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ABSTRACT

We have developed a simple and practical optical frequency comb (OFC) stabilization method for comb linewidth reduction in this Letter. Two comb modes of an Er-fiber optical frequency comb (OFC) have been phase-locked to a kilometer-long fiber delay line, while narrow linewidth lasers are not required as optical references. The fractional frequency stability of the 1542-nm comb mode in the Er-fiber OFC reaches 9.13×10^{-13} at 12.8 ms average time, and its short-term linewidth is 580 Hz, which is compressed by a factor of ~170 compared to the free-running condition. The whole stabilization scheme gets rid of nonlinear progress, which can be an alternative approach for OFC stabilization, especially in ultra-high repetition-rate combs, e.g., electro-optic combs, quantum cascade laser combs, and micro-combs with low pulse energy.

Optical frequency comb (OFC) has become an indispensable tool for high precision scientific and industrial applications in the past two decades.[1,2] Evolution and rapid advances in OFC sources have largely been powered by laser stabilization techniques.[3–5] A fully stabilized OFC is often obtained by phase locking two degrees of freedom, namely, carrier-envelope offset frequency (f_{ceo}) and the repetition rate frequency (f_{rep}) to an absolute radio frequency (RF) reference, e.g., a Cesium clock. In this manner, absolute frequency of each comb mode is linked to an atomic clock via the comb equation, $\nu_n = nf_{rep} + f_{ceo}$, where n represents the number of the comb mode.[6] The associated fractional frequency uncertainty of comb modes can reach the 10^{-12}–10^{-13} level with 1 s averaging.[7,8] Despite the absolute optical frequency accuracy, the linewidth of comb modes is not necessarily narrowed down due to the inferior short-term stability of radio references. For commonly used fiber OFC sources, comb-mode linewidth remains on the order of several tens kHz to hundreds kHz,[8] which prohibits specific OFC applications that relies on narrow linewidth comb modes with ultra-low phase noise, such as optical clock comparison,[9] high spectral purity microwave signal generation,[10] distance ranging,[11] and molecular spectroscopy.[12]

To overcome the above issue, alternative optical references, which are usually single frequency lasers stabilized to high-finesse optical cavities through the Pound–Drever–Hall (PDH) approach, are implemented. In this approach, a heterodyne signal f_{beat} (obtained from the beat between a comb mode and the stable single frequency laser) is phase-locked to a RF reference through OFC's fast cavity length feedback while stabilizing f_{ceo} simultaneously. By doing this, the superior frequency stability of the optical cavity is transferred to each comb mode across the OFC. Fractional frequency stability down to the 10^{-17} level with 1 s averaging time has been reported.[13,14] The residual phase error is <1 rad, and the comb mode linewidth reaches sub-mHz levels.[15,16]

The aforementioned narrow linewidth OFC sources rely on cavity stabilized CW lasers. Despite the superior OFC stabilization performance, the system requires complicated and high-cost cavity-stabilized optical references. An optical fiber delay line has been routinely used for frequency stabilization of a CW laser as a reliable and low-cost alternative to optical cavity. Recently, Kwon *et al.* developed an all-fiber OFC source that utilizes a fiber delay line to phase lock an individual comb mode of an OFC. *f-2f* self-referencing is employed for f_{ceo} detection and stabilization. The fully stabilized OFC shows sub-10^{-15}-level fractional frequency stability and 28-Hz absolute linewidth.[17] However, an *f-2f* self-referencing is still required to detect f_{ceo}. In this work, we demonstrate an alternative approach for OFC stabilization, where two comb modes (1537 and 1566-nm) are simultaneously phase-locked to a single 1.25×2-km fiber delay line by high-speed pump power modulation and extra-cavity offset frequency modulation, respectively. Neither cavity stabilized CW laser nor *f-2f* interferometer is required. An out-of-loop measurement by beating the OFC with a narrow linewidth CW laser shows that the linewidth of comb mode is narrowed down by 170 times after full stabilization. For a comb mode at 1542-nm, the residual phase noise is 925 mrad (integrated from 10 MHz to 1 kHz) and the linewidth is 580 Hz at 2 ms averaging time. Further linewidth narrowing is limited by the slow drift of fiber delay line at longer averaging time.

