inj}$.

The coherent injection-locking leads to a unique frequency-pulling effect, particularly noticeable when $m_{sen} \neq m_{inj}$. Figure 3h–j illustrate these effects when f_{inj} is fixed at an off-resonance tone (the corresponding on-resonance injection results are shown in Supplementary Fig. 9), shifted from the free-running emission tone by $\Delta f_{off} = 8$ MHz. When $m_{sen} = m_{inj}$, the emission line is gradually pulled toward f_{inj} with increasing injection power P_{inj} , ultimately locking at f_{inj} (Fig. 3i). This behavior mirrors that observed in a continuous-wave source^{25,26}. However, the remarkable outcome arises when $m_{sen} \neq m_{inj}$. In this case, although no injection tone is applied around each sensing mode, notable emission lines are induced at the corresponding tones, termed “induced-injection tone” and labeled as f_{id} in Fig. 3b, d, h, 3j. The linewidth of the f_{id} lines is considerably narrower than those of the free-running emissions and the side-band harmonics (see Supplementary Fig. 10). Furthermore, neither f_{id} emission nor Kerr comb generation are observed with RF injection under zero DC bias voltage (Supplementary Fig. 11). These indicate that the f_{id} emissions originate from the mutual interactions among Josephson photons, injection photons, and the resonator's multi-modes, setting the f_{id} signals apart from the Kerr combs generated directly from RF pumping⁴⁴.

When $m_{sen} \neq m_{inj}$, as depicted in Fig. 3h, j, while the emissions of all the modes are pulled toward f_{id} tones with increasing P_{inj} , the f_{id} tones themselves also shift with P_{inj} . Consequently, this results in the locked

