Phase-stabilized 167 MHz Repetition Frequency Carbon Nanotube Fiber Laser Frequency Comb

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Abstract: The frequency comb generated by a high repetition frequency erbium-doped fiber ring laser using carbon nanotube saturable absorber is phase-stabilized for the first time. The comb's stability is compared a photonic crystal fiber acetylene reference.

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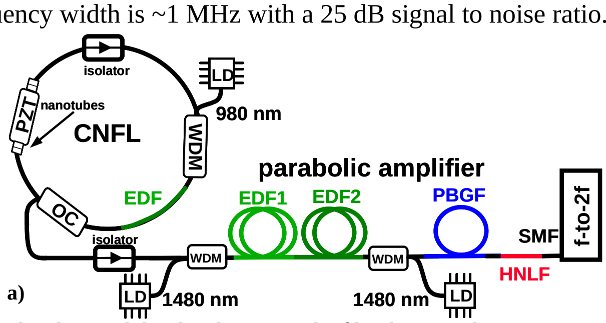
1. Introduction

Phase-locked femtosecond laser frequency combs are now indispensable tools for frequency metrology that allows the transfer of frequency stability from a microwave reference to the optical domain. The next generation of frequency combs will need to make the transition from laboratory instruments to field-usable systems. Erbium-doped fiber (EDF) laser based frequency combs have been shown to have comparable performance to Ti:sapphire combs [1] while providing significant advantages in terms of portability and affordability. Phase-stabilized fiber combs typically have repetition frequencies (f_{rep}) between 100 and 250 MHz [2, 3]. Mode-locked fiber lasers using single-walled carbon nanotubes as a saturable absorber have been developed with a dramatically reduced cavity length and threshold power [4]. This laser offers a format that has demonstrated 447 MHz repetition frequencies with further scaling possible. Such high repetition frequencies improve the comb's usefulness for frequency measurement by increasing the power per comb tooth and the tooth spacing.

In this paper we demonstrate for the first time a self-referenced frequency comb from a fiber laser passively modelocked by single walled carbon nanotubes. The carbon nanotube fiber laser (CNFL) shows stability comparable to that of a 56 MHz figure-eight laser (F8L) fiber comb in the RF frequency domain. An upper bound is set on the CNFL stability by beating it against a 1532 nm CW laser stabilized to an acetylene-filled kagome photonic crystal fiber infrared reference [5].

2. Phase-stabilization of the carbon nanotube fiber laser comb

The fiber comb set-up is shown in Fig. 1a. In the laser, the carbon nanotubes are placed on the end of an FC/APC connector of a piezo-electric transducer (PZT) fiber stretcher which is used to control the cavity length. The laser self starts as the 980 nm pump power is increased to the operating power of 25 mW. The laser produces nearly transform limited 250 fs sech^2 pulses with a bandwidth of 10.5 nm (1555 nm center) at 167 MHz repetition frequency. In order to generate the supercontinuum needed for the detection of the carrier-envelope offset frequency (f_0) this pulse was amplified and temporally compressed using a parabolic pulse fiber amplifier [6] which uses a low-dispersion-slope hollow core photonic bandgap fiber [7]. The 300 mW average power amplified pulse then is injected into 30 cm of highly nonlinear fiber (HNLF) for supercontinuum generation. The observed carrier envelope offset frequency width is ~1 MHz with a 25 dB signal to noise ratio. The sidebands are attributed to phase noise.



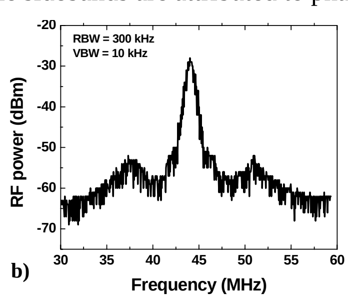


Fig. 1: a) The phase-stabilized carbon nanotube fiber laser comb generator. LD: laser diode; OC: output coupler; WDM: wavelength division multiplier; PBGF: hollow core photonic bandgap fiber; SMF: single mode fiber. b) The carrier envelope offset frequency was measured by the f-to-2f interferometer with a 1 MHz width (FWHM), resolution bandwidth (RBW) of 300 kHz.