The OFC stabilization concept derives from the delayed self-heterodyne (DSH) method, which was first implemented in the frequency noise detection and stabilization of CW lasers. In DSH setups, the CW laser's output is split and heterodyned with its delayed optical field. Frequency fluctuations are first converted into phase fluctuations, taking place in the delay line. Heterodyne detection then converts the phase fluctuations to voltage fluctuations. The error voltage is then feedback to the laser cavity; thus, the laser frequency is stabilized to the delay line. Within the locking bandwidth, the fractional frequency noise of the CW laser $\delta\nu(f)/\nu$ equals to the length fluctuation of the delay line $\delta L(f)/L$, where f is Fourier frequency. In practice, the DSH method is implemented in an asymmetric fiber interferometer configuration and a kilometer-long single mode fiber (SMF) is used as the delay line. The interferometer functions as a low thermal expansion high-finesse Fabry–Pérot cavity, and the frequency of the CW laser is effectively phase-locked to one of the cavity's transmission peaks (ν_{FSR}). Using this technique, frequency noise of a distributed-feedback laser can be reduced by 40 dB, leading to a frequency noise power spectral density (PSD) below 1 Hz^2/Hz level.[18]

We further exploit the DSH method for optical frequency comb stabilization. The procedure is to detect comb-line frequency noise at two wavelengths, λ_1 and λ_2, based on DSH. Then, the two error signals are used to stabilize two degrees of freedom of the OFC, respectively, as illustrated in Fig. 1. Since it is not possible to detect single comb tooth, a bunch of optical comb modes at λ_i (i = 1,2) are filtered out by a narrow bandpass filter for DSH. Assuming that the comb-line frequency noise within the filter passband is similar, the heterodyne beat carries the frequency noise, $p \cdot \delta[\tau(nf_{rep} + f_{ceo})]$. Here, n is the mode number, p is the number of comb lines within the filter passband, and τ accounts for the temporal delay in the delay line. Note that the frequency noise of comb modes is amplified by a factor of τ in the DSH process. Therefore, long fiber delay line is beneficial for a high frequency noise discrimination sensitivity. The error signal from λ_1 is fed back to extra-cavity AOFS for carrier envelope offset frequency stabilization, while error signal from λ_2 is fed back to pump power for repetition rate stabilization. By doing this, frequency noise of all the optical modes in the OFC is traced to a single delay line's instability $\delta\tau/\tau$. In frequency domain, all the comb modes of the OFC are strictly aligned

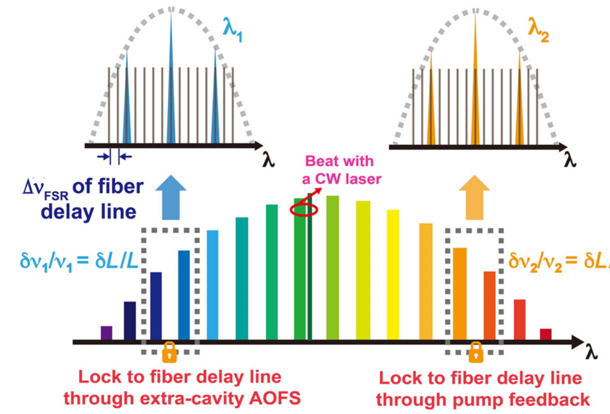

FIG. 1. Scheme of optical frequency comb reference to a fiber delay line. AOFS, acousto-optic frequency shifter. Two insets show the filtered out optical comb modes. Gray lines represent the transmission peaks of the fiber delay line.

to the transmission peaks (ν_{FSR}) of the fiber interferometer (gray lines in Fig. 1). An out-of-loop measurement by beating certain comb mode with a narrow linewidth CW laser could be conducted to evaluate the noise performance of the stabilized OFC.

The laser source used in our experiment is a home-made nonlinear polarization evolution (NPE) mode-locked Er-doped fiber laser with a 205 MHz repetition rate. A manual linear translation stage is installed under one of the collimators to coarsely tune the laser's repetition rate (see Sec. S1 in the supplementary material). The output average power of the laser is ~120 mW (~0.5 nJ). The laser works at stretched pulse mode-locking regime with close to zero net-cavity dispersion. A fiber AOFS (AA Opto-Electronic, MT110-IIR20-Fio-SM0) is connected to the output of the laser to modulate f_{ceo} of the laser at a 25-MHz 3-dB bandwidth with the transmission efficiency of 58%. Conversely, we used pump power modulation for fast repetition rate stabilization. The 3-dB bandwidth for pump power modulation is around 30 kHz, limited by the pump diode driver (Thorlabs, LDC 8020). A dense wavelength division multiplexer (DWDM) filters out three bunches of comb lines around 1537, 1566, and 1542 nm. The first two bunches are used for OFC stabilization, while the last bunch is used for out-of-loop comb mode stability evaluation. The filter bandwidth of DWDM is 200 GHz, corresponding to ~1.6 nm bandwidth in wavelength.