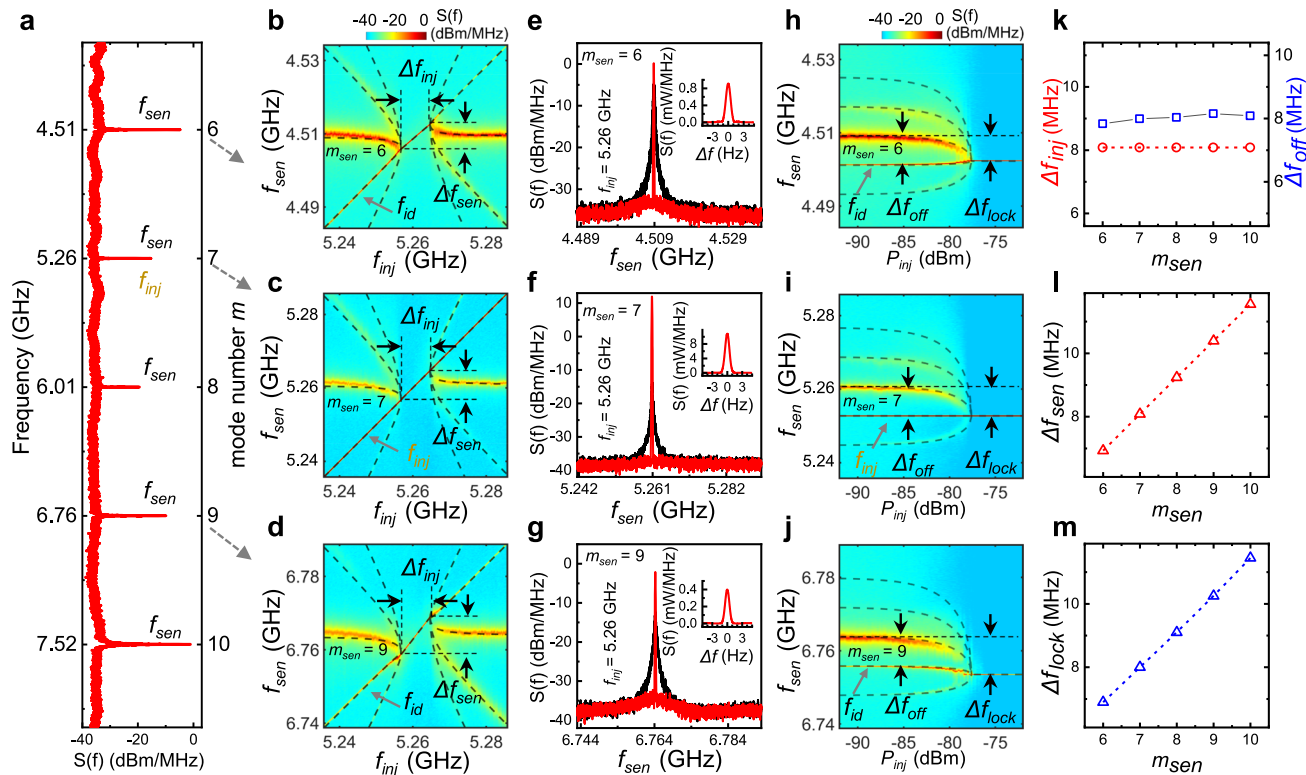


Fig. 3 | Coherent injection-locking effect. **a** A comb spectrum showing five observed modes. **b–d** Spectrum maps obtained by sweeping the injection frequency f_{inj} around f_j at a fixed power ($P_{inj} = -82$ dBm), and at various sensing modes $m_{sen} = 6$ (**b**), 7 (**c**), and 9 (**d**), respectively. The emission signals are locked within the range Δf_{inj} and Δf_{sen} . **e–g** Comparison of spectra between free-running (black) and injection-locking (red) states. Insets show the linewidth, which is ≤ 1 Hz for all locked

modes. **h–j** Spectra maps obtained by varying injection power (P_{inj}) with an off-resonance tone ($f_{inj} = f_j - \Delta f_{off}$, $f_j = 5.26$ GHz, $\Delta f_{off} = 8$ MHz). The shifts of the locked tone from the free-running tones are indicated by Δf_{lock} . The long-dashed lines in (**b–d**, **h–j**) are fittings to extended Adler’s Eq. (2). **k–m** Plots of Δf_{inj} and Δf_{off} (**k**), Δf_{sen} (**l**), and Δf_{lock} (**m**) as functions of mode number m .

frequency range $\Delta f_{lock} \neq \Delta f_{off}$ (see Fig. 3h, j). Figure 3m demonstrates that Δf_{lock} is also proportional to m with $\Delta f_{lock} = \frac{m}{m_{inj}} \Delta f_{off}$, perfectly aligned with the requirements of the comb formula (1) for the emissions within the locking range.

There is no existing theory that can describe our observed coherent injection-locking effect. We have derived an extended Adler’s equation to quantitatively describe these unique phenomena. As analyzed above, in the locking range Δf_{inj} , all comb emissions are described by the comb formula (1). In the unlocking range outside Δf_{inj} , the emission signals are given by (please refer to Method for detailed derivation):

$$f_{m,n} = \frac{m}{m_{inj}}(f_{inj} + f_h) + nf_h \quad (2)$$

Here, f_h denotes the repetition frequency of the harmonic emissions induced by off-resonance injection, and nf_h represents the n th harmonic shift. The f_h is given by:

$$f_h = (f_{m_{inj}} - f_{inj}) \sqrt{1 - \left(\frac{\Delta f_{inj}/2}{f_{m_{inj}} - f_{inj}} \right)^2} \quad (3)$$

where $\Delta f_{inj} = \alpha \sqrt{P_{inj}}$ (with α as a constant related to cavity losses), and $f_{m_{inj}}$ is the mode frequency at m_{inj} . Notably, when $m = m_{inj}$, the extended Adler’s Eq. (2) reduces to the standard Adler’s equation. The perfect fittings in Fig. 3b–d, 3h–j indicate that our extended Adler’s Eq. (2) accurately describes all the coherent injection-locking effects in our superconducting microcomb.

In previous studies of continuous-wave superconducting lasers, the downconversion of higher-order Josephson frequencies to the resonator’s fundamental mode has been demonstrated²⁵. However, the upconversion of Josephson photons to higher mode has not been reported. In Fig. 4a, we present a comb spectrum (red) within our typical experimental bandwidth of 3–10 GHz. The applied DC bias voltage across the Josephson junction is $V_{dc} = 36.387$ μ V, corresponding to a Josephson frequency $f_j = 17.60$ GHz. As illustrated in Fig. 4a, all the comb modes with $f_m < f_j$ are generated through downconversion, and any modes with $f_m > f_j$ (if existing) would result from upconversion. However, emissions with $f_m > 17.60$ GHz lie beyond the bandwidth of our spectrum measurements, preventing their direct observation.

