Photonic microwave signals with zeptosecond-level absolute timing noise

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Photonic synthesis of radiofrequency (RF) revived the quest for unrivalled microwave purity because of its ability to convey the benefits of optics to the microwave world1-11. In this work, we perform a high-fidelity transfer of frequency stability between an optical reference and a microwave signal via a low-noise fibre-based frequency comb and cutting-edge photodetection techniques. We demonstrate the generation of the purest microwave signal with a fractional frequency stability below 6.5 × 10⁻¹⁶ at 1 s and a timing noise floor below 41 Hz Hz⁻¹/₂ (phase noise below −173 dBc Hz⁻¹ for a 12 GHz carrier). This outperforms existing sources and promises a new era for state-of-the-art microwave generation. The characterization is achieved through a heterodyne cross-correlation scheme with the lowest detection noise. This unprecedented level of purity can impact domains such as radar systems12, telecommunications13 and time–frequency metrology2,14. The measurement methods developed here can benefit a characterization of a broad range of signals.

Photonic microwave generation methods, such as the optoelectronic oscillator1, Brillouin oscillator5, sideband-injection-locked laser4, electro-optical-frequency division1 and Kerr-frequency-comb oscillator2, have drawn attention because of their interesting properties, such as high frequency, large bandwidth (BW), tunability and chip-scale packaging. In particular, ultrastable lasers and a frequency-comb-based optical-to-microwave division scheme can produce microwave signals with both extremely high stability and low noise2,3,9. Combining these forefront optoelectronics devices and cutting-edge techniques, sundry important techniques are proposed and implemented. To increase the signal-to-noise ratio, a fibre-based optical-pulse repetition-rate multiplier is used to redistribute the photocurrent to the harmonic of interest19 (the 48th in our case). After four multiplying stages, we obtain over 2.5 mW of microwave power at 12 GHz for a d.c. photocurrent of 8 mA. A dispersion-compensation fibre unit is inserted to ensure that the optical pulses impinging on the photodiode are less than 800 fs long (Methods, Dispersion management). In this ultrashort pulse limit, the shot-noise-distribution imbalance between amplitude and phase allows us to reduce the shot-noise-induced phase noise20. Careful pulse compression proved essential to achieve the final result.

Fibre-based lasers exhibit significant relative intensity noise (RIN), which can result in excess phase noise through amplitude-to-phase (AM–PM) conversion in the photodiode. We limit the RIN by meticulously choosing the laser working state (Methods, Optical frequency comb) and operate the photodiode in conditions in which nonlinear saturation effects help to zero the AM–PM conversion for the 12 GHz signal21. Rejection of amplitude noise by more than 33 dB is typically obtained (Methods, AM–PM conversion characterization and control).

Combining these forefront optoelectronics devices and cutting-edge techniques, microwave signals with a phase noise below −173 dBc Hz⁻¹ at 10 kHz offset are made possible. As phase noise is only a reasonable figure of merit of an oscillator if its carrier frequency is provided, we choose to express it as a timing noise density, once normalized against the 12 GHz carrier. This represents an impressive timing noise below 41 Hz Hz⁻¹/₂.

The thorough characterization of such ultralow phase noise signals is a major challenge in itself, even more so for high-frequency
carriers. In high-precision measurements, phase-noise characterization is usually a process that involves comparing a signal from the device under test (DUT) with a reference source. When the signal under test has a lower phase noise than the available reference, two separate but identical systems can be built and compared\(^9\). The data are then analysed assuming that the two identical systems contribute equally to the phase noise. However, to realize two equally good systems is not straightforward and a minute excess noise using a heterodyne digital cross-correlation method. The auxiliary optoelectronic microwave references A and B are also obtained by low-noise optical division of the light from two additional distinct ultrastable laser references at 1,542 nm using two separate optical frequency combs. ADC, analog-to-digital converter; CSO, cryogenic sapphire oscillator; DCF, dispersion compensation fibre; DDS, direct digital synthesizer; OCXO, oven-controlled crystal oscillator.

To assess the additional phase noise introduced by the optical frequency division process, including comb and photodetectors, we measure the microwave phase noise obtained when locking the two auxiliary microwave references and the DUT to the same ultrastable optical reference. In this configuration, the laser noise is common to the three systems and then suppressed. The obtained phase-noise PSD is shown in Fig. 2 (red curve). At Fourier frequencies up to 3 kHz, although there are numerous peaks caused by acoustic noise, the photodiode flicker noise can be inferred to be below \(-140 \, \text{dBc Hz}^{-1}\), which, to our knowledge, is the lowest level ever reported\(^{23}\). At lower Fourier frequencies, the phase noise departs from a 1/f behaviour, which we explain by residual long-term drift that results from the noisy laboratory environment and the significant amount of non-noise-cancelled fibred optics (several tens of metres, mostly in the pulse-rate multipliers). From 3 to 100 kHz, we measure a shot-noise-limited white-phase-noise floor at \(-173 \, \text{dBc Hz}^{-1}\) that is more than 10 dB below previously reported results obtained with comparable schemes\(^{9,24}\). This shot-noise floor corresponds to a timing noise of 41 zs Hz\(^{-1/2}\) and depends on the optical pulse duration (Methods, Shot-noise limit). Thermal noise is intrinsically rejected in the cross-correlation process\(^{25}\), but from the measured microwave power it can be deduced as \(-181 \, \text{dBc Hz}^{-1}\). Between 100 kHz and 1 MHz, we are limited by a servo bump because of the residual in-loop errors from the comb phase-lock loop.

