Narrow-linewidth optical frequency comb reference to a fiber delay line

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Abstract: A fully-stabilized Er:fiber optical frequency comb referenced to a km-long fiber delay line is presented. The comb mode’s fractional frequency stability is at 10⁻¹² level in 12.8 ms. The absolute linewidth is 587 Hz. © 2021 The Author(s)

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1. Introduction

Over the past two decades, optical frequency combs (OFCs) have played essential roles in wide variety of high-precision applications such as distance ranging, dual-comb spectroscopy, to name only a few [1-2]. Operation of narrow linewidth OFCs requires low noise optical references. The state-of-the-art approach is to phase lock the comb modes to a narrow-linewidth optical reference, which is stabilized to a high-finesse optical cavity using Pound-Drever-Hall (PDH) technique. This method can push the comb modes’ frequency fractional stability down to 10⁻¹⁵ level (1 s average time), residual phase error to < 1 rad and linewidth to sub-mHz levels [3]. However this approach requires f-2f interferometry and cavity-stabilized optical standards, which makes the whole system complicated and high-cost. To overcome this, optical fibers show significant potential of being reliable references for narrow linewidth OFC operation due to its superior short-term stability [4-5].

In this work, we derive a compact, highly-integrated narrow-linewidth OFC regarding a kilometer-long fiber delay line as reference. Through high-speed pump power modulation and extra-cavity offset frequency modulation, 1537-nm comb modes and 1566-nm comb modes in the OFC are simultaneously phase-locked to a 1.25×2-km fiber delay line. Out-of-loop measurement characterizes that the 1542-nm comb mode has fractional frequency stability of 10⁻¹² level at 12.8 ms average time and 587 Hz linewidth. The entire phase-locking system is compact and highly-integrated for the reason that it is free from optical amplifiers, f-2f interferometers, high-finesse cavities, optical or radio references. The presented narrow-linewidth OFC provides reliable laser source for low-noise-OFC-based precise metrology, microwave generation and dual-comb spectroscopic applications outside the laboratory.

2. Experimental setup

Delayed self-heterodyne (DSH) method is utilized to phase lock the comb mode of the target OFC to a km-long fiber delay line. Two wavelengths from the OFC, \( \lambda_1 = 1537 \) nm and \( \lambda_2 = 1566 \) nm are filtered out and directed into an asymmetric fiber interferometer for heterodyne beat generation, as shown in Fig. 1(a). In the fiber interferometer, two spectral segments are reflected back by a faraday rotating mirror at the end of the reference arm. However in the delayed arm, two spectral segments pass through a 1.25-km long fiber spool, a delay control unit, an acoustic-optical frequency shifter and are reflected by another faraday rotating mirror at the end of the arm. The fiber spool is sealed by silicon rubber within a compact size (12-cm diameter) and put in a vacuum glassware. Such compact and robust fiber packaging enables the reduction of various technical noise induced by mechanical vibrations and temperature change at low Fourier frequency (<10 Hz). AOFS2 is placed in the delayed arm to shift the optical signals’ frequency twice at \( f_{\text{m}} = 100 \) MHz, resulting 100-MHz heterodyne beats. At the output of the asymmetric fiber interferometer, another DWDM de-multiplexes \( \lambda_1 \) and \( \lambda_2 \) for separately heterodyne beat detection. Two heterodyne beats are filtered out, amplified to > 5 dBm and frequency divided to 25 MHz. Divided heterodyne beats are then mixed with \( 2f_{\text{m}}/2 \) from the waveform generator that drives AOFS2. The resulting discrimination results from the mixers could be regarded as error signals of comb modes’ frequency noise. The error signal from 1566 nm is fed back upon the extracavity AOFS1 through a PID servo for \( f_{\text{ceo}} \) stabilization. The error signal from 1537 nm is fed back upon pump power modulation through a PI servo for repetition rate stabilization. To this end, both repetition rate and carrier-envelope offset frequency of the OFC are phase locked to the fiber delay line, leading to the frequency noise reduction of all the optical modes.
The laser and the asymmetric fiber interferometer are all put in an aluminum box and placed on a vibration isolation table. The isolation table enables active control with cut-off frequency of 1 Hz. Through this careful package, acoustic noise induced by mechanical vibrations, air flow and temperature change could be partly rejected, leading to at least 6 hours continuous operation of narrow-linewidth OFC operation.