The coherent injection-locking effect provides an advanced methodology for sensing comb emissions beyond the detection bandwidth. To demonstrate this, we perform injection-locking measurements using various injection tones with $m_{inj} = 1, 6, 54$, as illustrated in Fig. 4a, while selecting a fixed sensing tone within the detection bandwidth, such as $m_{sen} = 7$. Figures 4b–d display the coherent injection-locking effects. The injection-locking phenomenon arises from the nonlinear interaction between emission tone and external injection signal⁴³. Since no injection signal is applied at $m = 7$, the coherence injection-locking effect displayed in Fig. 4d suggests the presence of a comb emission tone at $f_{s4} = 39.28$ GHz, which is significantly higher than the Josephson frequency $f_j = 17.6$ GHz. This observation provides evidence for the upconversion process of Josephson photons to higher modes. The presence of comb emissions at $m = 1$ (Fig. 4b) and 54 (Fig. 4d) indicates that our Josephson

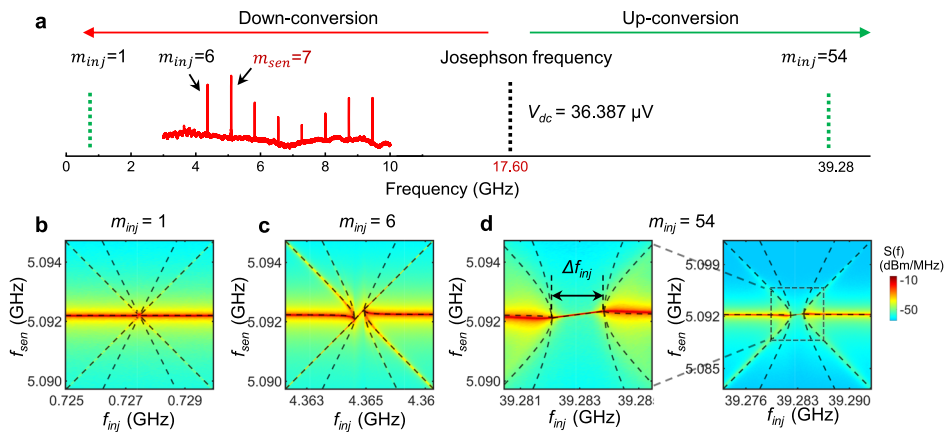


Fig. 4 | Up- and down-conversion of Josephson photons into multiple modes. **a** Illustration of the up- and down-conversion. A comb spectrum (red) is obtained at $V_{dc} = 36.39 \mu\text{V}$, corresponding to a Josephson frequency of 17.6 GHz. **b–d** Coherent

injection-locking effects with $m_{sen} = 7$ and for injections at $m_{inj} = 1$ (**b**), 6 (**c**), and 54 (**d**), respectively. The dashed lines are fittings to extend Alder's Eq. (2).

microcomb spans a frequency range exceeding five octaves, a span typically challenging to achieve in semiconductor-based frequency combs. It is essential to note that this octave value is limited by the upper-frequency limit of the microwave generator used in our experiments. Hence, it is highly likely that even higher modes could exist beyond this range.

Discussion

We have demonstrated a fully integrable superconducting microcomb. Unlike previously reported superconductor-based frequency combs^{44–52}, which all operated under microwave pumping using externally supplied, expensive, and energy-consuming microwave sources, our superconducting microcomb is driven solely by a DC bias voltage. This makes it highly desirable for scalable and on-chip integration. The initiation of our microcomb requires simply tuning on a low-power DC bias source, with a minimal input power as low as 40 pW (Fig. 1b)—approximately nine orders of magnitude lower than the semiconductor-based frequency combs. This presents significant advancement for ultrasensitive and energy-efficient applications.

The exceptional coherence of our comb enables a unique coherent injection-locking effect previously inaccessible in frequency combs, leading to an ultra-high-resolution and tunable comb. This innovation introduces unique functionalities, such as the generation of coherent subcombs through four-wave mixing, as showcased in Supplementary Fig. 12. The simultaneous up- and down-conversion of Josephson photons significantly expands the comb's frequency range over multiple octaves. These capabilities offer added flexibility and tunability for applications of superconducting microcomb technology.