An asymmetric fiber interferometer is implemented to generate the heterodyne beat, f_{hb1} and f_{hb2}, for filtered wavelengths at $\lambda_1 = 1537$ nm and $\lambda_2 = 1566$ nm, as shown in Fig. 2(a). A 2×2 fiber coupler splits the two filtered spectral segments into the reference arm and delayed arm. In the reference arm, two spectral segments are simply bounced back by an FRM at the end of the arm. In the delayed arm, two spectral segments pass through a 1.25-km long fiber spool (848-m SMF-28 + 402-m DCF38), a delay control unit (DCU), and an AOFS and are reflected by an FRM at the end of the arm. The fiber spool is sealed by silicon rubber within a compact size (12-cm diameter) and installed in a low-pressure glassware. Such a compact and robust fiber packaging effectively blocks various technical noises induced by mechanical vibrations and heat conduction at <10 kHz. We characterized the phase noise of the fiber delay line (the experimental implementation can be found in Sec. S2 in the supplementary

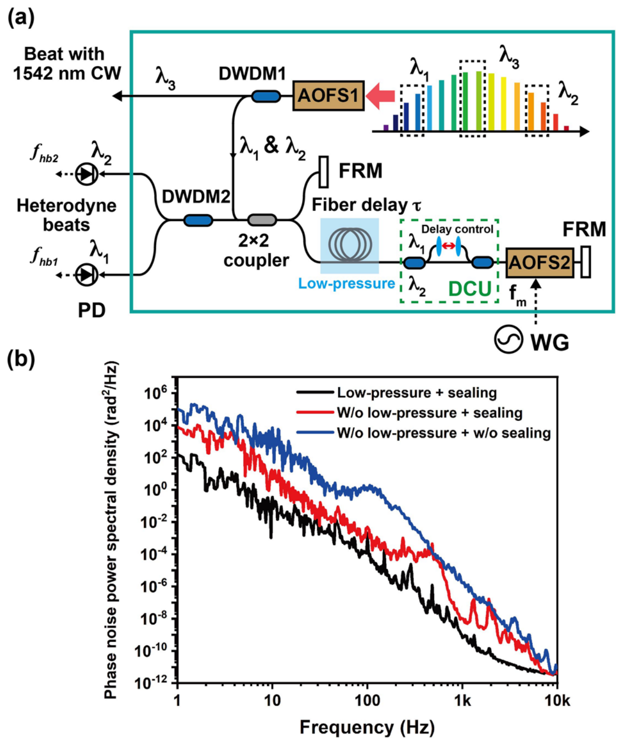

FIG. 2. (a) Experimental setup of asymmetric fiber interferometer. FRM, faraday rotating mirror; DWDM, dense wavelength division multiplexer; AOFS, acoustic optical frequency shifter; PD, photodetector (Menlo Systems, FPD510); DCU, delay control unit; WG, waveform generator. (b) Phase noise PSD of the fiber delay line under different environmental conditions.

material) under different environmental conditions: (1) with sealing, with low pressure; (2) with sealing, without low pressure; and (3) without sealing, without low pressure (open air case). The results are shown in Fig. 2(b), which indicates that the sealing and 70-kPa low-pressure yield 30-dB phase-noise rejection from 1 Hz to 1 kHz offset frequency. A waveform generator (Rigol, DG4162) drives the AOFS2 in the delayed arm for shifting the optical signals' frequency by $2f_m = 100$ MHz, where f_m is modulation frequency. Consequently, the pulses in long fiber arm have a frequency offset of 100-MHz-frequency from that in the reference arm. At the output of the asymmetric fiber interferometer, another DWDM de-multiplexes λ_1 and λ_2, which illuminate two photodiodes, respectively, for heterodyne beat detection.

To obtain the 100-MHz beat note with a high signal-to-noise ratio, one needs to match multiples of laser cavity length to the fiber delay line. This step is equivalent to loosely matching the optical modes around λ_i with ν_{FSR} of the fiber delay line. Considering the fiber delay line's group delay dispersion, the temporal delay for λ_1 and λ_2 is adjusted separately by the delay control in the DCU of the fiber interferometer.

The laser and asymmetric fiber interferometer are put in an aluminum box and placed on a vibration isolation table (Table Stable Ltd, AVI-200M/LP). The isolation table enables active control with a cutoff frequency of 1 Hz. Through this careful package, acoustic noise induced by mechanical vibrations, air flow, and temperature change could be partly blocked, leading to at least 6 h continuous operation of narrow-linewidth OFC operation.

