Optical frequency combs—coherent light sources that connect optical frequencies with microwave oscillations—have become the enabling tool for precision spectroscopy, optical clockwork, and attosecond physics over the past decades. Current benchmark systems are self-referenced femtosecond mode-locked lasers, but Kerr nonlinear dynamics in high-Q solid-state microresonators has recently demonstrated promising features as alternative platforms. The advance not only fosters studies of chip-scale frequency metrology but also extends the realm of optical frequency combs. We report the full stabilization of chip-scale optical frequency combs. The microcomb’s two degrees of freedom, one of the comb lines and the native 18-GHz comb spacing, are simultaneously phase-locked to known optical and microwave references. Active comb spacing stabilization improves long-term stability by six orders of magnitude, reaching a record instrument-limited residual instability of 3.6 mHz/√Hz. Comparing 46 nitride frequency comb lines with a fiber laser frequency comb, we demonstrate the unprecedented microcomb tooth-to-tooth relative frequency uncertainty down to 50 mHz and 2.7 × 10⁻¹⁶, heralding novel solid-state applications in precision spectroscopy, coherent communications, and astronomical spectroscopy.

**INTRODUCTION**

High-Q microresonators (1), by efficiently trapping photons in wavelength-scale structures for as long as microseconds, greatly enhance the light-matter interaction and enable novel studies in a wide range of fields, including cavity quantum electrodynamics (2), parity-time symmetry breaking (3), single-molecule detection (4), and dynamical nonlinear science (5, 6). Moreover, continuous-wave-pumped high-Q microresonators have recently emerged as promising alternative platforms for ultrashort pulse and optical frequency comb generation (7–11). Combs spacing uniformity of microresonator-based optical frequency combs, or Kerr microcombs, has been studied either by comparison with a fiber laser frequency comb (FFC) (12) or by parametric comb folding technique (13). Full comb stabilization has been demonstrated in a silica microtoroid with a free spectral range of 86 GHz (14), and f·2f or 2f·3f comb self-referencing techniques have been applied to these whispering gallery mode (WGM) microresonators (15). Kerr microcombs are unique in their compact footprints and suitably large comb spacings, thereby expanding the already remarkable applications of frequency comb metrology. Microresonators with microwave free spectral ranges have recently been advanced in both WGM structures (16–19) and planar ring geometries (20–22). Although complementary metal-oxide semiconductor (CMOS)–compatible ring resonators are particularly attractive because of their monolithic electronic and photonic integration capabilities, to date, there has been no demonstration of the full stabilization of these chip-scale planar microresonators.

Here, we report the first fully stabilized CMOS-compatible chip-scale Kerr microcomb with a frequency relative uncertainty of 2.7 × 10⁻¹⁶. The silicon nitride spiral resonator is designed and fabricated to generate a Kerr microcomb, at 18-GHz native spacing and spanning more than 8 THz over more than 400 comb lines. The comb’s two degrees of freedom, one of the comb line frequencies and the comb spacing, are phase-locked to a known optical reference and a microwave synthesizer, respectively. Active stabilization on the comb spacing improves the radio-frequency (RF) stability by six orders of magnitude, reaching a residual instrument-limited close-to-carrier (10 Hz) phase noise of −70 dBc/Hz and an Allan deviation of 3.6 mHz/√τ. In the optical frequency, 46 lines of the Kerr microcomb subset are selected and compared against the current benchmark FFC, and the frequency relative uncertainty of the stabilized Kerr microcomb is demonstrated down to 50 mHz. The reported system is a promising compact platform for coherent Raman spectroscopy (23), optical clockwork (24, 25), coherent communications (26), arbitrary waveform generation (27), and astrophysical spectroscopy (28–30).

**RESULTS**

Figure 1A shows the experimental setup for the generation and stabilization of the Kerr microcomb. The silicon nitride spiral resonator is fabricated with CMOS-compatible processes, and the waveguide cross section is designed to have small and flattened group velocity dispersion for broadband comb generation. Planar ring geometry is used because of the reduced sensitivity to environmental perturbation, along with the fewer discrete transverse resonator modes, and the flexibility to tailor the cavity dispersion for efficient and broadband comb generation. Properties of the Si₃N₄ microresonator are detailed in section SI. The loaded quality factor Q of the pump mode is 660,000 (intrinsic Q, ~1,300,000), and 1 W of pump power is critically coupled to the microresonator, resulting in a maximum coupled pump power five times higher than the threshold pump power. The output is first short-pass-filtered using a 1550/1590-nm wavelength division multiplexer and then boosted in power with a 13-dBm C-band preamplifier to increase the signal-to-noise ratio (SNR) of the photodetector signal. Figure 1B shows the Kerr microcomb spectrum, spanning more than 8 THz and consisting of more than 400 comb lines. To ensure that the Kerr microcomb is
driven from a noisy state to a phase-locked state (22) and to verify that it does not consist of many sub-comb families with offsets (31, 32), we monitored RF amplitude noise and the fundamental beat note of different filtered Kerr microcomb segments, with details shown in sections SII and SIII.

