A phase-stabilized carbon nanotube fiber laser frequency comb

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Abstract: A frequency comb generated by a 167 MHz repetition frequency erbium-doped fiber ring laser using a carbon nanotube saturable absorber is phase-stabilized for the first time. Measurements of the in-loop phase noise show an integrated phase error on the carrier envelope offset frequency of 0.35 radians. The carbon nanotube fiber laser comb is compared with a CW laser near 1533 nm stabilized to the $\nu_1 + \nu_3$ overtone transition in an acetylene-filled kagome photonic crystal fiber reference, while the CW laser is simultaneously compared to another frequency comb based on a Cr:Forsterite laser. These measurements demonstrate that the stability of a GPS-disciplined Rb clock is transferred to the comb, resulting in an upper limit on the locked comb's frequency instability of 1.2×10^{-11} in 1 s, and a relative instability of $<3 \times 10^{-12}$ in 1 s. The carbon nanotube laser frequency comb offers much promise as a robust and inexpensive all-fiber frequency comb with potential for scaling to higher repetition frequencies.

OCIS codes: (120.3930) Metrological instrumentation; (320.7090) Ultrafast lasers; (060.5295) Photonic crystal fibers

References and Links:

1. D. J. Jones, S. A. Diddams, J. K. Ranka, A. Stentz, R. S. Windeler, J. L. Hall, and S. T. Cundiff, "Carrier-envelope phase control of femtosecond mode-locked lasers and direct optical frequency synthesis," Science **288**(5466), 635–640 (2000).
2. T. W. Hänsch, J. Alnis, P. Fendel, M. Fischer, C. Gohle, M. Herrmann, R. Holzwarth, N. Kolachevsky, Th. Udem, and M. Zimmermann, "Precision spectroscopy of hydrogen and femtosecond laser frequency combs," Philos Transact A Math Phys Eng Sci **363**(1834), 2155–2163 (2005).
3. T. Steinmetz, T. Wilken, C. Araujo-Hauck, R. Holzwarth, T. W. Hänsch, L. Pasquini, A. Manescau, S. D'Odorico, M. T. Murphy, T. Kentischer, W. Schmidt, and T. Udem, "Laser frequency combs for astronomical observations," Science **321**(5894), 1335–1337 (2008).
4. S. A. Diddams, Th. Udem, J. C. Bergquist, E. A. Curtis, R. E. Drullinger, L. Hollberg, W. M. Itano, W. D. Lee, C. W. Oates, K. R. Vogel, and D. J. Wineland, "An optical clock based on a single trapped $^{199}Hg^+$ ion," Science **293**(5531), 825–828 (2001).
5. L.-S. Ma, Z. Bi, A. Bartels, L. Robertsson, M. Zucco, R. S. Windeler, G. Wilpers, C. Oates, L. Hollberg, and S. A. Diddams, "Optical frequency synthesis and comparison with uncertainty at the $10^{(-19)}$ level," Science **303**(5665), 1843–1845 (2004).
6. M. J. Thorpe, K. D. Moll, R. J. Jones, B. Safdi, and J. Ye, "Broadband cavity ringdown spectroscopy for sensitive and rapid molecular detection," Science **311**(5767), 1595–1599 (2006).
7. S. Blatt, A. D. Ludlow, G. K. Campbell, J. W. Thomsen, T. Zelevinsky, M. M. Boyd, J. Ye, X. Baillard, M. Fouché, R. Le Targat, A. Brusch, P. Lemonde, M. Takamoto, F.-L. Hong, H. Katori, and V. V. Flambaum, "New limits on coupling fundamental constants to gravity using ^{87}Sr optical lattice clocks," Phys. Rev. Lett. **100**(14), 140801 (2008).
8. T. M. Fortier, N. Ashby, J. C. Bergquist, M. J. Delaney, S. A. Diddams, T. P. Heavner, L. Hollberg, W. M. Itano, S. R. Jefferts, K. Kim, F. Levi, L. Lorini, W. H. Oskay, T. E. Parker, J. Shirley, and J. E. Stalnaker, "Precision atomic spectroscopy for improved limits on variation of the fine structure constant and local position invariance," Phys. Rev. Lett. **98**(7), 070801 (2007).
9. T. Rosenband, D. B. Hume, P. O. Schmidt, C. W. Chou, A. Brusch, L. Lorini, W. H. Oskay, R. E. Drullinger, T. M. Fortier, J. E. Stalnaker, S. A. Diddams, W. C. Swann, N. R. Newbury, W. M. Itano, D. J. Wineland, and J. C.

