# Self-Referenced Er-fiber Laser Comb with 300 MHz Comb Spacing

Jin-Long Peng, Tze-An Liu and Ren-Huei Shu
Center for Measurement Standards (CMS)
Industrial Technology Research Institute (ITRI)
Hsinchu, Taiwan
jlpeng@itri.org.tw

***Abstract*—A self-referenced, passively mode-locked Er-fiber laser via nonlinear polarization rotation with fundamental repetition rate of 300 MHz is demonstrated. The stabilized repetition frequency has an out-of-loop tracking instability of 2.7×10$^{-13}$ at 1 s. The stabilized carrier-envelope offset frequency has a residual fluctuation of 1.7 mHz measured with a 1-s gate time. This is, to our knowledge, the highest repetition rate of self-referenced fiber laser comb.**

## I. INTRODUCTION

Mode-locked (ML) fiber laser as an optical frequency comb has attracted increasing attention in recent years due to the excellent stability, turn-key operation, compactness, and low cost. High repetition rate femtosecond ML fiber laser are desirable for many applications, such as optical frequency counting [1, 2], high speed asynchronous optical sampling [3], absolute distance measurement [4], and wavelength calibration of astronomical spectrograph [5]. In the frequency metrology related applications, octave-spanning spectrum is usually preferred for the stabilization of the carrier-envelope offset (CEO) frequency of the ML laser. Frequency-stabilized, octave-spanning fiber laser combs with repetition rate as high as 250 MHz has been realized based on polarization additive pulse mode-locking (P-APM), i.e. nonlinear polarization rotation [6]. Higher repetition rate of passively ML fiber laser oscillators based on saturable Bragg reflector have also been reported [7, 8], but no study about the spectral broadening was reported. This work demonstrates a passively ML fiber laser based on P-APM mode-locking with fundamental repetition rate of 300 MHz and with spectrum broadened to an octave. The f-2f self-referencing technique is utilized in the stabilization of the CEO frequency. To the best of our knowledge, this is the highest repetition rate of frequency-stabilized fiber laser comb with octave-spanning spectrum.

## II. EXPERIMENTAL SETUP AND RESULTS

The experimental setup of the fiber laser comb is shown in Fig. 1. An Er-fiber ring laser is mode-locked by P-APM mechanism. The Er-fiber is counter pumped by a 600 mW laser diode (LD) and delivers pulse trains with a repetition frequency of 300 MHz. A piezoelectric transducer (PZT) is mounted on the Er-fiber to control the cavity length. The PZT has a resonant frequency of 68 kHz and can tune the repetition frequency up to about 7 kHz with a maximal driving voltage of 150 V. The pulse trains are extracted out of the cavity though the rejection port from the polarization beam splitter (PBS). The output from PBS has an average power of about 60 mW. The measured optical spectrum and autocorrelation signal of the fs laser are shown in Fig. 2. The pulse has hyperbolic secant shape with pulse width of 93 fs. The output from the PBS is further coupled into a single mode fiber and then split into three branches for further applications. For example, one branch is amplified by an Er-fiber amplifier with combined forward and backward pumping. The total pumping power is about 1100 mW. After amplification, the laser has a