For stabilization of the Kerr microcomb, one of the comb lines and the comb spacing are phase-locked to a known optical reference and a microwave synthesizer, respectively. In our system, the known optical reference is derived from an approximately 200-Hz stabilized erbium fiber (Menlo Systems), which is also used as a calibration standard to assess the uncertainty of the Kerr microcomb. A rubidium-locked diode laser can also be used as the optical reference (33, 34), with details presented in section SV.

In Fig. 1A, 1% of the pump mode, which is also the strongest Kerr microcomb line, is tapped and beat with the optical reference on a photodetector. To ensure that the beat note has sufficient SNR for reliable feedback stabilization [more than 35 dB with a 100-kHz resolution bandwidth (RBW)], we built a 0.2-nm narrow-bandwidth monochromator to filter the FFC before it is beat with the pump. Figure 2A is the free-running beat note, showing a few megahertz of pump frequency drift in 1 s. For high-bandwidth control of the pump frequency, the diode current of the external-cavity diode laser (ECDL) is directly modulated. However, such high-bandwidth feedback control has a trade-off—amplitude modulation of the pump power and, consequently, excess instability in the comb spacing. Figure S4B depicts the dependence of comb spacing on pump power. This effect is partly compensated for by saturating the erbium-doped fiber amplifier.
Details confirming the continuous equidistance of the Kerr microcomb are summarized in sections II and III. Figure 2E illustrates the nonlinear second-harmonic-generation optical intensity autocorrelation to reveal the time-domain picture of the Kerr microcomb. Careful checks are done to make sure no colinear second-harmonic background is collected in the setup. Although the Kerr microcomb is operated in a low-noise state, clean circulating mode-locked pulses (9) are not formed, as evidenced by the elevated autocorrelation background of nearly half of the peak. Furthermore, the autocorrelation measurements are performed at three different delays, evidently showing the repetitive temporal structures of the Kerr microcomb and excluding the possibility of noise correlation. Here, a fixed phase relationship between different comb lines is obtained, but the phase relationship may contain some abrupt changes associated with the local dispersion disruptions. Thus, mode-locking is prohibited and $\delta - \Delta$ matching becomes the underlying mechanism that drives the Kerr microcomb into a low-noise state (16, 19, 31, 32).

The comb spacing is then phase-locked and stabilized to a microwave synthesizer by controlling the pump power with a fiber EOM. Pump power is an effective way to control the comb spacing through thermal expansion and thermo-optic effects (35) and nonlinear phase accumulation. Figure 3A shows the stabilized beat note, with a resolution-limited linewidth of 6 Hz and a low close-to-carrier phase noise. To characterize the frequency stability of the comb spacing, we measured the single sideband (SSB) phase noise spectra and Allan deviations and present the data in Fig. 3B. Free running with none of the feedback loops engaged, the phase noise of the comb spacing shows a $f^{−3.5}$ dependence on the offset frequency in the vicinity of the carrier. Such close-to-carrier behavior suggests that the phase noise is now dominated by a mixture of technical noise of frequency flicker (30 dB/decade) and frequency random walk (40 dB/decade), rather than limited by quantum noise phase diffusion (36). Because the microresonator is not thermally insulated from the environment, its interaction with the fluctuating ambient temperature results in the random walk of the comb spacing. Meanwhile, the pump wavelength drift leads to the flicker noise mediated by the residual optical absorption in the microresonator (22). However, such technical noise can be removed by phase-locking the beat note to a high-performance microwave synthesizer. As shown in Fig. 3B, the resulting close-to-carrier phase noise can reach the level of $\pm 70$ dBc/Hz at 10 Hz with a $f^{−1.5}$ dependence on the offset frequency, limited only by the noise of the microwave synthesizer.

**DISCUSSION**

For offset frequency above 10 kHz, the phase noise of the fully stabilized comb spacing is better than that of the 18-GHz local oscillator used for downmixing the electronic signal. The measurement is instrument-limited to the level of $\geq 108$ dBc/Hz from 10 to 300 kHz and to the level of $\sim 130$ dBc/Hz at 1 MHz. It is therefore informative to calculate the theoretical limit of the phase noise at large offset frequencies and compare it with the measurement. Using the equations with the pump-resonance detuning of $\frac{2\pi f^2}{f_{p}}$ derived from the study by Matsko and Maleki (36) and assuming $\frac{2\pi f^2}{f_{p}} \ll 1$, we obtain the lower limit of the phase noise expressed as

$$L(f) \approx \frac{2\sqrt{5\pi} c n_2}{n_0^2 V_0} Q^2 \left[\frac{23}{24} + \left(\frac{4 + \frac{\pi^2}{96n^2}}{f^2}\right)^{1/2}\right]$$

