OPTICS

Generation of multiple ultrastable optical frequency combs from an all-fiber photonic platform

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Frequency-stabilized optical frequency combs have created many high-precision applications. Accurate timing, ultralow phase noise, and narrow linewidth are prerequisites for achieving the ultimate performance of comb-based systems. Ultrastable cavity-based comb-noise stabilization methods have enabled sub–10^{-15}-level frequency instability. However, these methods are complex and alignment sensitive, and their use has been mostly confined to advanced metrology laboratories. Here, we have established a simple, compact, alignment-free, and potentially low-cost all-fiber photonics-based stabilization method for generating multiple ultrastable combs. The achieved performance includes 1-femtosecond timing jitter, few times 10^{-15}-level frequency instability, and <5-hertz linewidth, rivalling those of cavity-stabilized combs. This method features flexibility in configuration: As a representative example, two combs were stabilized with 180-hertz repetition rate difference and ~1-hertz relative linewidth and could be used as an ultrastable, octave-spanning dual-comb spectroscopy source. The demonstrated method constitutes a mechanically robust and reconfigurable tool for generating multiple ultrastable combs suitable for field applications.

INTRODUCTION

Optical frequency combs have evolved to become an essential tool for many emerging high-impact applications, such as optical atomic clocks (*1*), comb-based spectroscopy (*2*–*5*), low-noise microwave generation (*6*, *7*), precision dimensional metrology (*8*), synchronization of ultrafast x-ray facilities (*9*, *10*), and photonic signal processing (*11*, *12*), to name only a few. The performance of many comb applications is greatly benefited by stabilizing the comb-line frequencies. Among different methods for stabilization, optical frequency division (OFD) could achieve subfemtosecond timing jitter with sub–10^{-15} fractional frequency instability of microwave and optical frequency for ~1 s (*6*, *7*). This method is based on transferring the ultrastable mechanical stability of the Fabry-Pérot cavity via a continuous wave (CW) laser and subsequently locking the self-referenced [carrier-envelope offset frequency (f_{ceo})–stabilized] frequency comb to the cavity-locked CW laser. However, the implementation of high-performance OFD systems has been mostly limited to a few advanced metrology laboratories due to the technical complexity, high cost, and environmental sensitivity of these systems.

As an alternative approach, one can use an optical fiber delay line as both a timing reference and a frequency discriminator with an enhanced sensitivity. Because of the low-loss nature of telecommunications-grade optical fiber, an effective quality factor of $>10^9$ can be achieved with 1-km-long fiber (*13*). Previously, a CW laser frequency was stabilized by a 1-km-long fiber link, resulting in an 8-Hz linewidth (*13*). More recently, the comb spacing (repetition rate) of free-running mode-locked oscillators could be stabilized to $<10^{-13}$ frequency instability using a 10-km-long fiber delay line (*14*). However, so far, there has been no work on optical frequency combs fully stabilized by all-fiber photonics with performance approaching that of optical cavity-based stabilization methods. Here, we have established a simple yet powerful platform that can stabilize multiple optical frequency combs directly to a single fiber delay line with 5.7×10^{-15} frequency instability within 1 s.

RESULTS

Operation principles

Figure 1 shows a conceptual diagram of the proposed all-fiber photonics-based multiple ultrastable optical frequency comb generator. Standard self-referenced mode-locked laser frequency combs are used as individual comb sources. Note that f_{ceo} control of typical fiber combs can be routinely achieved by f-$2f$ interference with 10^{-16}-level instability and 100-mrad integrated root mean square (RMS) phase noise (*15*), which is the case for our experiment as well. The output of the i-th optical frequency comb is filtered by each individual (and spectrally nonoverlapping) narrow optical bandpass filter (OBPF), which has a center frequency of ν_i ($i = 1, 2, \ldots, n$), and is applied to a Michelson interferometer with a long fiber delay line in one arm. In this work, a compactly packaged 1-km-long SMF-28 fiber spool with an inner (outer) diameter of 7 cm (8 cm), which is made by the fiber gyroscope coil winding method, is used as the fiber delay line. The filtered comb-line frequency is directly locked to the stability of this long delay line with equivalent timing stability $\delta\tau/\tau$, where τ is the delay time. Note that the projected thermomechanical and thermo-conductive noise-limited timing stability of a 1-km-long SMF-28 fiber is 1.7×10^{-15} level in 1 s (*16*, *17*). By stabilizing $f_{\text{ceo},i}$ and ν_i simultaneously, the entire comb lines of the i-th comb source can be frequency stabilized to the 10^{-15} level. Furthermore, by using different filter center wavelengths, multiple combs can be simultaneously stabilized. Note that, although the cavity-based stabilization methods can also stabilize multiple combs, our method can directly stabilize multiple combs to a single fiber link without any CW lasers.