This DC-biased superconducting microcomb with ultra-low power consumption (down to a few tens of picowatts) can work at ultra-low temperatures, aligning seamlessly with the operating conditions of superconducting quantum circuits. For a typical dilution refrigerator, which has a cooling power of hundreds of microwatts at 20 mK, in principle, it is feasible to integrate up to millions of the combs at the base temperature based on their energy efficiency. Our comb can serve as a multifrequency microwave source for multiplexed quantum measurement⁵³. An important potential application of our superconducting microcomb is the development of a low-cost, on-chip arbitrary waveform generator. This could be achieved by controlling the intensities of the comb teeth⁵⁴, which is possible by integrating our superconducting comb with a series of frequency-tunable superconducting resonators serving as adjustable filters⁵⁵. This advancement promises substantial benefits for future quantum technologies. Moreover, implementing superconducting frequency combs

in the terahertz domain could be feasible by using intrinsic Josephson junctions in high-temperature superconductors⁵⁶. This approach could also extend the technology's working temperature range.

Methods

Device fabrication

We fabricated four superconducting microcombs (#1–#4), and detailed parameters are listed in Supplementary Tables 1. The superconducting resonators are fabricated using a superconducting Nb film for device #1 and a Ta (α -phase) film⁵⁷ for devices #2, #3, and #4. The film was sputtered on a 10 mm by 10 mm sapphire substrate (C-plane, thickness 650 μm). Standard photolithography followed by reactive ion etching in a CF₄ was then used to define the resonators. The Al/AlO_x/Al (Al thicknesses 40 nm/80 nm) Josephson junction was fabricated using standard double-angle evaporation and lift-off techniques. To ensure good electrical contact between the Josephson junction and the resonator layers, the sample was ion-beam milled to remove residual oxides and resist residue from the surface of the resonator before the double-angle evaporation.

Experiments

The devices are mounted in a dilution refrigerator with a base temperature of 20 mK. A complete circuit is shown in Supplementary Fig. 13. We adopt a similar approach to refs. 25,30,31 for the low noise biasing scheme to measure the tunneling current and provide a stable voltage bias to the device. The bias voltage is supplied by an on-chip voltage divider circuit consisting of a 10 Ω shunt resistor and a 10 Ω reference resistor. The current through the device is then measured via the voltage drop V_r across the 10 Ω reference resistor. The current I_D and voltage V_{dc} of the device is given by $I_D = V_r/10$ and $V_{dc} = 10I_{bias} - 20I_D$. Here, V_r is obtained from a nano voltmeter (Keithley 2182 A) and I_{bias} is the output from a current source (Keithley 6221). Additional filtering for the circuit is provided by two 100 μF chip capacitors. Additionally, all low-frequency lines are heavily filtered outside the PCB with multi-pole RC and PI low-pass filters located in the mixing chamber of the dilution refrigerator.

The device's output signal is amplified by an amplifier chain consisting of a cryogenic amplifier (+42 dB) and two room-temperature amplifiers (+32 dB). The spectra are acquired by an Agilent N9010A spectrum analyzer (S/A), and the waveforms are recorded using a Keysight MSOV334A digital oscilloscope (D/O). The injection signal to the resonator is generated by an Agilent N5183A analog signal generator (S/G) and is attenuated by a low-temperature attenuation chain to assure that the thermal contribution of photons to the cavity is negligible.

Extended Adler's equation

In the unlocking range outside Δf_{inj} , the emission signals for $m_{\text{sen}} = m_{\text{inj}}$, which can be described by Adler's theory⁴³, are given by:

$$f_{m_{\text{inj}},n} = (f_{\text{inj}} + f_h) + n f_h \quad (3)$$

where f_h is the repetition frequency of the harmonic emissions. The comb's emission at m_{inj} , $f_{\text{inj}} + f_h$, accounts for the comb's emission at m_{inj} , while $n f_h$ represents the n th harmonic shift. The f_h is given by:

$$f_h = (f_{m_{\text{inj}},0} - f_{\text{inj}}) \sqrt{1 - \left(\frac{\Delta f_{\text{inj}}/2}{f_{m_{\text{inj}},0} - f_{\text{inj}}} \right)^2}$$

where $\Delta f_{\text{inj}} = \alpha \sqrt{P_{\text{inj}}}$ (with α as a constant related to cavity losses). The comb's emission at m_{inj} corresponds to $n = 0$, therefore we obtain $f_{m_{\text{inj}},0} = f_{\text{inj}} + f_h$ from Eq. (3). Utilizing the superconducting microcomb formula (1) (see the main text), we can express the comb's emissions for any arbitrary m as $f_{m,0} = \frac{m}{m_{\text{inj}}} f_{m_{\text{inj}},0} = \frac{m}{m_{\text{inj}}} (f_{\text{inj}} + f_h)$. By adding the n th harmonic shift $n f_h$, we derive an extended Adler's Eq. (2), as shown in the main text, for the coherent injection-locking in our superconducting combs.