Feedback control was used to lock both f_0 and f_{rep}. The CNFL was placed in a simple thermal isolation box with no active cooling where the change in f_r was 50 Hz over one hour. The repetition frequency is locked using feedback control with the PZT fiber stretcher. The offset frequency was simultaneously phase-locked using feedback control to the 980 nm laser pump power. A 10 MHz reference from a GPS disciplined Rb clock (Rb GPS) was used for all synthesizers and counters. The phase-locked frequency comb was locked over 4 hours, limited by the dynamic range of the PZT fiber stretcher.

The phase-locked f_{rep} and f_0 were counted with frequency counters and their fractional stabilities were calculated with Allan deviation. Figure 2a shows the repetition frequency has a ~0.4 mHz deviation at 1s gate time corresponding to ~400 Hz in the optical frequency which is below the worst-case specification for the RMS frequency resolution of the counter. As seen in Fig. 2b, the CNFL f_0 fractional stability had a similar stability even though the f_0 beat note exhibited sidebands. To investigate the origin of these sidebands, the relative intensity noise (RIN) of the 980 nm pump diode and the CNFL AM response roll-off frequency (ν_{3dB}) were measured [8]. From the RIN and ν_{3dB} the f_0 width (Δf_0) was calculated to be 1.1 MHz, which agrees with the observed Δf_0. The measured ν_{3dB} of 32 kHz was higher than that of other EDF combs (typically 5 to 17 kHz), which is consistent with the wider Δf_0 and more noise on f_0 [8]. We expect this noise can be compensated by adding a feed forward control to our current control set-up, by operating the pump diode at the high power, or by phase-lead compensation [9].

To characterize the CNFL frequency comb in the optical domain, we beat it against a 1532 nm CW laser that was locked to a sub-Doppler feature in the P(13) overtone transition of an acetylene-filled kagome fiber reference at ~1532 nm [5]. The Allan deviation of the measured beat note frequency was calculated for different counter gate times and plotted in Fig. 2c. These data set an upper bound for the stability of the comb in the optical domain. At 1 and 10 s gate times, the fractional stability is below the Rb GPS specifications, and at longer times, likely dominated by the acetylene frequency reference.

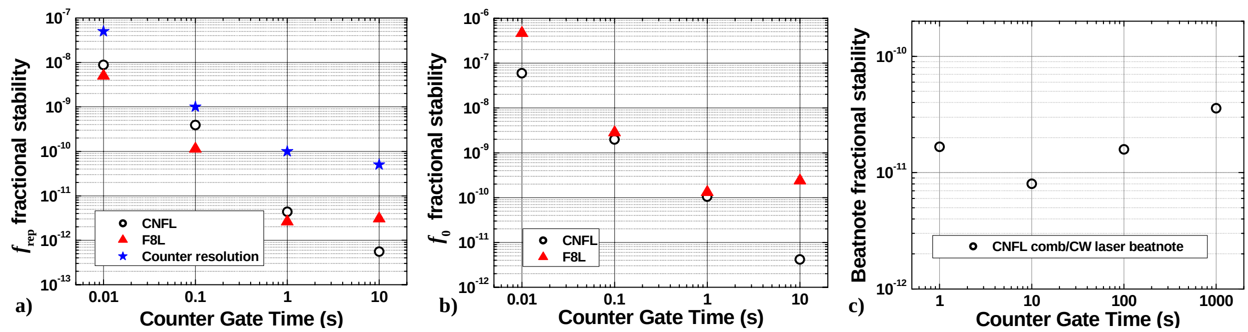


Fig. 2:The CNFL f_{rep} and f_0 fractional stability compared with those of our F8L laser. a) The f_{rep} fractional stability, which is beyond the Rb GPS specification. b) The f_0 fractional stability. The CNFL comb shows a comparable fractional stability to the F8L comb. c) The fractional stability of the beat between an acetylene stabilized CW laser against the CNFL comb.

3. Summary

An erbium-doped fiber laser passively modelocked by single-walled carbon nanotubes has been phase-stabilized for the first time and its stability has been compared to another fiber frequency comb. The CNFL comb offers much promise as a truly portable, reliable, and inexpensive fiber frequency comb with further potential for scaling to higher repetition frequencies. This work was supported by the AFOSR under contract No. FA9950-08-1-0020, the NSF under Grant No. ECS-0449295 and the K.C. Wong Education Foundation, Hong Kong.

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