For effective interference between two optical pulses (each reflected back from short and long arms) at the interferometer output, optical delay control is required for each comb-line frequency ν_i. Here, delay control can be implemented by a precise translation stage (*14*) or dispersion compensating fiber (*18*). For multiple comb stabilization, independent delay control for each ν_i is required, and this control

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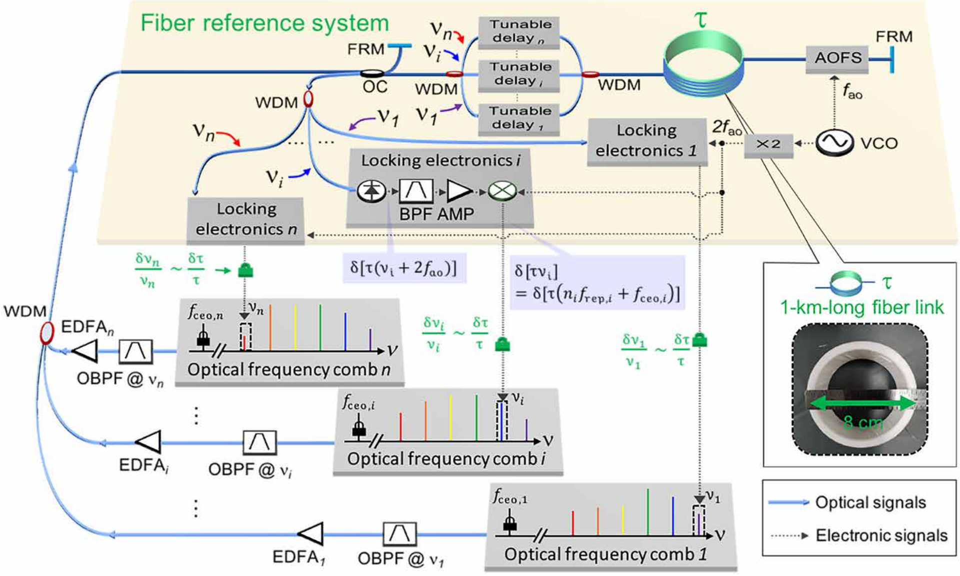

Fig. 1. Schematic of generating ultrastable optical frequency combs based on an all-fiber photonics platform. The comb-line frequency ν_i ($i = 1, 2, \ldots, n$) of each comb source is directly locked to the stability of the fiber reference ($\delta\tau/\tau$) while stabilizing the carrier-envelope offset frequency $f_{ceo,i}$ ($i = 1, 2, \ldots, n$) of each comb. Using WDM couplers and tunable delay, multiple optical frequency combs are simultaneously locked to the fiber reference. AMP, radio frequency amplifier; AOFS, acousto-optic frequency shifter; BPF, radio frequency bandpass filter at $2f_{ao}$; EDFA, erbium-doped fiber amplifier; FRM, Faraday rotating mirror; OC, 2 × 2 optical coupler; WDM, wavelength-division multiplexer; VCO, voltage-controlled oscillator. Photo credit: Dohyeon Kwon, KAIST

can easily be realized by wavelength multiplexing/demultiplexing and delay tuning for each wavelength, as shown in Fig. 1. Another powerful feature of the demonstrated method is that, by tuning the filtering center wavelengths and optical delay, any arbitrary repetition rates of frequency combs can be stabilized. This property increases flexibility in the system designs: As a representative example, two combs with slightly different repetition rates can be stabilized to a single fiber delay line, resulting in an ultrabroadband and ultrastable dual-comb source (which is experimentally demonstrated later in this paper).

The outputs of the interferometer are divided by center wavelengths and photodetected for extracting comb-line frequency noise. To avoid the baseband background noise in the electronic domain, synchronous detection is used by inserting an acousto-optic frequency shifter (AOFS), driven by frequency f_{ao}, in the fiber delay line. The photodetected frequency noise of the i-th comb source is weighted by the fiber delay time τ and written as $\delta[\tau(\nu_i + 2f_{ao})]$. By frequency mixing this noise with $2f_{ao}$, $\delta[\tau\nu_i] = \delta[\tau(n_i f_{rep,i} + f_{ceo,i})]$ can be extracted, where n_i, $f_{rep,i}$, and $f_{ceo,i}$ are the mode number, repetition rate, and carrier-envelope offset frequency, respectively, of the i-th comb source. Driving intracavity actuators in the comb source completes the stabilization process. More detailed information on the experimental setup is provided in Materials and Methods and the Supplementary Materials.

Absolute phase and frequency noise, linewidth, and frequency instability performances

Figure 2 (A and B) shows the optical phase noise and frequency noise power spectral density (PSD), respectively, at 1540 nm when stabilizing a nonlinear amplifying loop mirror mode-locked erbium fiber comb (denoted as comb-A; see Materials and Methods) to a 1-km-long fiber delay line. Both spectra are measured in an out-of-loop manner using a second fiber interferometer (see Materials and Methods and the Supplementary Materials). As expected, the stabilized phase and frequency noise approach the limits set by mechanical dissipation due to thermal fluctuations of the fiber delay (blue dashed lines in Fig. 2, A and B) (*16*, *17*). Noise spikes in the 20- to 200-Hz range are mostly caused by the vibration noise (from the bottom of the setup) coupled to the fiber link (see the Supplementary Materials). A strong peak at 2 Hz is caused by the resonance frequency of the air-floating optical table. Overall, these technical noise components can be further suppressed by better environmental shielding (e.g., one example of vibration isolation method is shown in the Supplementary Materials). From the β-separation line for linewidth prediction (*19*) in Fig. 2B, the expected linewidth of the comb line is ~5 Hz. Note that if the strong 2-Hz peak is removed by better shielding, the linewidth can be further narrowed down to <1 Hz. Figure 2C shows the measured absolute linewidth by beating the comb line against a frequency-stabilized 1550-nm CW fiber laser. The measured linewidth is ~28 Hz, which is limited by the CW laser linewidth used (see Materials and Methods and the Supplementary Materials). The fractional frequency instability (Fig. 2D) is converted from the phase noise data (for <0.1 s) and time-domain measurement with a data logger (for >0.1 s). The frequency instability reaches 5.7×10^{-15} at 0.4 s averaging time and diverges after 0.4 s due to linear temperature drift in the fiber link. The calculated temperature drift and measured frequency drift are 1.7 nK/s and 3.4 Hz/s at 194 THz, respectively (*20*).