#113025 - $15.00 USD Received 19 Jun 2009; revised 24 Jul 2009; accepted 26 Jul 2009; published 30 Jul 2009

Bergquist, "Frequency ratio of Al^+ and Hg^+ single-ion optical clocks; metrology at the 17th decimal place," Science **319**(5871), 1808–1812 (2008).
10. T. R. Schibli, K. Minoshima, F.-L. Hong, H. Inaba, A. Onae, H. Matsumoto, I. Hartl, and M. E. Fermann, "Frequency metrology with a turnkey all-fiber system," Opt. Lett. **29**(21), 2467–2469 (2004).
11. I. Coddington, W. C. Swann, L. Lorini, J. C. Bergquist, Y. Le Coq, C. W. Oates, Q. Quraishi, K. S. Feder, J. W. Nicholson, P. S. Westbrook, S. A. Diddams, and N. R. Newbury, "Coherent optical link over hundreds of metres and hundreds of terahertz with subfemtosecond timing jitter," Nat. Photonics **1**(5), 283–287 (2007).
12. W. C. Swann, J. J. McFerran, I. Coddington, N. R. Newbury, I. Hartl, M. E. Fermann, P. S. Westbrook, J. W. Nicholson, K. S. Feder, C. Langrock, and M. M. Fejer, "Fiber-laser frequency combs with subhertz relative linewidths," Opt. Lett. **31**(20), 3046–3048 (2006).
13. J. J. McFerran, W. C. Swann, B. R. Washburn, and N. R. Newbury, "Suppression of pump-induced frequency noise in fiber-laser frequency combs leading to sub-radian f_{ceo} phase excursions," Appl. Phys. B **86**(2), 219–227 (2007).
14. N. R. Newbury, and W. C. Swann, "Low-noise fiber laser frequency combs," J. Opt. Soc. Am. A **24**(8), 1756–1770 (2007).
15. Menlo Systems, *www.menlosystems.com*.
16. B. R. Washburn, S. A. Diddams, N. R. Newbury, J. W. Nicholson, M. F. Yan, and C. G. Jørgensen, "Phase-locked, erbium-fiber-laser-based frequency comb in the near infrared," Opt. Lett. **29**(3), 250–252 (2004).
17. C. X. Yu, H. A. Haus, E. P. Ippen, W. S. Wong, and A. Sysoliatin, "Gigahertz-repetition-rate mode-locked fiber laser for continuum generation," Opt. Lett. **25**(19), 1418–1420 (2000).
18. S. Y. Set, H. Yaguchi, Y. Tanaka, and M. Jablonski, "Ultrafast fiber pulsed lasers incorporating carbon nanotubes," IEEE J. Sel. Top. Quantum Electron. **10**(1), 137–146 (2004).
19. J. W. Nicholson, and D. J. DiGiovanni, "High repetition frequency, low noise, fiber ring lasers modelocked with carbon nanotubes," IEEE Photon. Technol. Lett. **20**(24), 2123–2125 (2008).
20. F. Wang, A. G. Rozhin, Z. Sun, V. Scardaci, R. V. Penty, I. H. White, and A. C. Ferrari, "Fabrication, characterization, and mode locking application of single-walled carbon nanotube/polymer composite saturable absorbers," Int. J. Mater. Form. **1**(2), 107–112 (2008).
21. K. Knabe, A. Jones, K. L. Corwin, F. Couny, P. S. Light, and F. Benabid, "Saturated absorption spectroscopy of C_2H_2 inside hollow, large-core kagome photonic crystal fiber," in *Proceedings of Conference on Lasers and Electro-optics (CLEO)*, (Optical Society of America, 2008)
22. Y. Wang, J.-K. Lim, R. Amezcua-Correa, J. C. Knight, and B. R. Washburn, "Sub-33 fs Pulses from an All-Fiber Parabolic Amplifier Employing Hollow-Core Photonic Bandgap Fiber," in *Proceedings of Frontiers in Optics*, (Optical Society of America, 2008)
23. F. Ö. Ilday, J. R. Buckley, W. G. Clark, and F. W. Wise, "Self-similar evolution of parabolic pulses in a laser," Phys. Rev. Lett. **92**(21), 213902 (2004).
24. C. J. S. de Matos, S. V. Popov, A. B. Rulkov, J. R. Taylor, J. Broeng, T. P. Hansen, and V. P. Gapontsev, "All-fiber format compression of frequency chirped pulses in air-guiding photonic crystal fibers," Phys. Rev. Lett. **93**(10), 103901 (2004).
25. R. Amezcua-Correa, F. Gèrôme, S. G. Leon-Saval, N. G. R. Broderick, T. A. Birks, and J. C. Knight, "Control of surface modes in low loss hollow-core photonic bandgap fibers," Opt. Express **16**(2), 1142–1149 (2008), http://www.opticsinfobase.org/oe/abstract.cfm?URI=oe-16-2-1142.
26. J. W. Nicholson, M. F. Yan, P. Wisk, J. Fleming, F. DiMarcello, E. Monberg, A. Yablon, C. G. Jørgensen, and T. Veng, "All-fiber, octave-spanning supercontinuum," Opt. Lett. **28**(8), 643–645 (2003).
27. R. Thapa, K. Knabe, K. L. Corwin, and B. R. Washburn, "Arc fusion splicing of hollow-core photonic bandgap fibers for gas-filled fiber cells," Opt. Express **14**(21), 9576–9583 (2006), http://www.opticsinfobase.org/oe/abstract.cfm?URI=oe-14-21-9576.
28. C. Hönninger, R. Paschota, F. Morier-Genoud, and M. Moser, "Q-swiching stability limits of continuous-wave passive mode-locking," J. Opt. Soc. Am. B **16**(1), 46–56 (1999).
29. F. Tauser, A. Leitenstorfer, and W. Zinth, "Amplified femtosecond pulses from an Er:fiber system: Nonlinear pulse shortening and selfreferencing detection of the carrier-envelope phase evolution," Opt. Express **11**(6), 594–600 (2003), http://www.opticsexpress.org/abstract.cfm?URI=OPEX-11-6-594.
30. S. T. Dawkins, J. J. McFerran, and A. N. Luiten, "Considerations on the measurement of the stability of oscillators with frequency counters," IEEE Trans. Ultrason. Ferroelectr. Freq. Control **54**(5), 918–925 (2007).
31. B. R. Washburn, W. C. Swann, and N. R. Newbury, "Response dynamics of the frequency comb output from a femtosecond fiber laser," Opt. Express **13**(26), 10622–10633 (2005), http://www.opticsinfobase.org/oe/abstract.cfm?URI=oe-13-26-10622.
32. R. Thapa, K. A. Tillman, A. Naweed, A. Jones, B. R. Washburn, K. L. Corwin, J. W. Nicholson, and M. F. Yan, "Phase-stabilized Prism-based Cr:forsterite Laser Frequency Comb for Absolute Frequency Measurements," in *Proceedings of Conference on Lasers and Electro-Optics*, (Optical Society of America, 2007)

