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Generation of ultrastable microwaves via optical frequency division

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There has been increased interest in the use and manipulation of optical fields to address the challenging problems that have traditionally been approached with microwave electronics. Some examples that benefit from the low transmission loss, agile modulation and large bandwidths accessible with coherent optical systems include signal distribution, arbitrary waveform generation and novel imaging[1]. We extend these advantages to demonstrate a microwave generator based on a high-quality-factor (*Q*) optical resonator and a frequency comb functioning as an optical-to-microwave divider. This provides a 10 GHz electrical signal with fractional frequency instability $\leq 8 \times 10^{-16}$ at 1 s, a value comparable to that produced by the best microwave oscillators, but without the need for cryogenic temperatures. Such a low-noise source can benefit radar systems[2] and improve the bandwidth and resolution of communications and digital sampling systems[3], and can also be valuable for large baseline interferometry[4], precision spectroscopy and the realization of atomic time[5–7].

Several photonic systems, including optical delay-line oscillators[8], whispering-gallery-mode parametric oscillators[9] and dual-mode lasers[10] have been investigated for the generation of low-noise microwave signals. An alternative approach, based on high-*Q* optical resonator and all-optical frequency division, shows promise for the generation of microwaves with excellent frequency stability[6,7,11–13]. This is because low absorption and scattering in the optical domain can yield quality factors approaching 1×10^{11} in a room-temperature Fabry–Perot (FP) resonant cavity. For a well-isolated cavity, average fluctuations in the cavity length amount to ~100 am on a 1 s timescale. A continuous wave (c.w.) laser stabilized to such a cavity can achieve a fractional frequency instability as low as $\sim 2 \times 10^{-16}$ for averaging times of 1–10 s (refs 14–18). Transfer of this stability to a microwave signal is the topic of this paper, and we demonstrate a 10 GHz electronic signal with exceptional frequency stability and spectral purity.

Figure 1 outlines the principle of the photonic oscillator we have developed. Phase-coherent division of the stable optical signal to the microwave domain preserves the fractional frequency instability, while reducing the phase fluctuations by a factor of $\sim 5 \times 10^4 =$ (500 THz/10 GHz). Such frequency division is accomplished by phase-locking a self-referenced femtosecond laser frequency comb to the optical reference[11]. This transfers the frequency stability of the stable c.w. laser oscillator to the timing between pulses in the laser pulse train, and hence to a microwave frequency that is detected as the pulse repetition rate ($f_r \approx 0.1$–10 GHz). In the case of a high-fidelity optical divider, the sub-hertz optical linewidth of the reference laser is translated into a microhertz linewidth on f_r. A fast photodiode that detects the stabilized pulse train generates photocurrent at frequencies equal to f_r and its harmonics, continuing up to the cutoff frequency of the photodiode.

Using this photonic oscillator approach, we demonstrate a 10 GHz signal with an absolute instability of $\leq 8 \times 10^{-16}$ at 1 s of averaging. This corresponds to a single sideband phase noise $L(f) = -104$ dBc Hz^{-1} at 1 Hz offset from the carrier, decreasing to near the photon shot-noise-limited floor of -157 dBc Hz^{-1} at an offset of 1 MHz. The integrated timing jitter over this bandwidth is 760 as. This measurement represents a significant improvement over previous work, with a reduction of phase noise power by a factor of 10 to 1,000 across the measured spectrum (1 Hz–1 MHz)[7] and a factor of 4 reduction in the 1 s instability[7,11]. This absolute timing characterizes one of the lowest phase-noise microwave signals generated by any source.

As the microwaves generated from our photonic approach have a phase noise that is lower than that available from commercially available microwave references, characterization of the generated phase noise requires that we build and compare two similar, but fully independent systems. The optical dividers in our photonic systems are based on octave-spanning 1 GHz Ti:sapphire femtosecond lasers and cavity-stabilized lasers at 578 nm and 1,070 nm (ν_{opt1} and ν_{opt2} in Figs 1 and 2). Compared to results from 250 MHz Er:fibre combs[13], the 1 GHz Ti:sapphire combs provide a 25 dB reduction in the shot-noise floor. Although the exact wavelength of the c.w. lasers is not critical for microwave generation, what is significant is that the two systems are independent. In fact, the FP cavities are situated in laboratories on different wings and floors of our research building. The pulsed output of the frequency-stabilized Ti:sapphire laser illuminates a high-speed, fibre-coupled InGaAs P-I-N photodiode that produces a microwave signal at 1 GHz and harmonics up to ~15 GHz. A band-pass filter selects the 10 GHz tone, which is subsequently amplified in a low-phase noise amplifier. The amplified signal is combined on a mixer with a similar signal from the second system, and the output of the mixer is analysed to determine the relative frequency and phase fluctuations. In addition to the 10 GHz microwave signal, we also measure the optical stability of the frequency comb and the c.w. lasers, thereby obtaining a lower limit of the timing stability of the microwave signals. This is accomplished by measuring and analysing the optical beat signal f_b between the second stabilized c.w. laser ν_{opt2} and a tooth of the frequency comb that is independently stabilized by ν_{opt1} (Fig. 1).