Curve (i) in Fig. 3 shows the comb-line phase noise scaled to a 10-GHz carrier frequency. As the equivalent f_{ceo} noise [curve (ii) in Fig. 3] is much lower, this phase noise corresponds to the repetition rate phase noise with integrated RMS timing jitter of 1.18 fs (integration bandwidth, 1 Hz to 100 kHz). The phase noise performance is comparable to or superior to that of state-of-the-art microwave generators [curves (iii) to (v) (*21*–*23*)] and cavity-based OFD results [curves (vi) and (vii) (*6*, *7*)]. As advanced high-speed photodetection (*6*, *7*) or microwave oscillator phase locking (*24*) methods can both

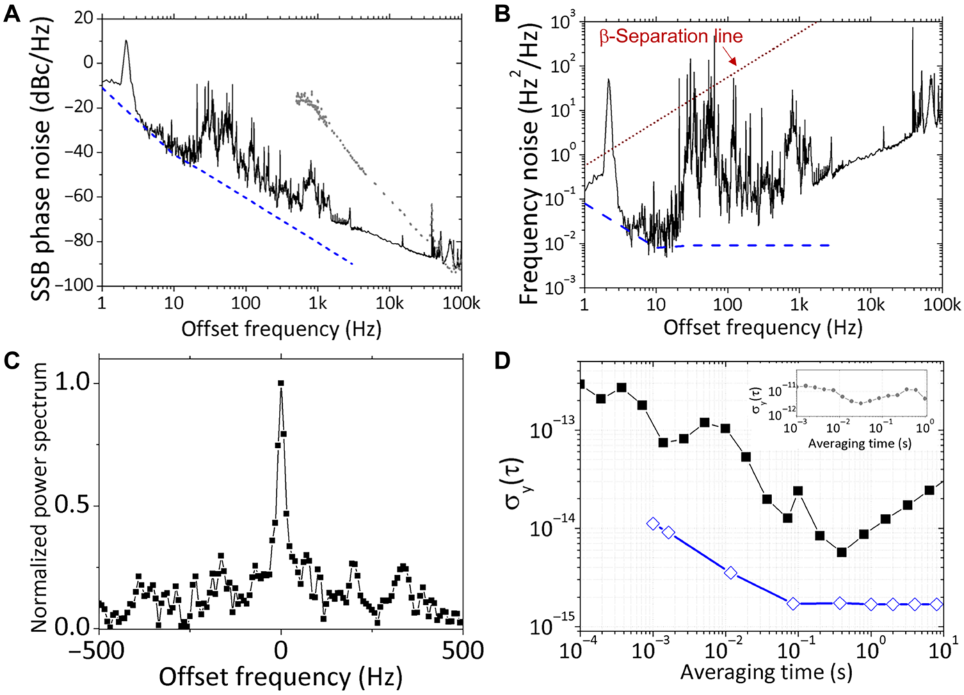

Fig. 2. Absolute phase noise, frequency noise, linewidth, and frequency instability of the fiber delay–stabilized frequency comb. (**A**) Measured single-sideband (SSB) optical phase noise PSD of the fiber delay–stabilized comb at 1540 nm (black), phase noise PSD projected from thermomechanical and thermoconductive fiber length fluctuation (blue dashed curve), and measured optical phase noise PSD of the free-running comb (gray dotted curve). (**B**) Measured frequency noise PSD of the fiber delay–stabilized comb at 1540 nm (black) and frequency noise PSD projected from thermomechanical and thermoconductive fiber length fluctuation (blue dashed curve). (**C**) Measured linewidth at 1550 nm of the fiber delay–stabilized comb using a frequency-stabilized CW fiber laser. (**D**) Fractional frequency instability of the fiber delay–stabilized comb (black, squares) and projected instability from thermomechanical and thermoconductive length fluctuation (blue, diamonds). The inset gray curve is the fractional frequency instability of the free-running comb.

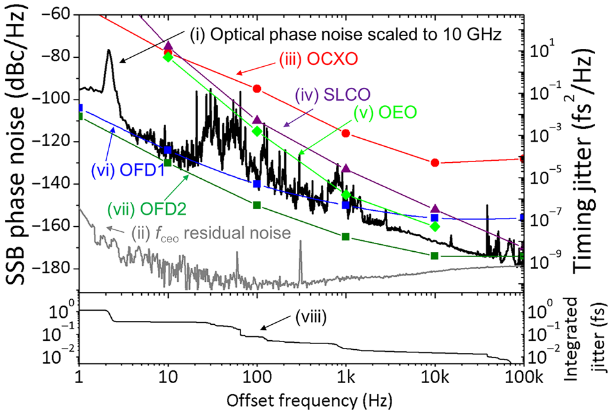

Fig. 3. Absolute phase noise of repetition rate (i.e., timing jitter) of the fiber delay–stabilized frequency comb. Curve (i), measured optical phase noise of the fiber delay–stabilized comb scaled to the 10-GHz carrier (black). Curve (ii), measured residual f_{ceo} noise scaled to 10 GHz (gray). For comparison, the phase noise of a 10-GHz oven-controlled crystal oscillator (OCXO) (*21*) [curve (iii), red circles], 10-GHz sapphire-loaded cavity oscillator (SLCO) (*22*) [curve (iv), purple triangles], 10-GHz optoelectronic oscillator (OEO) (*23*) [curve (v), right green diamonds], and 10-GHz microwaves generated by OFD (*6*, *7*) [curve (vi), blue squares; curve (vii), green squares] are also shown. Curve (viii), integrated RMS timing jitter of the measured repetition-rate phase noise.

show low excess noise in the optical-to-electronic (O-E) conversion process (e.g., <−120 dBc/Hz at 1 Hz and <−155 dBc/Hz at 10 kHz) (*24*), the repetition-rate phase noise can be transferred to the microwave domain when a careful O-E conversion process is used.