Two 100-MHz heterodyne beats from two wavelengths contain frequency noise information of filtered optical comb modes. We utilize two narrow bandpass filters with the 100 MHz center frequency to filter out the two beat notes and amplify them to >5 dBm. Two frequency dividers are used to divide 100-MHz heterodyne beats to 25 MHz. Divided heterodyne beats are then mixed with $f_m/2$ from the same waveform generator. The output error voltages from the mixers are proportional to frequency noise, $p\cdot[\tau(mf_{rep} + f_{ceo})]$, of filtered optical comb modes. Here, m represents the mode number and $p = 980$ represents the number of filtered comb modes. The error signal from 1566 nm is fed back upon the extracavity AOFS1 through a PID servo (Vescent Photonics, D2-125) for f_{ceo} stabilization. On the other hand, the error signal from 1537 nm is fed back upon pump power modulation through a PI servo (Newfocus, LB1005) for repetition rate stabilization. The detailed setup for phase locking could be found in Sec. S3 in the supplementary material.

After the two phase-locked loops are closed, two degrees of freedom of the OFC are both stabilized, resulting a full-stabilized narrow linewidth OFC. The bandwidths of two phase-locked loops are around 40 kHz, which is mainly limited by the first null frequency in the transfer function of fiber delay line (see Fig. S4 in the supplementary material). To evaluate the noise performance of the stabilized frequency comb, comb modes around 1542 nm are filtered out by DWDM1 and beat with a commercial narrow-linewidth CW laser working at 1542 nm Stable Laser Systems. The typical linewidth of the laser is 1 Hz. In this case, the phase noise, the Allan deviation, and the linewidth of out-of-loop beat signal (f_{beat}) represent those of the individual comb mode at 1542 nm in the stabilized OFC because the reference CW laser has negligible noise compared to the stabilized optical frequency comb.

The residual phase noise power spectral density (PSD) of f_{beat} is characterized by a signal source analyzer (SSA) (Keysight, E5052b), as represented by an orange curve in Fig. 3. Compared with the free-running state (the black curve), the phase noise within locking bandwidth is effectively suppressed. The resulting residual integrated phase noise is 925 mrad (integrated from 10 MHz to 1 kHz). The β-separation line [red-dashed curve in Fig. 3(a)] indicates that estimated linewidth of 1542 nm comb mode is below 1 kHz. The noise of fiber delay line is also measured and plotted in the gray curve in Fig. 3.

The frequency variations of the f_{beat} are recorded by a frequency counter (Keysight, 53220A) with 100 μs gate time. Fractional Allan deviation of f_{beat} is calculated and presented in Fig. 3(b). The frequency stability has been improved by at least one order of magnitude after phase-locking. Allan deviation averages down as $\tau^{-1/2}$ until 10 ms and reaches 9.13×10^{-13} at 12.8 ms. For longer timescale (>100 ms), Allan deviation increases with τ^{+1}, which is affected by the long-term drifting of the referenced fiber delay line. Green shaded parts in Fig. 3(b) show the short-term stability of several microwave atomic clocks (see Sec. S5 in the supplementary material). The comparison exhibits that OFC's short-term stability is superior to that of H masers at <40 ms timescale, superior than that of Cs clock at <100 ms timescale and superior than that of Rb clock at <1 s timescale. This reveals that fiber delay line stabilized OFC has comparative or even superior short-term stability than the OFCs that are traced to microwave references.

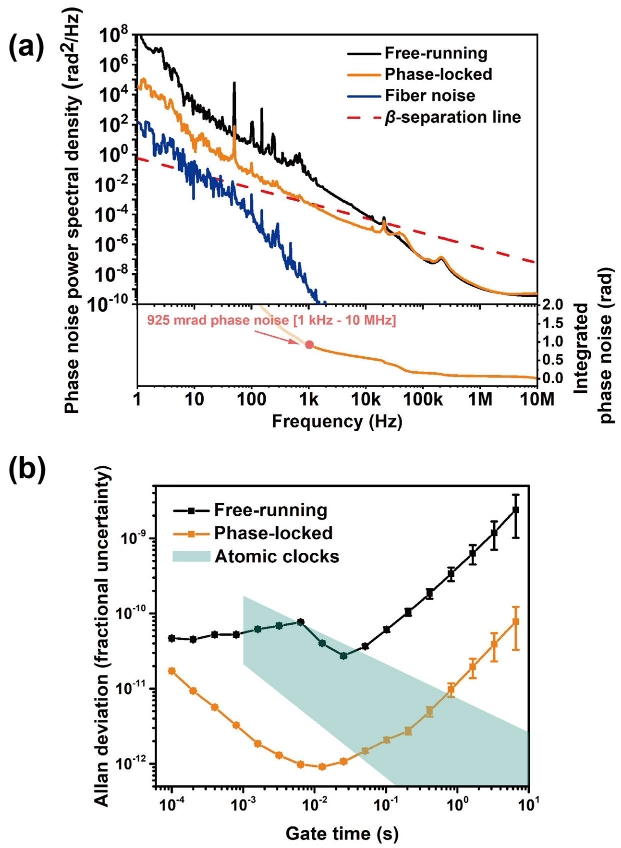

FIG. 3. Out-of-loop phase noise PSD (a) and frequency stability (b) of 1542-nm comb mode.