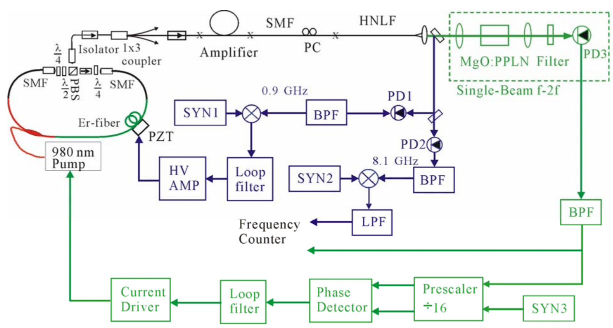
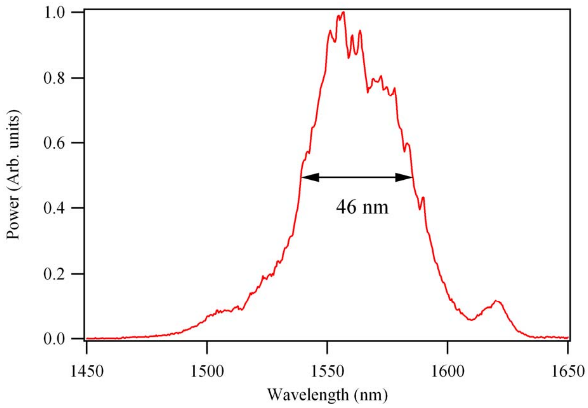
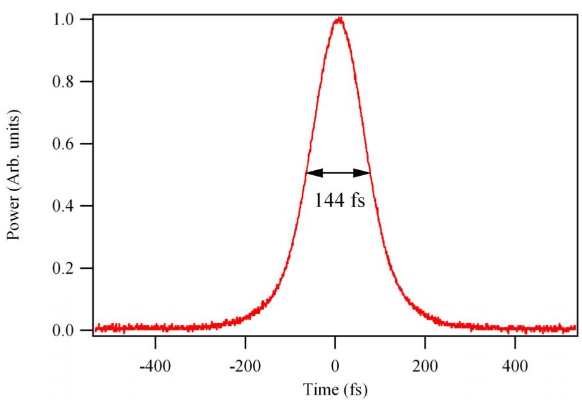



Figure 1. Experimental setup of the fiber laser comb. The repetition frequency was phase-locked to SYN1 by controlling the PZT. The offset beat signal was detected with single beam f-2f heterodyne technique. The offset frequency was phase-locked to SYN3 by controlling the current of the pump laser diode. The residual frequency fluctuation was measured with a frequency counter. PC: polarization controller, SYN: synthesizer, PD: photodiode, BPF: band pass filter, LPF: low pass filter.

This work is supported by the Bureau of Standards, Metrology and Inspection, Taiwan.




(a)




(b)

Figure 2. (a) Optical spectrum and (b) autocorrelation signal detected from the PBS output of the laser oscillator.

typical average power of 290 mW. The pulse trains are then compressed by a section of standard single mode fiber (SMF). The oscillator and amplifier are mounted on a 10 mm-thick, 19×25 $cm^2$ aluminum plate, of which the temperature is controlled by a thermal-electric cooler to improve the long-term stability of the laser.

A 40 cm-long dispersion-flattened highly nonlinear fiber (HNLF) is spliced to the SMF to generate an octave-spanning supercontinuum (SC). The HNLF has a mode field diameter of 3.98 μm, a dispersion of 2.12 ps/nm/km, and a dispersion slope of 0.011 $ps/nm^2/km$ at 1550 nm. The generated SC covers an octave spanning from 1100 nm to 2200 nm and has a total power of 260 mW. Fig. 3 shows the measured SC spectrum. The CEO beat signal is detected by a single-beam f-2f interferometer at 1100 nm and has a signal-to-noise (S/N) ratio of 38 dB with a resolution bandwidth of 100 kHz.

The $3^{rd}$ harmonic of the repetition rate and the offset frequency are detected by InGaAs detectors and stabilized to synthesizers (SYN), whose time bases are referenced to a 10 MHz low-noise oven-controlled quartz oscillator, which is phase-locked to a global positioning system receiver-disciplined Rb clock. Detail scheme for the frequency stabilization is similar to that presented elsewhere [9]. The 10