Demonstration of ultrabroadband and ultrastable all-fiber dual comb sources

The capability for stabilization of multiple comb sources with different repetition rates enables various system designs as needed. One such example is a dual-comb spectroscopy (*25*, *26*) source. So far, dual-comb sources have been mostly based on either simple but relatively lower performance mode-locked oscillators (*27*) or higher-performance but much more complicated ultrastable cavity-stabilized combs (*26*). As an alternative approach for achieving both simplicity and high performance, our proposed method can constitute an all-fiber photonic dual-comb source with high-resolution, high-frequency accuracy, and broad bandwidth. In our experiment (see Fig. 4A), two ~250-MHz erbium fiber combs (denoted as comb-A and comb-B; see Materials and Methods) with a 180-Hz repetition rate difference (Δf_{rep}) are simultaneously stabilized to a 1.23-km-long fiber delay line. Note that 180-Hz detuning is chosen to cover more than an octave (1 to 2 μm) from spectrally broadened erbium fiber frequency combs. For stabilization, 1540- and 1560-nm filtering with a 1-nm bandwidth are used for comb-A and comb-B, respectively. The comb-to-comb interferogram is acquired by a high-speed oscilloscope and is Fourier transformed into the radio frequency (RF) domain, which confirms that Δf_{rep} is 180 Hz (Fig. 4B). To evaluate the relative linewidth between the two combs, we measured the relative linewidths with respect to the CW laser locked to the same fiber reference (see Materials and Methods and the Supplementary Materials). As shown in Fig. 4C, the relative linewidth between

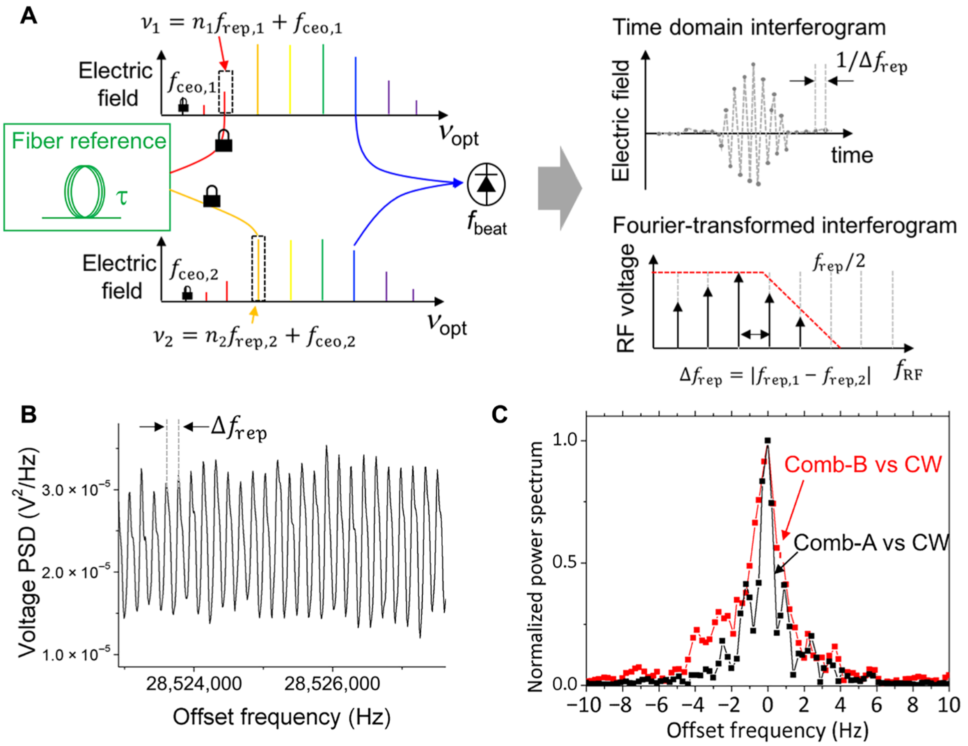

Fig. 4. Two optical frequency combs locked to a single fiber delay line. (**A**) Concept of dual-comb source stabilization using a single fiber delay line. (**B**) Fourier-transformed interferogram of the fiber delay–stabilized comb-A and comb-B. (**C**) Relative linewidth between each comb and the CW laser when both lasers are stabilized to the same fiber delay line.

comb-A (comb-B) and the CW laser is 0.8 Hz (1.8 Hz), which gives the estimated relative linewidth between the two combs as ~1-Hz level.

