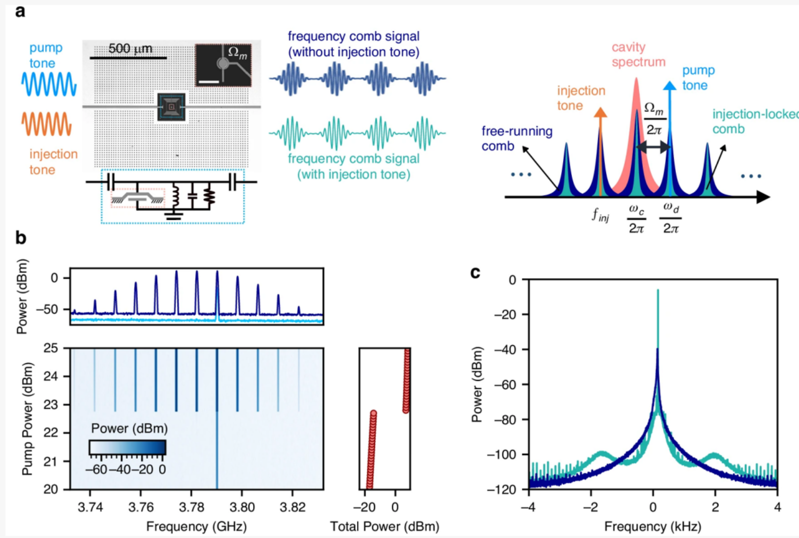
From fluctuations to precision: Injection locking boosts microwave comb stability

FAYETTEVILLE, GA, UNITED STATES, February 7, 2026 /EINPresswire.com/ -- Microwave [frequency combs](#) offer a powerful platform for precision timing, sensing, and signal processing, but their practical use has long been limited by intrinsic frequency fluctuations and phase noise. A new study demonstrates that the performance of microwave frequency combs generated in optomechanical systems can be dramatically improved by applying a injection locking strategy. By introducing an additional coherent tone near selected comb peaks, the researchers show that the entire comb spectrum can be synchronized, leading to a substantial enhancement in frequency stability. The work not only reveals previously unexplored nonlinear locking behaviors but also establishes a robust method for stabilizing microwave combs, opening new opportunities for ultra-stable signal generation in demanding environments.



Optomechanical generation of a microwave frequency comb and its injection locking.

Frequency combs—spectra composed of evenly spaced frequency lines—are indispensable tools in modern metrology, communications, and quantum technologies. While optical frequency combs are now widely deployed, their microwave counterparts have been less explored, requiring further development of techniques for comb stabilization. Optomechanical systems, which couple electromagnetic fields to mechanical motion, naturally produce microwave frequency combs under strong driving conditions. However, these combs tend to suffer from long-term frequency drift, excess phase noise, and sensitivity to environmental perturbations. Stabilization of optomechanical combs has so far been mostly demonstrated in the optical domain, which has imposed technical limitations for exploring stabilization methods. Based on these challenges, there is a strong need to develop advanced stabilization strategies for optomechanical frequency combs using new device platforms.

Researchers at the Korea Research Institute of Standards and Science, led by Jinwoong Cha, report stabilization of microwave frequency combs in a niobium-based superconducting optomechanical circuit. The study, published (DOI: 10.1038/s41378-025-01085-0) online on 24 November 2025 in Microsystems & Nanoengineering, demonstrates that sideband injection locking—achieved by introducing a weak external microwave tone near selected comb lines—can synchronize the entire comb spectrum. The approach significantly reduces frequency fluctuations and phase noise, marking a major step toward practical, high-stability microwave comb sources.

In the experiment, microwave frequency combs were generated by strongly driving the superconducting optomechanical circuit with a blue-detuned pump tone, pushing the system into a regime of self-sustained mechanical oscillation. This oscillation periodically modulates the cavity resonance, producing a series of equally spaced microwave spectral lines. To stabilize these combs, the team injected an additional microwave tone close to specific comb peaks and carefully tracked how the system responded as the injection frequency and power were varied.

The results revealed a rich and unconventional locking behavior. When the injection tone approached a comb peak, the peak was first pulled toward the injection frequency and then fully locked, synchronizing the repetition rate of the entire comb. Notably, the locking range depended strongly on both the sweep direction and the spectral position of the injection tone, leading to pronounced hysteresis effects. Such behavior could not be explained by existing the locking models based on the Kerr- nonlinearity.

Through numerical simulations, the researchers identified mechanical nonlinearity—specifically a cubic stiffening effect—as the key factor responsible for the broadened and asymmetric locking ranges. Importantly, stability measurements showed that injection locking reduced long-term frequency fluctuations by up to three orders of magnitude and suppressed phase noise by around 30 dBc/Hz at low offset frequencies. Together, these findings also demonstrate that mechanical nonlinearities can be harnessed as a resource rather than a limitation for comb stabilization.

“Frequency stability is the defining requirement for any practical frequency comb,” said the study’s corresponding author. “What surprised us was how strongly mechanical nonlinearity shaped the locking behavior. Instead of degrading performance, it actually expanded the locking range and enhanced stability. This shows that optomechanical systems can be engineered to achieve levels of control previously thought difficult in the microwave domain. Our work provides both experimental evidence and theoretical understanding that will be valuable for designing next-generation stable microwave combs.”

The demonstrated injection-locking strategy has wide-ranging implications for technologies that rely on ultra-stable microwave signals. Potential applications include on-chip microwave references, cryogenic timing systems, and low-noise pulse sources for quantum computing and sensing. Because the technique is compatible with MEMS, and NEMS platforms coupled to microwave and optical resonators, it could be implemented across a broad range of operating temperatures, including room temperature and deep cryogenic environments. For quantum applications, stabilized microwave combs from such superconducting optomechanical devices could provide compact, cryogenic platforms for qubit control and readout with enhanced system integration. More broadly, the work highlights a new pathway for exploiting nonlinear dynamics to enhance precision in nanoscale signal-generation systems

References
DOI
10.1038/s41378-025-01085-0

Original Source URL
https://doi.org/10.1038/s41378-025-01085-0

Funding Information
This work was supported by the National Research Foundation of Korea (NRF) grant (RS-2022-NR072112), the National Research Council of Science & Technology (NST) grant (No. CAP21034-000), Institute for Information Communications Technology Planning & Evaluation (IITP) grant (No. RS-2025-02219093), and the Korea Research Institute of Standards and Science (GP2025-0010-03) funded by the Korea government (MSIT).

Lucy Wang
BioDesign Research
email us here