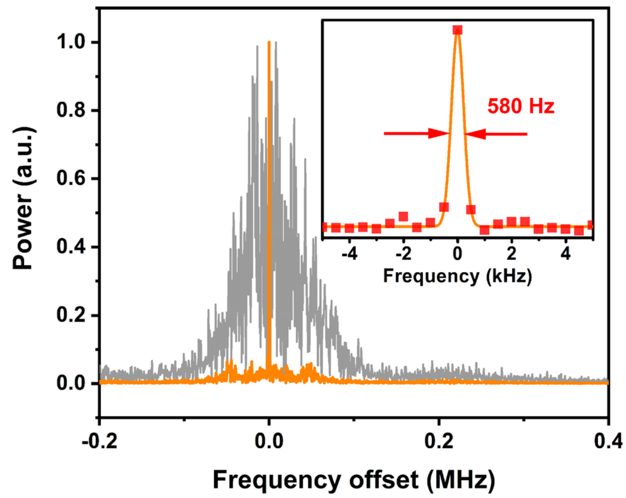

FIG. 4. Linewidth measurement of f_{beat} before (gray curve) and after (orange curve) phase-locking. Inset: the linewidth is estimated to be 580 Hz from Gaussian fit.

Finally, we characterize the absolute linewidth of comb modes in the stabilized OFC. We record the f_{beat} at 500 MHz sampling rate in 2 ms using an oscilloscope (LeCroy WaveRunner, 104Xi). Spectrum of f_{beat} could be characterized through Fourier transformation, as shown in Fig. 4. Compared with the free-running OFC, the linewidth of the 1542-nm comb mode has been compressed from ~100 kHz (as represented by gray curve in Fig. 4) to 580 Hz (as represented by an orange curve in Fig. 4) with a factor of ~170. This linewidth is close to the time-bandwidth limited resolution. Narrower linewidth measurement is prohibited by the slow drift of f_{beat}.

Despite the outstanding short-term stability, the above out-of-loop measurements show that frequency stability is gradually degraded at >10 ms average. Obviously, long-term instability of all the comb teeth in the OFC are still limited by the fiber length fluctuations due to thermal drift, mechanical vibrations at low Fourier frequencies despite careful sealing and low-pressure package of fiber delay line. The degraded long-term stability also prohibits comb linewidth narrowing with an increase in averaging time. To partly overcome this issue, a better temperature control to the whole system is required. The linewidth of the OFC referenced to a fiber delay line is two to three orders narrower than OFCs referenced to radio frequency atomic clocks (see Sec. S6 in the supplementary material). However, their linewidths are still not comparable to OFCs utilizing cavity-stabilized lasers as references. Nevertheless, OFCs with hundreds of Hertz absolute linewidth already allows for a number of high precision OFC applications, like comb-line resolved dual-comb spectroscopy.

To summarize, we provide a simple and practical approach for OFC stabilization. An all-fiber Er-fiber OFC is fully stabilized by phase-locking two comb modes to a 1.25 × 2-km fiber delay line. Out-of-loop measurement characterizes a significant short-term linewidth reduction and broadband frequency-noise power spectral density suppression after OFC stabilization. The residual phase noise for the 1542-nm comb mode is 925 mrad (integrated from 10 MHz to 1 kHz). The fractional frequency instability for this comb mode is 9.13×10^{-13} at 12.8 ms average time and the linewidth is 580 Hz. The whole system is reliable and low-cost since only a segment of long fiber is used as reference. Since heterodyne detection is a linear process, this scheme does not require a high level of pulse energy, but hundred-mW level average power. Therefore, it could be used for comb mode noise suppression in high-repetition rate OFCs where f_{ceo} stabilization based on octave spanning supercontinuum generation is not easy to implement due to low pulse energy.[19]

See the supplementary material for detailed configuration of the laser oscillator, description of fiber delay line's noise measurement, setup for phase locking, etc.

H. Tian is currently a postdoctoral researcher at the University of Electro-Communications.

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The authors declare that there are no conflicts of interest related to this article.

DATA AVAILABILITY

The data that support the findings of this study are available from the corresponding authors upon reasonable request.

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