DISCUSSION

We have demonstrated an all-fiber photonic platform for generating multiple ultrastable optical frequency combs with 5.7×10^{-15} frequency instability within 1 s. The frequency stabilization is based on only off-the-shelf, telecommunications-grade fiber-optic components, which enable both low cost and high reliability. Multiple combs with arbitrarily different repetition rates can be simultaneously stabilized to a single fiber delay line, and as a representative example, an octave-spanning ultrastable dual-comb source is demonstrated. Currently, the dominant source limiting the performance is temperature-dependent drift of the fiber link, and this limitation may be substantially improved by using lower-temperature coefficient fiber links (*28*, *29*). Although erbium fiber combs are used in this demonstration, any kind of comb source, including microresonator-based combs (*30*), can be stabilized as well. By selecting the right fiber, other spectral ranges from visible to mid-infrared can be effectively covered as well. Because of the alignment-free nature, the demonstrated method is particularly useful for many emerging field applications of stabilized combs such as microwave synthesizers (*6*, *7*), photonics-based radar (*11*), dual-comb spectroscopy (*4*, *5*, *25*–*26*), accurate dispersion measurement of microresonators (*31*), timing of ultrafast x-ray and electron science facilities (*9*, *10*), space-borne instruments (*32*), and many more to come in the future.

MATERIALS AND METHODS

Optical frequency comb sources

Two commercial erbium fiber mode-locked laser-based optical frequency comb sources are used for the demonstration experiment. Comb-A (used for Figs. 2 to 4 data) is a nonlinear amplifying loop mirror-based erbium fiber laser frequency comb (FC1500-250-ULN, Menlo Systems GmbH). Comb-B (used for Fig. 4 data) is a nonlinear polarization rotation-based erbium fiber laser frequency comb (FC1500, Menlo Systems GmbH). The fundamental repetition rate of both combs is ~250 MHz. The free-running repetition-rate (f_{rep}) phase noise (scaled to a 10-GHz carrier frequency) of comb-A and comb-B is measured to be −110 and −95 dBc/Hz, respectively, at a 1-kHz offset frequency. The integrated timing jitters of the free-running combs are 175 as (1.2 fs) and 389 as (7 fs) for comb-A and comb-B, respectively, when integrated from 10 kHz (1 kHz) to 1 MHz offset frequency. The f_{ceo} of comb-A is stabilized by home-built electronics with >100 kHz locking bandwidth using an intracavity electro-optic modulator (EOM). The f_{ceo} of comb-B is stabilized by built-in electronics with locking bandwidth of >10 kHz using pump current modulation. The self-referenced f_{ceo} stabilization performance for comb-A (comb-B) includes 6×10^{-16} (6×10^{-15}) frequency instability over 1 s and 100 mrad (2.5 rad) phase noise integrated from 1 Hz to 1 MHz. The free-running timing jitter and stabilized f_{ceo} PSD measurement results for comb-A and comb-B are presented in fig. S1.

Fiber reference systems

The fiber reference system in this work is based on a fiber Michelson interferometer with a long (~1 km) delay arm. The delay arm length is chosen to be ~1 km in this work by considering the trade-off between the achievable detection sensitivity and stability (which scales with the delay τ) and the achievable locking bandwidth (which scales with the inverse of the delay $1/\tau$). A tapping average optical power of >500 μW from the comb sources is enough for the stabilization. The 1-nm bandwidth fiber Bragg gratings (FBGs) centered at 1540 and 1560 nm are used as the OBPF (in Fig. 1) for comb-A and comb-B, respectively. Note that instead of FBG, narrow bandwidth wavelength-division multiplexing (WDM) fiber couplers also worked well. The filtered comb signal is amplified by an erbium-doped fiber amplifier (EDFA) up to ~10 to 20 mW. Note that, if the optical power is more than 30 mW, then nonlinear power-dependent intensity noise degrades the sensitivity of the system, as also reported in (*33*). This filtered and amplified signal is applied to the Michelson interferometer. A compact fiber delay line is manufactured by the fiber-optic gyroscope coil winding method.

An in-line AOFS (AMF-50-1550-2FP, Brimrose Inc.) is inserted in the long fiber delay arm and modulated by a 50-MHz source for synchronous detection. The interferometer output is split by colors using FBG or WDM. The filtered power is 1 to 2 mW and sent to a photodetector. The photodetected 100-MHz signal (twice the AOFS driving frequency) is filtered by a 100-MHz RF bandpass filter (24-MHz bandwidth) and amplified by a 40-dB RF amplifier. The 100-MHz signal is then down-converted to the baseband by mixing with a frequency-doubled AOFS driving signal. The baseband mixer output is low-pass–filtered and applied to the EOM and/or the piezoelectric transducer (PZT) in a mode-locked oscillator cavity.

For comb-A, an intracavity EOM is used, and the locking bandwidth of the stabilization is ~80 kHz, mainly limited by the $1/\tau$ frequency. For comb-B, an intracavity PZT and EOM are used, and the locking bandwidth is ~20 kHz, mainly limited by the EOM. The resulting stability and noise performance are greatly improved by better shielding against acoustic noise. A low-vacuum (~20 torr) environment was enough to suppress most of the acoustic noise coupled to the fiber delay line (see fig. S7). To avoid heat problems, the AOFS and motorized delay stage (in the long delay arm) are located outside the vacuum box without tight packaging. Although most of the acoustic noise (from the air) is removed by a low-vacuum shielding, the vibration noise coming from the bottom of the setup still affects the residual phase/frequency noise in the range of 20 to 200 Hz (as shown in Figs. 2, A and B, and 3). More detailed discussion on the vibration noise issues and a potential way to suppress the noise coupling are presented in the Supplementary Materials. Overall, we believe that optimization of the packaging setup may further improve the noise performance.