Phase noise data are presented in Fig. 3. The absolute single-sideband phase noise $L(f)$ on an individual 10 GHz signal is given by curve (a) in Fig. 3. This curve is 3 dB below the measured noise, under the assumption that the contribution from both oscillators is equal and uncorrelated (see Supplementary Information). The phase noise from the optical heterodyne between the two c.w. lasers using one of the combs is given by curve (b), which has been normalized to the 10 GHz carrier. This represents the present noise floor given by a single c.w. laser and the frequency

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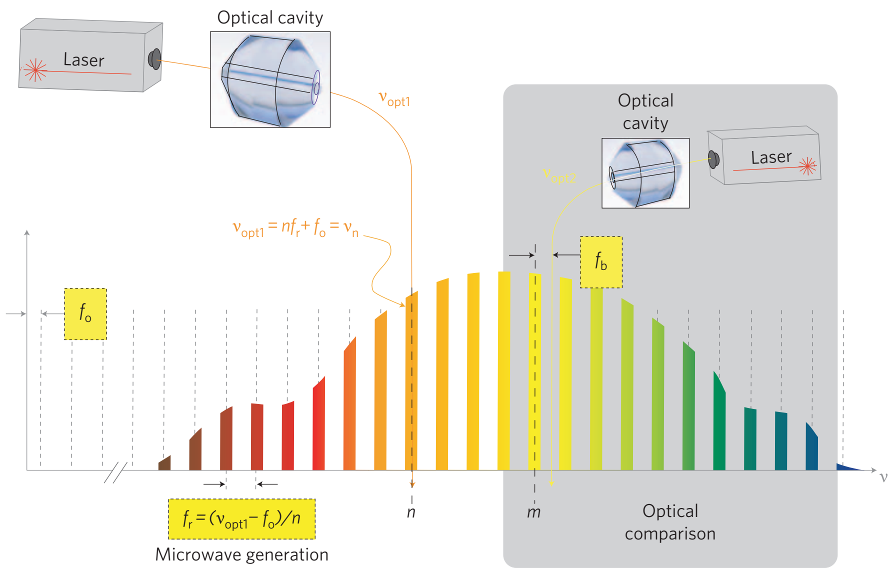


Figure 1 | How the OFC from a mode-locked laser acts as an optical frequency divider and comparator. The OFC spectrum is stabilized by phase-locking the *n*th comb element to an optical reference ν_{opt1} while simultaneously stabilizing the laser offset frequency f_o. This transfers the stability of the optical cavity to the OFC mode spacing $f_r = (\nu_{opt} - f_o)/n$. The beat signal $f_b = \nu_{opt2} - m \times f_r$ between a second stabilized c.w. laser (ν_{opt2}) and mode *m* of the OFC provides a measurement of the relative stability of ν_{opt1} and ν_{opt2}, including residual noise due to comb stabilization.