Data availability

All the data that support the findings of this study are available on the public repository <https://doi.org/10.6084/m9.figshare.25480621>

References

- Kippenberg, T. J., Holzwarth, R. & Diddams, S. A. Microresonator-based optical frequency combs. *Science* **332**, 555 (2011).
- Picqué, N. & Hänsch, T. W. Frequency comb spectroscopy. *Nat. Photon* **13**, 146–157 (2019).
- Fortier, T. & Baumann, E. 20 years of developments in optical frequency comb technology and applications. *Commun. Phys.* **2**, 153 (2019).
- Diddams, S. A., Vahala, K. & Udem, T. Optical frequency combs: coherently uniting the electromagnetic spectrum. *Science* **369**, 267 (2020).
- Chang, L., Liu, S. & Bowers, J. E. Integrated optical frequency comb technologies. *Nat. Photon* **16**, 95–108 (2022).
- Guo, Q. et al. Ultrafast mode-locked laser in nanophotonic lithium niobate. *Science* **382**, 708–713 (2023).
- Shu, H. et al. Microcomb-driven silicon photonic systems. *Nature* **605**, 457–463 (2022).
- Xiang, C. et al. Laser soliton microcombs heterogeneously integrated on silicon. *Science* **373**, 99–103 (2021).
- Kippenberg, T. J., Gaeta, A. L., Lipson, M. & Gorodetsky, M. L. Dissipative Kerr solitons in optical microresonators. *Science* **361**, 567 (2018).
- Xu, X. et al. 11 TOPS photonic convolutional accelerator for optical neural networks. *Nature* **589**, 44–51 (2021).
- Feldmann, J. et al. Parallel convolutional processing using an integrated photonic tensor core. *Nature* **589**, 52–58 (2021).
- Yang, Q. et al. Vernier spectrometer using counterpropagating soliton microcombs. *Science* **363**, 965–968 (2019).
- Riemensberger, J. et al. Massively parallel coherent laser ranging using a soliton microcomb. *Nature* **581**, 164–170 (2020).
- Stern, B., Ji, X., Okawachi, Y., Gaeta, A. L. & Lipson, M. Battery-operated integrated frequency comb generator. *Nature* **562**, 401–405 (2018).
- Bai, B. et al. Microcomb-based integrated photonic processing unit. *Nat. Commun.* **14**, 66 (2023).
- Shen, B. et al. Integrated turnkey soliton microcombs. *Nature* **582**, 365–369 (2020).
- Jin, W. et al. Hertz-linewidth semiconductor lasers using CMOS-ready ultra-high-Q microresonators. *Nat. Photon* **15**, 346–353 (2021).
- Marpaung, D., Yao, J. & Capmany, J. Integrated microwave photonics. *Nat. Photon* **13**, 80–90 (2019).
- Krantz, P. et al. A quantum engineer's guide to superconducting qubits. *Appl. Phys. Rev.* **6**, 021318 (2019).
- Blais, A., Girvin, S. M. & Oliver, W. D. Quantum information processing and quantum optics with circuit quantum electrodynamics. *Nat. Phys* **16**, 247 (2020).
- Clerk, A. A., Lehnert, K. W., Bertet, P., Petta, J. R. & Nakamura, Y. Hybrid quantum systems with circuit quantum electrodynamics. *Nat. Phys* **16**, 257 (2020).
- Blais, A., Grimsmo, A. L., Girvin, S. M. & Wallraff, A. Circuit quantum electrodynamics. *Rev. Mod. Phys.* **93**, 025005 (2021).
- Golubev, D. S., Il'ichev, E. V. & Kuzmin, L. S. Single-photon detection with a Josephson junction coupled to a resonator. *Phys. Rev. Appl.* **16**, 014025 (2021).
- Saira, O.-P., Zgierski, M., Viisanen, K. L., Golubev, D. S. & Pekola, J. P. Dispersive thermometry with a Josephson junction coupled to a resonator. *Phys. Rev. Appl.* **6**, 024005 (2016).
- Cassidy, M. C. et al. Demonstration of an ac Josephson junction laser. *Science* **355**, 939–942 (2017).
- Yan, C. et al. A low-noise on-chip coherent microwave source. *Nat. Electron* **4**, 885 (2021).
- Astafiev, O. et al. Single artificial-atom lasing. *Nature* **449**, 588–590 (2007).
- Meister, S. et al. Resonators coupled to voltage-biased Josephson junctions: from linear response to strongly driven nonlinear oscillations. *Phys. Rev. B* **92**, 174532 (2015).
- Rolland, C. et al. Antibunched photons emitted by a dc-biased Josephson junction. *Phys. Rev. Lett.* **122**, 186804 (2019).
- Chen, F. et al. Realization of a single-Cooper-pair Josephson laser. *Phys. Rev. B* **90**, 020506(R) (2014).
- Hofheinz, M. et al. Bright side of the Coulomb blockade. *Phys. Rev. Lett.* **106**, 217005 (2011).
- Grimm, A. et al. Bright on-demand source of antibunched microwave photons based on inelastic Cooper pair tunneling. *Phys. Rev. X* **9**, 021016 (2019).
- Simon, S. H. & Cooper, N. R. Theory of the Josephson junction laser. *Phys. Rev. Lett.* **121**, 027004 (2018).
- Danner, L., Padurariu, C., Ankerhold, J. & Kubala, B. Injection locking and synchronization in Josephson photonics devices. *Phys. Rev. B* **104**, 054517 (2021).
- Newbury, N. R. & Swann, W. C. Low-noise fiber-laser frequency combs. *J. Opt. Soc. Am. B* **24**, 1756–1770 (2007).
- Liehl, A. et al. Deterministic nonlinear transformations of phase noise in quantum-limited frequency combs. *Phys. Rev. Lett.* **122**, 203902 (2019).
- Liu, Y.-Y., Stehlik, J., Gullans, M. J., Taylor, J. M. & Petta, J. R. Injection locking of a semiconductor double-quantum-dot micromaser. *Phys. Rev. A* **92**, 053802 (2015).
- Liu, Y.-Y., Hartke, T. R., Stehlik, J. & Petta, J. R. Phase locking of a semiconductor double-quantum-dot single-atom maser. *Phys. Rev. A* **96**, 053816 (2017).
- Hillbrand, J., Andrews, A. M., Detz, H., Strasser, G. & Schwarz, B. Coherent injection locking of quantum cascade laser frequency combs. *Nat. Photon* **13**, 101–104 (2018).
- Gellie, P. et al. Injection-locking of terahertz quantum cascade lasers up to 35 GHz using RF amplitude modulation. *Opt. Express* **18**, 20799–20816 (2010).
- Barbieri, S. et al. Coherent sampling of active mode-locked terahertz quantum cascade lasers and frequency synthesis. *Nat. Photon* **5**, 306–313 (2011).