Frequency noise calibration method

The baseband signal from the mixer output is the frequency noise of the comb line multiplied by the delay time τ. The baseband signal is applied to the oscilloscope, fast Fourier transform (FFT) spectrum analyzer, and RF spectrum analyzer. The transfer function is written as $T(f) = V_{\mathrm{pk}}\,|(1\text{-}e^{-i2\pi f\tau})/(i \times f)|$, where V_{pk} is half of the measured peak-to-peak voltage of the low-pass–filtered mixer output, f is the offset frequency, and τ is the delay time induced by the fiber link. If the Fourier frequency is much lower than $1/\tau$, then the transfer function (i.e., detection sensitivity) can be written as $2\pi f\tau V_{\mathrm{pk}}$. The comb-line frequency noise is measured at the optical frequency (e.g., 194.67 THz corresponding to 1540 nm).

Out-of-loop comb-line frequency noise measurement method

The out-of-loop optical frequency and phase noise performance of the stabilized combs are characterized by a second interferometer with the same (~1 km) fiber delay line. Figure S2 shows a schematic diagram of the measurement setup. For effective pulse overlap, a 330-ps motorized delay line (MDL-330-FC/APC, General Photonics) is inserted in the out-of-loop fiber Michelson interferometer.

Absolute linewidth measurement method

To characterize the linewidth of the stabilized frequency comb, a 1550-nm CW fiber laser (ETH-20-1550.12-2-PZ10B-TT20-SL130, Orbits Lightwave Inc.), which is frequency locked to a 1-km-long fiber delay line, is used [similar way as shown in (*13*)]. The frequency instability of the fiber delay line-locked CW laser is 10^{-14} level over 1 s. The frequency noise PSD is shown in fig. S4, and the projected linewidth of the CW laser is ~26 Hz. The absolute linewidth of the stabilized combs is measured by an FFT analyzer with a 7.8125-Hz resolution bandwidth (RBW).

Dual-comb source experiment

Comb-A (filtered at 1540 nm) and comb-B (filtered at 1560 nm) are simultaneously locked to the 1-km-long fiber delay line. The optical spectrum ($\Delta\nu$) covered by dual-comb sources can be written as $\Delta\nu = f_{\mathrm{rep}}^{2}/2\Delta f_{\mathrm{rep}}$, where Δf_{rep} is the repetition rate frequency difference between two combs and f_{rep} is the repetition rate (*5*). In this experiment, to cover more than a 150-THz optical span, a 180-Hz repetition rate difference is selected. To achieve a small repetition rate difference (180 Hz in this work), dispersion compensation or group delay compensation between two spectral ranges is necessary. In this experiment, a spool of 100-m-long dispersion compensating fiber (LLWBDK, OFS) is used to compensate dispersion between 1540 and 1560 nm for the 1.23-km-long fiber spool. As the two combs have different free-running repetition-rate phase noise and achievable locking bandwidths due to different actuator performance, the stabilized phase noise PSDs are also different, as shown in fig. S5. As expected, comb-A has 10-dB lower phase noise than comb-B above 1-kHz offset frequency. The stabilized comb-A and comb-B are coupled by a 3-dB optical coupler (OC). The coupled signal is filtered by a 1-nm full width at half maximum OBPF at 1550 nm and photodetected. The photodetected signal is analyzed by a high-resolution oscilloscope (RTO2044, Rohde Schwarz). The sampling rate is 100 MHz, and the acquisition time is 100 ms. The RF spectrum shown in Fig. 4B is a Fourier-transformed interferogram by MATLAB. Since the repetition rates of the two combs are different, it is difficult to directly measure the relative linewidth of the two combs due to insufficient comb-line power (typically, the average power of each comb line is less than a microwatt). As an indirect evaluation method, the relative linewidth of the comb and CW laser is measured by locking both the comb and CW laser to the same fiber stabilization system (see fig. S6). The relative linewidth of the stabilized combs is measured by an FFT analyzer with a 244-mHz RBW.

SUPPLEMENTARY MATERIALS

Supplementary material for this article is available at http://advances.sciencemag.org/cgi/content/full/6/13/eaax4457/DC1

Section S1. Optical frequency comb sources
Section S2. Out-of-loop comb-line frequency noise measurement method
Section S3. Absolute linewidth measurement method
Section S4. Dual-comb source experiment

Section S5. Impact of acoustic noise, vibrations, and temperature fluctuations on the fiber delay line–based stabilization system
Fig. S1. Free-running f_{rep} phase noise PSD and locked f_{ceo} noise PSD of comb-A and comb-B.
Fig. S2. Experimental setup for out-of-loop optical phase noise measurement.
Fig. S3. Measured in-loop and out-of-loop optical phase noise of the fiber delay line–stabilized comb.
Fig. S4. Linewidth measurement at 1550 nm.
Fig. S5. Optical phase noise of the fiber delay line–stabilized dual-comb source.
Fig. S6. Relative linewidth measurement experiment between the comb and CW laser.
Fig. S7. Impact of acoustic shielding on the measured out-of-loop optical phase noise PSDs.
Fig. S8. Vibration sensitivity measurement.
Fig. S9. Comparison between the measured frequency noise PSDs (black) and the estimated frequency noise PSDs computed from the measured vibration PSDs (red).
Fig. S10. Frequency noise and vibration sensitivity reduction by a spring-mass mount.
References (*34*, *35*)