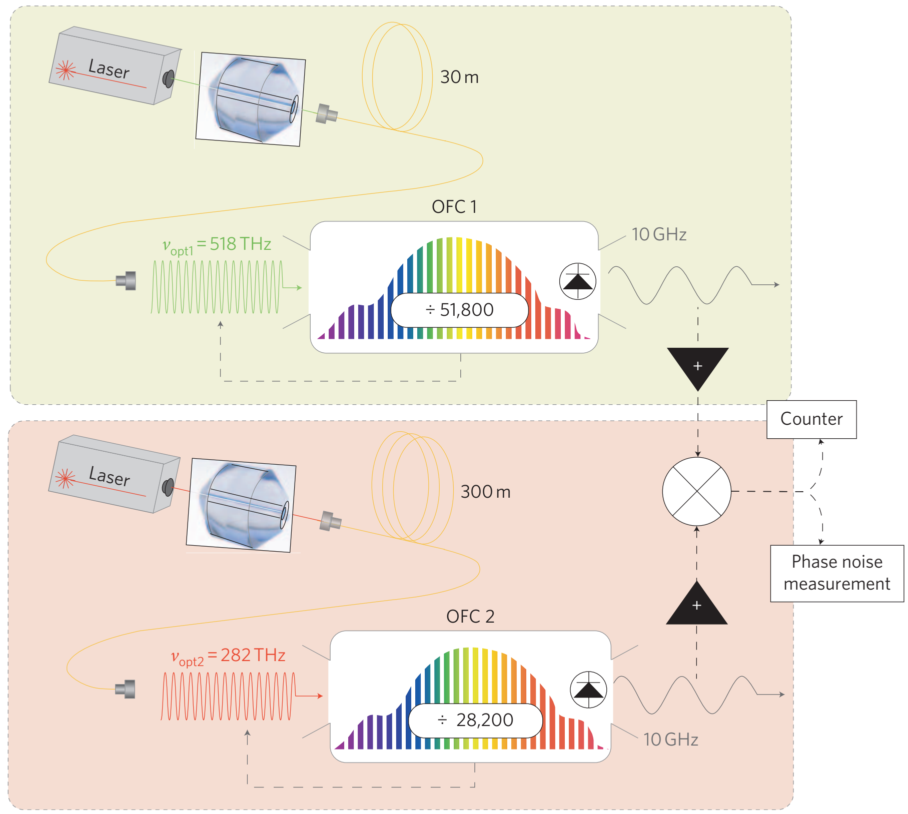
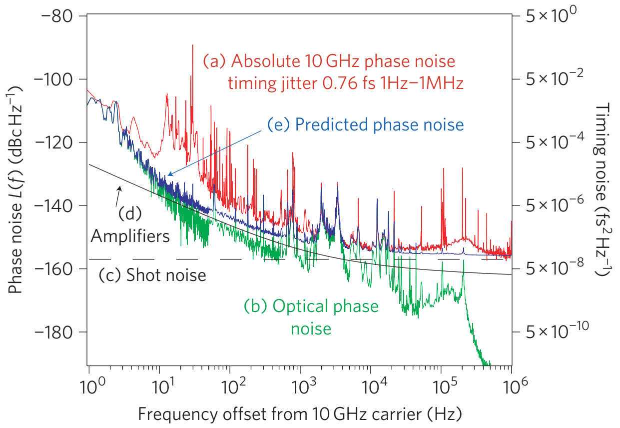


Figure 2 | Schematic of the experimental setup used for generation and characterization of the 10 GHz low-noise microwaves. In each independent system, an OFC based on a 1 GHz Ti:sapphire mode-locked laser is phase-locked to a cavity stabilized c.w. laser. Stable light from the two cavities is transferred to the OFCs through optical fibre. The 10th harmonic of the photodetected repetition rate yields a 10 GHz microwave signal that is phase-coherent with $\nu_{opt,i}$. The 10 GHz signal generated from each system is filtered and amplified, and the mixed down product is characterized via frequency and phase-noise measurements.

comb. As can be seen, the optical and microwave data converge at -104 dBc Hz^{-1} at 1 Hz. Above 10 kHz, the noise floor is set by the photon shot noise of the 10 GHz photodetector. Curve (c) shows the calculated shot noise floor of -157 dBc Hz^{-1} for the 10 GHz signal delivered at a power level of -8 dBm from 4 mA of average photocurrent. In the range of 10 Hz to 1 kHz, the noise contribution of microwave amplifiers cannot be neglected, as shown in curve (d). The combined noise of the c.w. laser, frequency



Q5 **Figure 3 | Phase noise spectrum of the photonically generated 10 GHz microwaves and contributing noise sources. a**,**b**, Measured phase noise for a single photonic oscillator (curve **a**, red) and a single optical reference (**b**, green) scaled to 10 GHz as determined from f_b of Fig. 1. **c**, Calculated shot noise floor (dashed black) for 4 mA of average photocurrent generated via photodetection of the laser repetition rate. **d**, Specified amplifier noise floor (solid black). **e**, Sum of curves **b**, **c** and **d** (blue trace), yielding the estimated phase noise achievable with the current systems.

comb, amplifiers and shot noise is given by curve (e). There is good agreement between this projection and the actual measurement, indicating that we have identified and properly accounted for the present limitations to the noise floor.