3. Results
After close of two phase locked loops, a full-stabilized narrow linewidth OFC is obtained. The bandwidths of two phase locking loops are nearly 40 kHz, which is mainly limited by the first null frequency in the transfer function of fiber delay line. To evaluate the noise performance of the stabilized frequency comb, the comb mode around 1542 nm are filtered out by DWDM1 and beat with a commercial 1542-nm narrow-linewidth CW laser. The typical linewidth of the laser is 1 Hz. In this case, the Allan deviation and the linewidth of out-of-loop beat signal ($f_{\text{beat}}$) represent those of the individual comb mode at 1542 nm in the stabilized OFC because the reference CW laser has negligible noise compared to stabilized frequency comb.

![Experimental setup. DWDM, dense wavelength division multiplexer; AOFs, acoustic optical frequency shifter; PD, photodetector. (b) Linewidth of 1542-nm comb mode after phase-locking. Linewidth is estimated to be 587 Hz from Gaussian fit (gray curve).](image)

The frequency variations of the $f_{\text{beat}}$ are recorded by a frequency counter with 100 µs gate time. Fractional Allan deviation of $f_{\text{beat}}$ is calculated. The frequency stability has been improved by at least one order of magnitude after phase-locking compared to the free-running condition. Allan deviation averages down as $\tau^{-1/2}$ until 10 ms and reaches $10^{-12}$ level at 12.8 ms. For longer time scale (> 12.8 ms), Allan deviation shows a drift behavior, which is affected by the long-term drifting of the referenced fiber delay line. Even so, the short-term stability of our fiber delay line stabilized OFC is still comparative or even better than the OFCs which are traced to microwave references.

The absolute linewidth of comb modes in the stabilized OFC is also characterized. Through sampling the $f_{\text{beat}}$ at 500 MHz sampling rate in 5 ms using an oscilloscope, spectrum of $f_{\text{beat}}$ could be characterized through Fourier transformation, as shown in Fig. 1(b). Compared with the free-running case, the linewidth of the 1542-nm comb mode has been compressed from ~ 100 kHz to 587 Hz with a factor of ~ 170.

4. Conclusion
In conclusion, we present a compact fully-stabilized narrow-linewidth OFC referenced to a 1.25×2-km fiber delay line. Compare with state-of-the-art fully-stabilized OFC systems with f-2f interferometers, our phase-locking system gets rid of spectrum broadening process, external optical or radio references making the entire system compact and highly-integrated. This derived phase-locking scheme is not restrained for mode-locked laser based OFCs, but could be also applied in noise suppression of EO-combs, QCL-combs, micro-combs, etc.

References
[1] T. Fortier and Esther Baumann, “20 years of developments in optical frequency comb,” Comm. Phys. 2(153), 1 (2019)
[2] J. Kim and Y. Song, “Ultralow-noise mode-locked fiber lasers and frequency combs: principles, status, and applications." Adv. Opt. Photonics. 8(3), 465-540 (2016).
[3] T. R. Schibli, et al, “Optical frequency comb with submillihertz linewidth and more than 10 W average power,” Nat. Photonics. 2, 355-359, (2008).
[4] D. Kwon and 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 1s," Opt. Lett. 42(24), 5186-5189, (2017).
[5] D. Kwon, et al. “Generation of multiple ultra-stable optical frequency combs from an all-fiber photonic platform,” Sci. Adv. 6, eaax4457, (2020)