REFERENCES AND NOTES

1. A. D. Ludlow, M. M. Boyd, J. Ye, E. Peik, P. O. Schmidt, Optical atomic clocks. *Rev. Mod. Phys.* **87**, 637–701 (2015).
2. A. Foltynowicz, T. Ban, P. Masłowski, F. Adler, J. Ye, Quantum-noise-limited optical frequency comb spectroscopy. *Phys. Rev. Lett.* **107**, 233002 (2011).
3. F. Adler, M. J. Thorpe, K. C. Cossel, J. Ye, Cavity-enhanced direct frequency comb spectroscopy: Technology and applications. *Annu. Rev. Anal. Chem.* **3**, 175–205 (2010).
4. B. Bernhardt, A. Ozawa, P. Jacquet, M. Jacquey, Y. Kobayashi, T. Udem, R. Holzwarth, G. Guelachvili, T. W. Hänsch, N. Picqué, Cavity-enhanced dual-comb spectroscopy. *Nat. Photonics* **4**, 55–57 (2010).
5. I. Coddington, N. Newbury, W. Swann, Dual-comb spectroscopy. *Optica* **3**, 414–426 (2016).
6. T. M. Fortier, M. S. Kirchner, F. Quinlan, J. Taylor, J. C. Bergquist, T. Rosenband, N. Lemke, A. Ludlow, Y. Jiang, C. W. Oates, S. A. Diddams, Generation of ultrastable microwaves via optical frequency division. *Nat. Photonics* **5**, 425–429 (2011).
7. X. Xie, R. Bouchand, D. Nicolodi, M. Guinta, W. Hänsel, M. Lezius, A. Joshi, S. Datta, C. Alexandre, M. Lours, P.-A. Tremblin, G. Santarelli, R. Holzwarth, Y. Le Coq, Photonic microwave signals with zeptosecond-level absolute timing noise. *Nat. Photonics* **11**, 44–47 (2017).
8. J. Lee, Y.-J. Kim, K. Lee, S. Lee, S.-W. Kim, Time-of-flight measurement with femtosecond light pulses. *Nat. Photonics* **4**, 716–720 (2010).
9. J. Kim, J. A. Cox, J. Chen, F. X. Kärtner, Drift-free femtosecond timing synchronization of remote optical and microwave sources. *Nat. Photonics* **2**, 733–736 (2008).
10. S. Schulz, I. Grguraš, C. Behrens, H. Bromberger, J. T. Costello, M. K. Czwalinna, M. Felber, M. C. Hoffmann, M. Ilchen, H. Y. Liu, T. Mazza, M. Meyer, S. Pfeiffer, P. Prędki, S. Schefer, C. Schmidt, U. Wegner, H. Schlarb, A. L. Cavlieri, Femtosecond all-optical synchronization of an X-ray free-electron laser. *Nat. Commun.* **6**, 5938 (2015).
11. P. Ghelfi, F. Laghezza, F. Scotti, G. Serafino, A. Capria, S. Pinna, D. Onori, C. Porzi, M. Scaffardi, A. Malacarne, V. Vercesi, E. Lazzeri, F. Berizzi, A. Bogoni, A fully photonics-based coherent radar system. *Nature* **507**, 341–345 (2014).
12. A. Khilo, S. J. Spector, M. E. Grein, A. H. Nejadmalayeri, C. W. Holzwarth, M. Y. Sander, M. S. Dahlem, M. Y. Peng, M. W. Geis, N. A. DiLello, J. U. Yoon, A. Motamedi, J. S. Orcutt, J. P. Wang, C. M. Sorace-Agaskar, M. A. Popović, J. Sun, G.-R. Zhou, H. Byun, J. Chen, J. L. Hoyt, H. I. Smith, R. J. Ram, M. Perrot, T. M. Lyszczarz, E. P. Ippen, F. X. Kärtner, Photonic ADC: Overcoming the bottleneck of electronic jitter. *Opt. Express* **20**, 4454–4469 (2012).
13. F. Kéfélian, H. Jiang, P. Lemonde, G. Santarelli, Ultralow-frequency-noise stabilization of a laser by locking to an optical fiber-delay line. *Opt. Lett.* **34**, 914–916 (2009).
14. D. Kwon, J. Kim, All-fiber interferometer-based repetition-rate stabilization of mode-locked lasers to 10^{-14}-level frequency instability and 1-fs-level jitter over 1 s. *Opt. Lett.* **42**, 5186–5189 (2017).
15. W. Hänsel, M. Guinta, K. Beha, M. Lezius, M. Fischer, R. Holzwarth, Ultra-low phase noise all-PM Er:fiber optical frequency comb, in *Proceedings of the OSA Advanced Solid State Lasers* (2015), Berlin, Germany, 4 to 9 October 2015, paper ATh4A.2.
16. L. Z. Duan, Intrinsic thermal noise of optical fibers due to mechanical dissipation. *Electron. Lett.* **46**, 1515–1516 (2010).
17. L. Duan, General treatment of the thermal noises in optical fibers. *Phys. Rev. A* **86**, 023817 (2012).
18. K. Jung, J. Kim, All-fibre photonic signal generator for attosecond timing and ultralow-noise microwave. *Sci. Rep.* **5**, 16250 (2015).
19. G. D. Domenico, S. Schilt, P. Thomann, Simple approach to the relation between laser frequency noise and laser line shape. *Appl. Optics* **49**, 4801–4807 (2010).
20. Y. T. Chen, Use of single-mode optical fiber in the stabilization of laser frequency. *Appl. Optics* **28**, 2017–2021 (1989).
21. Keysight Technologies, *E8257D PSG Microwave Analog Signal Generator—Data Sheet* (2015); http://literature.cdn.keysight.com/litweb/pdf/5989-0698EN.pdf [accessed 23 September 2015].