The spurious peaks in the 10 GHz phase noise (Fig. 3, curve a) between 5 Hz and 300 Hz arise from unidentified intermittent noise sources that also appear on the optical comparison. The largest spur at 29 Hz is a known vibration of our laboratory floor. The microwave data in curve (a) were chosen to show the upper limit to the phase noise. Optical data without the spurs (curve b) were chosen to display the lower limit to the phase noise with our current optical references and optical dividers, neglecting limitations due to photodetection of f_r. The right axis of Fig. 3 shows that even the largest spurs are sub-femtosecond, and the integration over 1 Hz to 1 MHz yields a timing jitter of 760 as. The extension of this integration to 5 GHz at the present shot-noise level yields timing jitter of ∼25 fs. Straightforward reduction of the noise floor with band-pass filters provides still lower integrated jitter.

In Fig. 4, the corresponding frequency counter data show the instability of the 10 GHz microwave signals and the optical instability of the c.w. lasers and frequency comb. The time record of frequency counter measurements (1 s gate time) is shown in Fig. 4a, and the fractional frequency instability calculated from these data are in Fig. 4b. Under the assumption of equal and uncorrelated oscillators, the data of Fig. 4b have been reduced by a factor of $\sqrt{2}$ from the measurement. We have not post-processed these data, and the slow oscillations and linear drift seen in Fig. 4a are the result of temperature variations of the independent FP cavity references.

The close-to-carrier phase noise and short-term instability with our photonic approach are lower than that achieved with any other room-temperature 10 GHz oscillator. With a thermal noise-floor limited optical cavity, a phase noise of $L(f) = -117$ dBc Hz^{-1} at a 1 Hz offset appears feasible[13,18]. Even lower phase noise levels could be achieved in the future with new optical references based on spectral hole burning techniques[19]. As can be seen in Fig. 5, the present noise is comparable to only the very best cryogenic dielectric oscillators[20–23]. Fibre delay-line oscillators have achieved lower noise floors at Fourier frequencies >1 kHz (ref. 8), but all such photonic devices have a noise floor ultimately limited by shot noise and the power-handling capabilities of the high-speed photodiode. In our case, a higher repetition rate comb would alleviate photodiode saturation effects, and a noise floor at high frequency near −165 dBc Hz^{-1} appears achievable[24]. A still lower noise floor would require higher-power photodetectors or a hybrid approach

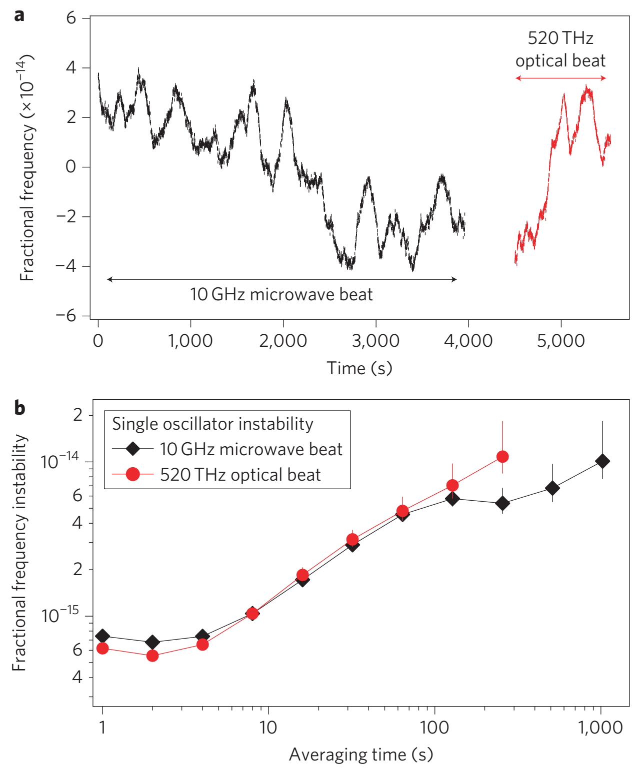


Figure 4 | Time record and fractional frequency instability. a, Time record of measured beat frequency between two photonically generated 10 GHz signals and the beat signal (f_b of Fig. 1) of the optical comparison of the two cavity stabilized reference lasers. **b**, Fractional frequency instability, calculated from the data in **a** for a single oscillator assuming equal contributions to the instability from each oscillator used in the 10 GHz microwave and optical comparisons.