(1)
where \( D = (\omega_{m+1} - \omega_{m}) - (\omega_{m} - \omega_{m-1}) \), \( Q, n_0, n_2, V_0, 2\gamma \), and \( f \) are the nonequidistance of the cold cavity modes, quality factor, linear refractive index, nonlinear refractive index, mode volume, full width at half maximum resonance linewidth, and frequency offset from the 17.9-GHz carrier, respectively. For our spiral microresonator, the estimated phase noise at 1 MHz is -148 dBc/Hz, and it grows quadratically with the inverse of the offset frequency. The estimated phase noise reaches -108 dBc/Hz at 10 kHz and starts to exceed the noise level of the 18-GHz local oscillator, matching the experimental observations (blue curve). Inset: Allan deviation of the comb spacing under free running (black empty squares), pump frequency stabilization (red semfilled squares), and full stabilization (blue filled squares). The fully stabilized comb spacing shows a consistent trend of 3.6 mHz/√(τ) (green dashed line) when the gate time is in the range from 0.5 to 200 s. The gray line denotes the counterlimited Allan deviation.

### Fig. 3. Stabilizing the comb spacing to the millihertz-level residual error.

(A) RF spectrum of the stabilized comb spacing, showing a resolution-limited linewidth of 6 Hz. Control of the comb spacing was achieved by modulating the pump power via a fiber EOM. (B) SSB phase noise of the free-running (black curve) and stabilized (red curve) comb spacing. Free running, the phase noise of the comb spacing shows a \( f^{-1.5} \) dependence on the offset frequency in the vicinity of the carrier. Such technical noise can be removed by phase-locking the beat note to a high-performance microwave synthesizer, and the resulting close-to-carrier phase noise can reach the level of -70 dBc/Hz at 10 Hz with a \( f^{-1.5} \) dependence on the offset frequency (pink dashed curve), limited only by the microwave synthesizer. On the other hand, for offset frequencies above 10 kHz, the phase noise of the comb spacing is better than that of the 18-GHz local oscillator used for downmixing the electronic signal (gray dashed curve), and the measurement is thus instrument-limited. The phase noise estimated from Eq. 1 is -148 dBc/Hz at 1 MHz, and it grows with a \( f^2 \) dependence on the offset frequency. The estimated phase noise reaches -108 dBc/Hz at 10 kHz and starts to exceed the noise level of the 18-GHz local oscillator, matching the experimental observations (blue curve). Inset: Allan deviation of the comb spacing under free running (black empty squares), pump frequency stabilization (red semfilled squares), and full stabilization (blue filled squares). The fully stabilized comb spacing shows a consistent trend of 3.6 mHz/√(τ) (green dashed line) when the gate time is in the range from 0.5 to 200 s. The gray line denotes the counterlimited Allan deviation.

in Fig. 1A. When the comb spacings of the FFC and Kerr microcomb are made unequal, the beat frequencies should strictly follow the relationship of

\[
f_{\text{beat}} = \delta + n \left( f_{\text{R,KC}} - \frac{f_{\text{R,FFC}}}{f_{\text{R,FFC}}} f_{\text{R,FFC}} \right)
\]

where \( \delta \) is the beat frequency at the pump mode, \( f_{\text{R,KC}} \) is the Kerr microcomb spacing, and \( f_{\text{R,FFC}} \) is the FFC spacing. Deviation from this expression poses an upper bound on the frequency uncertainty of the Kerr microcomb. Figure 4B shows two sample histograms of the frequency counting measurement. Six hundred counts are accumulated at the 1-s gate time for statistical analysis, and the Gaussian curve fitting is implemented to derive the mean values and SDs. Counting results on all 46 comb lines are shown in Fig. 4C. The mean values of the comb frequency stray from the ideal with a 190-mHz peak-to-peak deviation and a 50-mHz SD. The relative frequency uncertainty of the stabilized chip-scale frequency comb is thus calculated as 2.7 \times 10^{-16}, referenced to the optical carrier at 188 THz. Notably, the 17.9-GHz Kerr comb spacing generated directly from the microresonator is compatible with high-resolution astrospectroscopy; thus, sophisticated Fabry-Perot (FP) filtering cavities, which limit the precision of state-of-the-art astrocomb (28–30), are circumvented. Because of the residual FP cavity dispersion and fluctuations of the FP cavity resonance, leading to changes in the extraneous-line suppression, the uncertainty of the astrocomb line frequency is typically degraded to the kilohertz level (28–30). The uncertainty \( \epsilon \) then translates linearly into the systematic error \( \epsilon \) in astrophysical velocity measurements with an approximate relation of \( \epsilon \approx \frac{\sigma}{c} \cdot \epsilon \) (28). Thus, the 50-mHz frequency uncertainty of the Kerr microcomb can potentially improve the precision in astrophysical radial velocity measurements by orders of magnitude.