22. T. M. Fortier, C. W. Nelson, A. Hati, F. Quinlan, J. Taylor, H. Jiang, C. W. Chou, T. Rosenhand, N. Lemke, A. Ludlow, D. Howe, C. W. Oates, S. A. Diddams, Sub-femtosecond absolute timing jitter with a 10 GHz hybrid photonic-microwave oscillator. *Appl. Phys. Lett.* **100**, 231111 (2012).
23. D. Eliyahu, D. Seidel, L. Maleki, Phase noise of a high performance OEO and an ultra low noise floor cross-correlation microwave photonic homodyne system, in *Proceedings of the IEEE International Frequency Control Symposium* (IEEE, 2008), Honolulu, HI, USA, 19 to 21 May 2008, pp. 811–814.
24. K. Jung, J. Kim, Subfemtosecond synchronization of microwave oscillators with mode-locked Er-fiber lasers. *Opt. Lett.* **37**, 2958–2960 (2012).
25. S. Schiller, Spectrometry with frequency combs. *Opt. Lett.* **27**, 766–768 (2002).
26. I. Coddington, W. C. Swann, N. R. Newbury, Coherent multi heterodyne spectroscopy using stabilized optical frequency combs. *Phys. Rev. Lett.* **100**, 013902 (2008).
27. X. Zhao, G. Hu, B. Zhao, C. Li, Y. Pan, Y. Liu, T. Yasui, Z. Zheng, Picometer-resolution dual-comb spectroscopy with a free-running fiber laser. *Opt. Express* **24**, 21833–21845 (2016).
28. M. Bousonville, M. K. Bock, M. Felber, T. Ladwig, T. Lamb, H. Schlarb, S. Schulz, C. Sydlo, S. Hunziker, P. Kownacki, S. Jablonski, New phase stable optical fiber, in *Proceedings of the Beam Instrumentation Workshop* (Jefferson Lab, paper MOPG 033, 2012), pp. 101–103.
29. E. N. Fokoua, M. N. Petrovich, T. Bradley, F. Poletti, D. J. Richardson, R. Slavík, How to make the propagation time through an optical fiber fully insensitive to temperature variations. *Optica* **4**, 659–668 (2017).
30. T. J. Kippenberg, R. Holzwarth, S. A. Diddams, Microresonator-based optical frequency combs. *Science* **332**, 555–559 (2011).
31. P. Del'Haye, O. Arcizet, M. L. Gorodetsky, R. Holzwarth, T. J. Kippenberg, Frequency comb assisted diode laser spectroscopy for measurement of microcavity dispersion. *Nat. Photonics* **3**, 529–533 (2009).
32. M. Lezius, T. Wilken, C. Deutsch, M. Guinta, O. Mandel, A. Thaller, V. Schkolnik, M. Schiemangk, A. Dinkelaker, A. Kohfeldt, A. Wicht, M. Krutzik, A. Peters, O. Hellmig, H. Duncker, K. Sengstock, P. Windpassinger, K. Lapmann, T. Hülsing, T. W. Hänsch, R. Holzwarth, Space-borne frequency comb metrology. *Optica* **3**, 1381–1387 (2016).
33. O. Okusaga, J. Cahill, W. Zhou, A. Docherty, G. M. Carter, C. R. Menyuk, Optical scattering induced noise in RF-photonic systems, in *Proceedings of the IEEE International Frequency Control Symposium & European Frequency and Time Forum* (IEEE, 2011), San Francisco, CA, USA, USA, 2 to 5 May 2011, pp. 994–999.
34. D. Kwon, C.-G. Jeon, J. Shin, M.-S. Heo, S. E. Park, Y. Song, J. Kim, Reference-free, high-resolution measurement method of timing jitter spectra of optical frequency combs. *Sci. Rep.* **7**, 40917 (2017).
35. N. Bucalovic, V. Dolgovskiy, C. Schori, P. Thomann, G. Di Domenico, S. Schilt, Experimental validation of a simple approximation to determine the linewidth of a laser from its frequency noise spectrum. *Appl. Optics* **51**, 4582–4588 (2012).

Acknowledgments

Funding: This research was supported by the National Research Foundation of Korea (grant 2018R1A2B3001793). **Author contributions:** D.K. and J.K. conceived the idea and designed the experiments. D.K., I.J., W.-K.L., and M.-S.H. performed the experiments and measured data. D.K. and J.K. analyzed the data and wrote the manuscript with inputs from all authors. **Competing interests:** J.K. and D.K. are inventors on a patent application related to this work filed by Korea Advanced Institute of Science and Technology (KAIST) (no. US 16/572,636; filed 17 September 2019). The authors declare no other competing interests. **Data and materials availability:** All data needed to evaluate the conclusions in the paper are present in the paper and/or the Supplementary Materials. Additional data related to this paper may be requested from the authors.

Submitted 24 March 2019
Accepted 3 January 2020
Published 27 March 2020
10.1126/sciadv.aax4457

Citation: D. Kwon, I. Jeon, W.-K. Lee, M.-S. Heo, J. Kim, Generation of multiple ultrastable optical frequency combs from an all-fiber photonic platform. *Sci. Adv.* **6**, eaax4457 (2020).