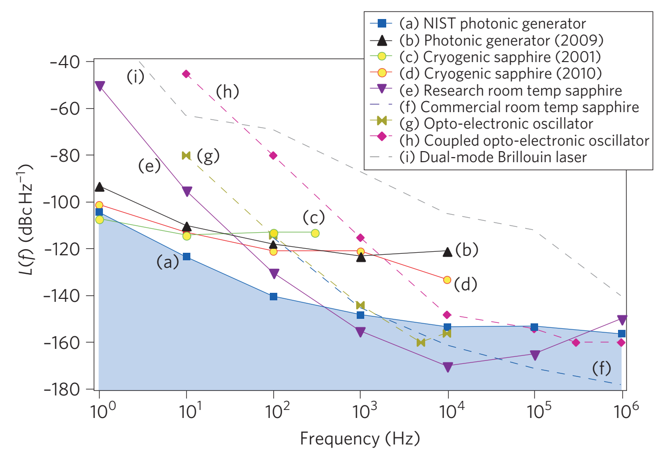


Figure 5 | Approximate single sideband phase noise for several leading microwave generation technologies in the 10 GHz range. Spurious tones have been neglected for all data. **a**, Result of the present work. **b**, Previous Er:fibre and Ti:sapphire optical frequency divider results[7]. **c**,**d**, Cryogenic sapphire oscillators[20,23]. **e**, Research room-temperature sapphire oscillator[25]. **f**, Commercial room-temperature sapphire oscillator. **g**,**h**, Long-fibre (**g**) and coupled (**h**) opto-electronic oscillators[8]. **i**, Dual-mode Brillouin laser[10]. Q6 with a low-noise dielectric sapphire oscillator[25] (see for example, Poseidon Scientific Instruments, http://psi.com.au.) locked to our photonic oscillator with a bandwidth of ~1 kHz.

Methods

Optical reference oscillators. Although details pertaining to the 518 THz (ref. 18) and 282 THz (ref. 14) c.w. reference lasers differ, we offer a general description of the systems. Both oscillators were based on fibre and solid-state lasers that are frequency-stabilized to a single transverse and longitudinal mode of a high-finesse optical cavity via the Pound–Drever–Hall locking scheme. The cavities were constructed of low-expansion ULE spacers with optically contacted high-reflectivity mirrors that exhibited a finesse of 200,000 and 300,000 for the 518 THz laser and the first harmonic of the 282 THz laser, respectively. In both systems, the intensity of the light incident on the high-finesse cavities was stabilized to minimize thermal instabilities of the cavity length due to heating of the mirrors. Mounting of the cavities and the cavity geometries themselves, although different, were both chosen Q1 to minimize the effects of accelerations on the optical cavity length. The design of the FP cavities for the 518 THz and 282 THz cavities were similar to those described in references 15 and 16, and 14, respectively. To isolate the cavities from external perturbations, each cavity was held in a temperature-controlled evacuated chamber mounted on an active vibration stage inside an acoustic isolation enclosure. The light generated from the two systems demonstrated optical linewidths <1 Hz and a frequency instability $<7\times10^{-16}$ at 1 s of averaging. For historical reasons, the two optical reference cavities were separated by ~300 m (located in laboratories on different floors of the NIST laboratory building). The frequency-stabilized light from the optical cavities was transmitted (with negligible change in optical stability or phase noise) via stabilized fibre-optical links[26] with lengths of 30 and 300 m to the optical frequency combs (OFCs) located in a third laboratory. We note that recent efforts have focused on characterizing and minimizing the acceleration sensitivity of such high-stability optical reference oscillators, including field tests where active cancellation of acceleration-induced frequency drifts have been demonstrated (see Supplementary Information).