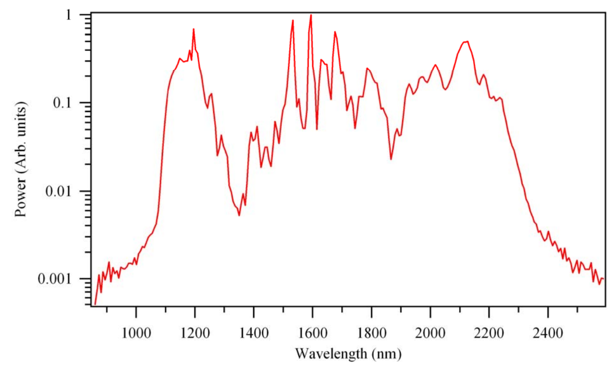
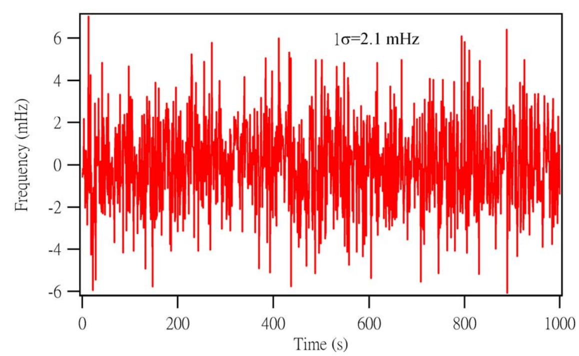
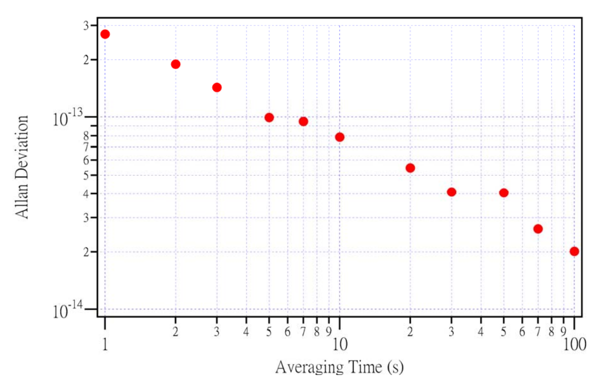



Figure 3. Spectrum of the supercontinuum generated from the HNLF.

MHz reference signal has an instability of less than $2\times10^{-12}$ for an integration time of over 1s and a relative uncertainty of $2\times10^{-12}$. To characterize the frequency stability, the out-of-loop repetition frequency is detected by another InGaAs detector (PD2). The $27^{th}$ harmonic of the repetition frequency is filtered out and then mixed down to 1 kHz with a synthesizer (SYN2). The 1 kHz signal is then counted with a Π counter (Stanford Research Systems SR620) in 1 s of gate time. The measured residual fluctuation of the 1 kHz signal is shown in Fig. 4a, which has one standard deviation (1σ) fluctuation of 2.1 mHz. The calculated Allan deviation is




(a)




(b)

Figure 4. (a) Residual fluctuations of the $27^{th}$ harmonic (8.1 GHz) of the out-of-loop repetition frequency and (b) the calculated Allan deviation.

shown in Fig. 4(b), which shows a tracking instability of $2.7\times10^{-13}$ at 1 s. Meanwhile, counting of a 1 kHz beat signal between SYN1 and SYN2 shows the same instability. This indicates that the measured instability of the repetition frequency is not intrinsic, but limited by the instability of our measurement system. The lower tracking instability than the instability of the reference standard indicates that a true instability of $2.7\times10^{-13}$ at 1 s for the repetition frequency can be reached by appropriately choosing a reference standard.

The stabilized in-loop CEO frequency is directly counted by a Λ counter (Agilent 53132A) in 1 s of gate time. The measured residual fluctuation is shown in Fig. 5, which has 1σ fluctuation of 1.7 mHz. The CEO frequency fluctuation alone will affect the frequency instability of the fiber laser comb less than $2\times10^{-17}$ for 1 s integration time. Thus, the stability of our fiber laser comb is mainly limited by the stability of the repetition frequency.