The measured absolute single-sideband (SSB) phase-noise PSD for the 12 GHz microwave signal generated by our optical-frequency–comb frequency division scheme, obtained by locking the two auxiliary microwave references and the DUT to three independent ultrastable optical references, is displayed in Fig. 3 (red curve). To our knowledge, this is the lowest absolute phase noise...
**Figure 2 | Additive phase-noise contribution of the frequency division scheme.** The green and blue lines are the phase noise of the 5 MHz RF signals obtained from the beat between the signal under test (at 12 GHz) and the auxiliary sources (at 11.995 and 12.005 GHz). The phase data that correspond to these two curves are cross-correlated to yield the phase noise of the DUT (red line). In this measurement, all the lasers are stabilized using the same laser reference so that it represents the residual phase noise introduced in the optical division process and, thus, the quality of the frequency-stability transfer. It reaches a white timing noise floor of $41 \times 10^{-12}$ Hz$^{-1/2}$ (thick blue line). The outstanding photodiode flicker can be inferred to be below $-140$ dBc Hz$^{-1}$ (thick grey line). The orange line is the projected RIN-induced phase noise after 33 dB of AM–PM conversion rejection. The dashed black line is the measurement noise floor.

**Figure 3 | Absolute transfer of spectral purity from optics to microwave.** The absolute phase noise of the 12 GHz microwave signal we generated (red line) is limited by the optical phase noise of the laser reference at 1.542 nm (blue line) and by the residual in-loop error of the phase-lock loop used to synchronize the repetition rate of the comb with the optical reference (bump above 700 kHz offset frequency). The phase noise of the 12 GHz signal sticks almost entirely to the optical phase noise, which indicates a close-to-complete absolute transfer of spectral purity from optics to microwave. Between 3 and 100 kHz Fourier frequency, the transfer remains partial but offers an original opportunity to probe shot-noise levels. The spur that range from 10 Hz to 1 kHz result from acoustic noise picked up in the various fibre links and from electromagnetic interference. The optical phase noise has been characterized independently by the cross-correlation of RF optical beats from ultrastable cavities.
ever reported both close and far from the carrier. At low offset Fourier frequencies, from 1 to 400 Hz, the phase noise is almost fully determined by the CW laser reference, which indicates that we performed a close-to-complete transfer of frequency stability from optics to microwave. The −106 dBc Hz−1 at a 1 Hz offset phase-noise level is only 3 dB higher than that inferred from the measured optical reference phase noise. The spurs in the Fourier frequency range from 10 Hz to 3 kHz originate from the 50 Hz power line harmonics as a result of imperfect electromagnetic shielding and acoustic noise coupling to the fibre-optics set-up despite the laser being acoustically isolated and the fibre link from the CW laser to the comb system being noise-cancelled. Between 3 kHz and 1 MHz, the transfer is only limited by the residual phase noise of the optical frequency division scheme and the in-loop errors from the reference laser Pound–Drever–Hall (PDH) lock.

Improvements to the close-to-carrier phase noise could be obtained with better ultrastable laser frequency stability. Longer or cryogenic reference cavities26,27 with crystalline coatings28 or spectral hole-burning stabilization29 could lower the phase-noise limit by one order of magnitude. To be limited solely by the optical reference, shot noise could be reduced by using a photodiode with higher power-handling capabilities30. However, the most stringent requirement is photodiode flicker below the state-of-the-art −140 f−1 dBc Hz−1 demonstrated here. Our extremely low-noise set-up is the ideal testbed for that development, as it offers the opportunity to study fundamental photodetection limits and is suitable for any phase-noise characterization beyond comb-based systems.

Terabit communication systems with high-speed data transmission, high-stability fountain atomic clocks, very long baseline radio astronomy, high-accuracy navigation and radar systems are direct applications that could benefit from the new level of microwave purity demonstrated in this Letter. In particular, low phase noise in defence pulse-Doppler radar will enhance the detection of moving targets to an unprecedented level of resolution. Furthermore, this result paves the way to compact, robust and mobile microwave sources with ultralow phase noise based on reliable technologies that have become readily accessible.

Methods

Methods and any associated references are available in the online version of the paper.

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Author contributions

X.X., R.B. and D.N. set up the experiment and carried out the measurements. M.G., W.H., M.L. and R.H. conceived and built the low-noise optical frequency combs. A.I. and S.D. provided the photodiodes. C.A. programmed the cross-correlator hardware. M.L. made the RF chains in the cross-correlator. P.-A.T. and G.S. fabricated the pulse rate multipliers. X.X. and R.B. obtained the final data, prepared the manuscript and gathered the contributions from all the other co-authors. Y.L.C. designed the experiment and lead the project.