Frequency comb details and stabilization. The OFCs were Ti:sapphire ring lasers with a cavity length $L=30$ cm, which gave a repetition rate of 1 GHz, or a spacing between adjacent pulses of 1 ns. One laser system was located on a passively isolated (air legs) optical table and was enclosed in nested aluminium and plexiglass boxes. The second comb system was separated from the first by a few metres. It was enclosed in a free-standing isolation box that provided ~30 dB of acoustic suppression. The base plate of this comb was isolated from seismic vibrations by a piezo-actuated platform. Each laser was pumped with ~8 W of 532 nm light, and produced ~1 W of mode-locked power. Both lasers produced an optical spectrum with usable bandwidth from 550 nm to 1,200 nm, which exceeds the gain bandwidth of the laser[27]. As a result, measurement of the offset frequency f_o was obtained directly from the laser by doubling the low-frequency end of the laser spectrum at 1,100 nm and referencing it to the high-frequency end at 550 nm (ref. 27). Optical interference of these two signals provided f_o, which was filtered, amplified and mixed Q2 with a radiofrequency reference frequency f_{rf} to provide an error signal that was fed back to the laser pump power to maintain the condition $f_o=f_{rf}$. A heterodyne beat between the c.w. laser frequency (ν_{opt}) and a single mode of the self-referenced frequency comb provided an error signal, which was used in an active servo loop that controlled the cavity length using a piezoelectric actuated mirror to force the comb mode to oscillate in phase with ν_{opt} (ref. 27). Although the Ti:sapphire systems described here demonstrate excellent performance in the laboratory, more robust Er:fibre frequency combs have been demonstrated that have excellent close-to-carrier phase noise performance and low acceleration sensitivity. Such systems could be an important component for a future optical frequency divider that operates outside the laboratory (see Supplementary Information).

Photodetection and measurement system. Photodetection of the laser repetition rate was accomplished using a pair of jointly packaged, fibre-coupled, 12 GHz, InGaAs P-I-N photodiodes (50 Ω terminated, +9 V bias). The photodiodes were 60 μm in diameter, with a responsivity of 0.34 A W^{-1} at 900 nm, and featured a 0.3 μm InP cap layer. Previously identified limitations were addressed by the combination of larger detector area and a thinner InP cap layer, which improved the power handling and reduced the conversion of amplitude noise to phase noise (AM-to-PM) in photodetection[28]. Light near 980 nm (with ~50 nm bandwidth) was coupled to the photodiodes using a 5 m fibre-optical cable from one comb system and a 2 m fibre-optical cable from the second comb system. The residual intensity noise (RIN) on this light was close to −100 dBc Hz^{-1} at 1 Hz offset, which we estimate to not significantly impact the present phase noise (via AM-to-PM in the photodiodes). With ~12 mW of light incident on the photodiodes, we directly obtained approximately −8 dBm in the 10 GHz carriers, which was then amplified to between 0 dBm and +7 dBm for input to the mixer. At Fourier frequencies above ~10 kHz, the achieved phase noise of Fig. 3 approached the shot-noise limited floor of −157 dBc Hz^{-1}. In the absence of photodiode saturation, this phase noise floor should decrease proportionately to the detected optical power, implying that a 10-fold increase in optical power leads to a 10 dB decrease in the noise floor (see Supplementary Information).

For phase noise measurements, the repetition rates of the two combs were adjusted so that the beat between the two 10 GHz signals was ~1–5 MHz. This mixed-down signal was input to a digital phase-noise measurement system that used cross-spectrum analysis to reduce the white noise floor below −160 dBc Hz^{-1} (depending on duration of averaging). For the counting measurements, the offset beat between the two 10 GHz signals was tuned to ~50 kHz. The output of the mixer was low-pass filtered, amplified and input to a high-resolution Λ-type counter[29]. The fractional frequency instability of Fig. 4b was calculated from a time series of these counter measurements for both the microwave and optical data. By integration of the appropriately weighted phase noise spectrum of Fig. 3, we verified that the 1 s instability presented here was consistent with the counter data of Fig. 4 and with the more conventional Allan Deviation[29]. Further details about microwave phase noise measurements at the low levels described here can be found in refs 8, 20–23 and 25.

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Author contributions
T.M.F., M.S.K., F.Q., J.T. and S.A.D. built, characterized and operated the femtosecond lasers and measurement systems. J.C.B., T.R., N.L., A.L., Y.J. and C.W.O. constructed and operated the stable c.w. laser sources. S.A.D., T.M.F. and F.Q. acquired and analysed the data and prepared the manuscript.

Additional information
The authors declare no competing financial interests. Supplementary information accompanies this paper at www.nature.com/naturephotonics. Reprints and permission information is available online at http://www.nature.com/reprints/. Correspondence and requests for materials should be addressed to T.M.F. and S.A.D. Q4

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