42. St-Jean, M. R. et al. Injection locking of mid-infrared quantum cascade laser at 14 GHz, by direct microwave modulation. *Laser Photon. Rev.* **8**, 443–449 (2014).
43. Adler, R. A study of locking phenomena in oscillators. *Proc. IRE* **34**, 351–357 (1946).
44. Erickson, R. P., Vissers, M. R., Sandberg, M., Jefferts, S. R. & Pappas, D. P. Frequency comb generation in superconducting resonators. *Phys. Rev. Lett.* **113**, 187002 (2014).
45. Wang, S.-P., Chen, Z. & Li, T. Controllable microwave frequency comb generation in a tunable superconducting coplanar-waveguide resonator. *Chin. Phys. B* **30**, 048501 (2021).
46. Lu, P. et al. Nearly quantum-limited Josephson-junction frequency-comb synthesizer. *Phys. Rev. Appl.* **15**, 044031 (2021).
47. Shin, J. et al. On-chip microwave frequency combs in a superconducting nanoelectromechanical device. *Nano Lett.* **22**, 5459–5465 (2022).
48. Wu, S. et al. Hybridized frequency combs in multimode cavity electromechanical system. *Phys. Rev. Lett.* **128**, 153901 (2022).
49. Han, X. et al. Superconducting cavity electromechanics: the realization of an acoustic frequency comb at microwave frequencies. *Phys. Rev. Lett.* **129**, 107701 (2022).
50. Khan, S. & Türeci, H. E. Frequency combs in a lumped-element Josephson-junction circuit. *Phys. Rev. Lett.* **120**, 153601 (2018).
51. Solinas, P., Gasparinetti, S., Golubev, D. & Giazotto, F. A Josephson radiation comb. *Sci. Rep.* **4**, 12260 (2015).
52. Ilin, D., Poshakinskiy, A. V., Poddubny, A. N. & Iorsh, I. Frequency combs with parity-protected cross-correlations and entanglement from dynamically modulated qubit arrays. *Phys. Rev. Lett.* **130**, 023601 (2023).
53. Essig, A. et al. Multiplexed photon number measurement. *Phys. Rev. X* **11**, 0311045 (2021).
54. Cundiff, S. T. & Weiner, A. M. Optical arbitrary waveform generation. *Nat. Photon* **4**, 760–766 (2010).
55. Strickland, W. M. et al. Superconducting resonators with voltage-controlled frequency and nonlinearity. *Phys. Rev. Appl.* **19**, 034021 (2023).
56. Ozyuzer, L. et al. Emission of coherent THz radiation from superconductors. *Science* **318**, 1291–1293 (2007).
57. Shi, L. et al. Tantalum microwave resonators with ultra-high intrinsic quality factors. *Appl. Phys. Lett.* **121**, 242601 (2022).