Additional information

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Competing financial interests

The authors declare no competing financial interests.
Methods

Optical frequency comb. The FOFC consists of three parts: a femtosecond laser, an f–2f interferometer module and an erbium-doped fibre amplifier (EDFA), all made with polarization-maintaining fibre. Based on the nonlinear amplifying loop mirror mode-locking principle, the laser reaches a steady state in a few seconds and can remain in the mode-locked state for several months. The repetition rate of the FOFC is coarsely tunable over 5 MHz around 250 MHz to accommodate the mode spacing and thus tune the frequency of the optically generated microwave signal. An intracavity electro-optical modulator (EOM) provides feedback on the comb repetition rate with a BW of roughly 1 MHz (ref. 31).

The laser output is pre-amplified up to 30 mW by a first EDFA and split into two parts that are used to seed the f–2f interferometer for the CEP frequency detection and by a second EDFA for microwave generation. The second high-power EDFA boosts the optical power up to 350 mW and passively reduces the RIN through seed saturation. It is pumped by three low-noise single-mode high-power laser diodes, all set to specific currents to avoid parasitic mode hopping. For each diode, the lowest RIN is observed when the current set point is at an equal distance from two successive mode hops. The output shows a pulse width below 50 fs, with an optical spectrum broader than 60 nm FWHM.

Ultrastable laser and its phase noise characterization. The reference CW laser is a 1,542 nm semiconductor laser locked to an ultrastable Fabry–Perot cavity (Q > 380,000) via PDH techniques (500 kHz BW), which provides a fractional frequency stability of 5.5 × 10⁻¹⁶ at 1 s. The reference laser light is transferred to the FOFC using a 50 m fibre link with an acousto-optic modulator (AOM)-based fibre-noise canceller.21. The laser phase noise is characterized by the same cross-correlation scheme that is used for the microwave system, but operating on optical beat notes rather than microwave-mixed signals. Three 1,542 nm ultrastable lasers locked to three distinct cavities via the PDH scheme were used. For each optical phase-noise measurement two lasers act as references to characterize the third one. The frequency difference between these three lasers is below 600 MHz.

Optical frequency comb phase locking. The optical phase-locking scheme of the FOFC to the ultrastable reference laser is similar to that reported previously.23,24. Briefly, the booster-amplifier output is followed by a fibre-coupled three-port thin-film optical add-drop multiplexer. The first output port delivers a signal filtered around 1,542 nm with a bandwidth of 0.8 nm. At the second output, the unfiltered part of the initial spectrum is used for the microwave generation. The filtered signal is beat with the ultrastable reference laser ω_CW, which leads to a beat-note signal ω_CW − ω_M = Nf0 − f0. This beat-note signal is mixed with the CEO frequency fCEO to obtain an f0-independent signal at 880 MHz. This frequency is digitally divided by eight and compared with a fixed frequency from a direct digital synthesizer to generate an error signal. The error signal is then processed through a fast analogue loop filter, and fed to the intracavity EOM and piezoelectric actuators so as to stabilize the repetition rate of the comb.

High-linearity low-noise photodiode. A top–illuminated dual-depletion region InGaAs/InP photodiode with an optimized illumination profile was used for this work. The illumination profile is improved through beam shaping via gradient-index lens coupling. The power-handling capability and linearity of the photodiode, which are limited by the collapse of the applied electric field because of the photogenerated space-charge effects, increase monotonically with its reverse bias. At a 15 V reverse bias, the photodiode shows a linear response up to a 4 Vpp output amplitude and delivers a complete output up to 10 Vpp. To avoid any induced device failure, the photodiode chip was integrated with a thermoelectric cooler and temperature sensor and assembled in a compact eight-pin microwave package to avoid any parasitic feedback that has been observed to undermine the phase-noise result and the AM–PM conversion coefficient measurement. After the mixers, two heterodyne beat notes at 5 MHz are obtained and sent to the digital heterodyne cross-correlator. Each heterodyne signal is sampled at 250 mega samples per second (MS s⁻¹) in an analog-to-digital converter clocked by a specific low phase-noise oven-controlled crystal oscillator (30 Hz BW phase). The signal is digitally low-pass converted to d.c. and processed in an FPGA to yield in-phase and quadrature components down-sampled to 2 MS s⁻¹. The samples are transferred via Gbit-Ethernet to a computer where they are real-time analysed by a Python-based software to obtain the phase-noise information. The typical phase-noise floor of the instrument for a 10 MHz bandwidth is below 140 dBc Hz⁻¹ at 1 Hz offset and below 180 dBc Hz⁻¹ for Fourier frequencies beyond 1 kHz. Moreover, the heterodyne nature of the cross-correlator renders it only a little sensitive to amplitude noise with more than 20 dB of AM–PM conversion rejection. The usual averaging time required to obtain the results displayed in Fig. 2 is around 18 h.

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