In summary, we report the first fully stabilized CMOS-compatible solid-state optical frequency comb. On the basis of the silicon nitride spiral resonator, a native 18-GHz Kerr microcomb is generated, and its
SSB phase noise reaches the instrument-limited floor of $-130 \text{ dBc/Hz}$ at $1\text{-MHz}$ offset. The comb’s two degrees of freedom, one of the comb line frequencies and the comb spacing, are phase-locked to a known optical reference and a microwave synthesizer, respectively, reaching an instrument-limited residual comb spacing instability of $3.6 \text{ mHz}$.

Forty-six Kerr microcomb lines are compared with the current benchmark FFC, and the relative frequency uncertainty of the fully stabilized Kerr microcomb is measured down to $2.7 \times 10^{-16}$. The reported system is a promising scalable platform for coherent Raman spectroscopy, high-precision optical clockwork, high-capacity coherent communications, arbitrary waveform generation, and astrophysical spectroscopy.

MATERIALS AND METHODS

Microresonator characteristics
The silicon nitride waveguide cross section was designed to be $2 \text{ mm} \times 0.75 \text{ mm}$ so that not only the group velocity dispersion but also the third-order dispersion was small at the pump wavelength. The spiral design ensured that the total footprint of the relatively large resonator could be minimized (less than $0.9 \times 0.8 \text{ mm}^2$), eliminating the additional cavity losses associated with the photomask stitching and discretization errors. The intrinsic quality factor of the spiral resonator was estimated to be $1,300,000$. Bends in the resonator have diameters greater than $160 \text{ mm}$ to minimize the bending-induced dispersion. Adiabatic mode converters were implemented on the side of the chip to improve the coupling efficiency from the free space to the bus waveguide, to less than a 3-dB coupling loss per facet. The gap between the bus waveguide and the microresonator was $500 \text{ mm}$, leading to a critical coupling at the pump wavelength.

Kerr comb generation
A tunable ECDL (Newfocus TLB-6730) was amplified by an L-band EDFA to $2 \text{ W}$ and then coupled to the microresonator. The pump wavelength was $1598.7 \text{ nm}$. A $1583\text{-nm}$ longpass filter removed the amplified spontaneous emission noise from the EDFA. The microresonator chip temperature was actively stabilized to $\pm 10 \text{ mK}$. A three-paddle fiber polarization controller and a polarization beam splitter cube were used to ensure proper coupling of the transverse-electric polarization into the microresonator. To obtain the Kerr microcomb, we first tuned the pump wavelength into the resonance from the high-frequency side at a step of $10 \text{ pm}$ until primary comb lines were observed on the optical spectrum analyzer, before fine control, to drive the comb from a noisy state to a phase-locked state. The threshold pump power was estimated to be $200 \text{ mW}$ using the equation $P_{th} = \frac{\eta \omega_p}{8 \pi n_d n_r A_{FSR}} \Delta$, where $A = 1.3 \text{ mm}^2$ is the mode area, $\eta = 0.5$ is the coupling parameter, $\omega_p$ is the pump frequency, and $\omega_{FSR}$ is the cavity’s free spectral range ($16$).

Device fabrication
First, a $3\text{-mm}$-thick SiO$_2$ layer was deposited via plasma-enhanced chemical vapor deposition (PECVD) on p-type 8-inch silicon wafers to serve as the under-cladding oxide. Next, low-pressure chemical vapor deposition (LPCVD) was used to deposit a $750$-nm silicon nitride
for the spiral resonators, with a gas mixture of SiH2Cl2 and NH3. The resulting silicon nitride layer was patterned by optimized 248-nm deep ultraviolet lithography and etched down to the buried SiO2 via optimized reactive ion dry etching. The sidewalls were observed under a scanning electron microscope with an etch verticality of 82° to 88° (see section SI). Then, the silicon nitride spiral resonators were annealed at 1200°C to reduce the N–H overtones absorption at the shorter wavelengths. Finally, the silicon nitride spiral resonators were overcladded with a 3-μm-thick SiO2 layer, deposited initially with LPCVD (500 nm) and then with PECVD (2500 nm). The propagation loss of the Si3N4 waveguide was ~0.2 dB/cm at the pump wavelength.
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Author contributions: S.-W.H. designed the measurements, analyzed the data, and wrote the paper. S.-W.H. and J.Y. performed the measurements. S.-W.H., J.Y., and C.W.W. designed the layout. M.Y. and D.-L.K. performed the device nanofabrication. BHM and T.Z. aided in the measurements performed with the Menlo Systems FFC. All authors contributed to the discussion and revision of the manuscript.

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