Acknowledgements

This work is supported by the National Key R&D Program of China (2021YFA0718802 (Y.-Y.L., Y.-L.W., and H.W.), 2018YFA0209002 (Y.-L.W.), and 2023YFF0718400 (Y.D.)), the National Natural Science Foundation of China (62274086 (Y.L.W.), 62288101 (H.W.), 12204434(Y.D.), and 62271245 (X.T.)), Postdoctoral Fellowship Program of CPSF (W.-C.Y. and Y.-Y.L.), Jiangsu Outstanding Postdoctoral Program (W.-C.Y. and Y.-Y.L.), Shenzhen Science and Technology Program

(KQTD20200820113010023 (X.D.)), and Jiangsu Key Laboratory of Advanced Techniques for Manipulating Electromagnetic Waves.

Author contributions

Y.L.W., H.W., and P.W. conceived and supervised the project. C.-G.W. designed and fabricated the devices, as well as conducted the experiments. L.S., J.J., T.G., C.C., X.J., and J.C. provided support for the fabrication of resonators. T.L., Y.-Y.L., and G.S. assisted in the fabrication of Josephson junctions. W.X., C.L., W.-C.Y., X.T., and L.K. provided support for optical lithography. W.X., S.D., P.Z., Y.-Y.L., J.P., and L.Z. assisted in microwave spectrum and waveform measurements. C.G.W. and Y.L.W. performed the analysis and interpretation of the experimental data. C.-G.W., X.D., Y.D., and Y.-L.W. conducted the theoretical analysis. C.-G.W. and Y.-L.W. wrote the manuscript. Y.-L.W. and H.W. edited the manuscript.

Competing interests

The authors declare no competing interests.

Additional information

Supplementary information The online version contains supplementary material available at <https://doi.org/10.1038/s41467-024-48224-1>.

Correspondence and requests for materials should be addressed to Yong-Lei Wang, Huabing Wang or Peiheng Wu.

Peer review information *Nature Communications* thanks David Pappas, and the other, anonymous, reviewer(s) for their contribution to the peer review of this work. A peer review file is available.

Reprints and permissions information is available at <http://www.nature.com/reprints>

Publisher's note Springer Nature remains neutral with regard to jurisdictional claims in published maps and institutional affiliations.

Open Access This article is licensed under a Creative Commons Attribution 4.0 International License, which permits use, sharing, adaptation, distribution and reproduction in any medium or format, as long as you give appropriate credit to the original author(s) and the source, provide a link to the Creative Commons licence, and indicate if changes were made. The images or other third party material in this article are included in the article's Creative Commons licence, unless indicated otherwise in a credit line to the material. If material is not included in the article's Creative Commons licence and your intended use is not permitted by statutory regulation or exceeds the permitted use, you will need to obtain permission directly from the copyright holder. To view a copy of this licence, visit <http://creativecommons.org/licenses/by/4.0/>.

© The Author(s) 2024