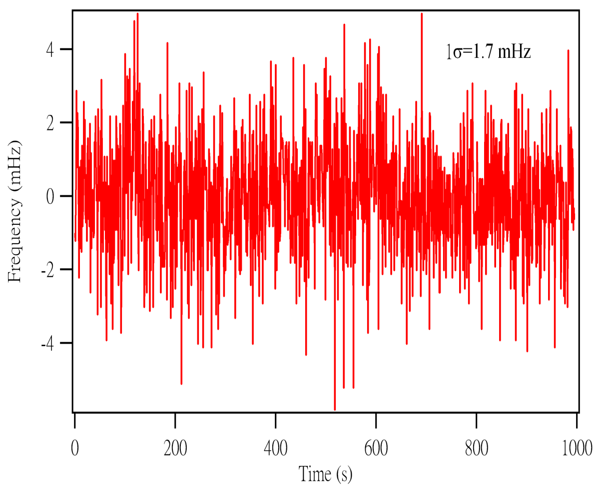



Figure 5. Residual fluctuation of the in-loop CEO frequency.

## III. CONCLUSIONS

In conclusion, we have demonstrated a frequency-stabilized, octave-spanning fiber laser combs with comb spacing of 300 MHz. The stabilized repetition frequency has an out-of-loop tracking instability of $2.7\times10^{-13}$ at 1 s and $2\times10^{-14}$ at 100 s, which is limited by the frequency measurement system. The stabilized carrier-envelop offset frequency has a residual fluctuation of 1.7 mHz measured with a 1-s gate time. This is to the best of our knowledge the highest repetition rate of self-referenced fiber laser comb.

## ACKNOWLEDGMENT

The authors thank Y.-C. Cheng for her contribution to the electronics used in this work.

## REFERENCES

[1] T.-A Liu, R.-H Shu, and J.-L. Peng, "Semi-automatic, octave-spanning optical frequency counter," Opt. Express, vol. 16, pp. 10728-10735 (2008).

[2] J.-L. Peng,T.-A Liu, and R.-H Shu, "Optical frequency counter based on two mode-locked fiber laser combs," Appl. Phys. B, vol. 92, pp. 513-518 (2008)

[3] A. Bartels, R. Cerna, C. Kistner, A. Thoma, F. Hundert, C. Janke, and T. Dekorsy, "Ultrafast time domain spectroscopy based on high-speed asynchronous optical sampling," Rev. Sci. Instrum., vol. 78, pp. 035107-1-8 (2007).

[4] K.-N Joo, Y. Kim, and S.-W Kim, "Distance measurements by combined method based on a femtosecond pulse laser," Opt. Express , vol. 16, pp. 19799-19086 (2008).

[5] T. Steinmetz et al., "Laser frequency combs for astronomical observations," Science, vol. 321, pp. 1335-1337 (2008).

[6] T. Wilken, T. W. Hänsch, R. Holzwarth, P. Adel, and M. Mei, "Low phase noise 250 MHz repetition rate fiber fs laser for frequency comb applications," CLEO-IQEC 2007, Baltimore, May 2007 , paper CMR3.

[7] J. J. McFerran, L. Nenadović, W. C. Swann, J. B. Schlager, and N. R. Newbury, "A passively mode-locked fiber laser at 1.54 µm with a fundamental repetition frequency reaching 2 GHz," Opt. Express, vol. 15, pp. 13155-13166 (2007).

[8] H. Byun, D. Pudo, J. Chen, E. P. Ippen, F. X. Kärtner, "High repetition rate, 491 MHz, femtosecond fiber laser with low timing jitter," Opt. Lett., vol. 33, pp. 2221-2223 (2008).

[9] J.-L. Peng, H. Ahn, R.-H. Shu, H.-C. Chui and J. W. Nicholson, "Highly stable, frequency-controlled mode-locked erbium fiber laser comb," Appl. Phys. B, vol. 86, pp. 49-53 (2007).