1. Introduction

The control of optical frequency combs [1] has rapidly led to their use in exploring fundamental science [2–9]. Phase-stabilized femtosecond laser frequency combs are indispensable tools for optical frequency metrology and optical clocks. They allow for the transfer of frequency stability from a radio frequency (RF) reference to the optical domain and vice versa. Frequency combs based on femtosecond erbium-doped fiber (EDF) lasers recently

#113025 - $15.00 USD Received 19 Jun 2009; revised 24 Jul 2009; accepted 26 Jul 2009; published 30 Jul 2009

have shown reliable performance comparable to Ti:sapphire combs [10–12]. Since mode-locked fiber lasers are robust and portable, they are ideal candidates for a commercial phase-stabilized frequency comb source.

Although fiber frequency combs have been stabilized and used for precision measurements, they are not without their drawbacks [13]. Fiber combs have more intrinsic noise than their Ti:sapphire counterparts, but this problem can be alleviated by various means [12,14]. Another drawback of fiber combs is their low repetition frequency and thus low energy per comb tooth. Octave-spanning fiber combs used for frequency metrology typically have repetition frequencies between 100 and 250 MHz [15,16], while higher repetition frequency lasers have been used for generating combs that span several hundred nanometers [17]. Mode-locked fiber lasers using single-walled carbon nanotubes as a fast saturable absorber [18] offer a format that has demonstrated a fundamental pulse repetition frequency of 447 MHz [19]. Such high repetition frequencies improve the fiber comb's usefulness for frequency measurements by increasing the power per comb tooth and the tooth spacing. Mode-locked lasers that use carbon nanotubes have been measured to have a pulse fluence of 13.9 μJ/cm^2 and exhibit a saturable absorption of 17% [20]. The main advantage that carbon nanotube fiber lasers have over other fiber laser designs is their simplicity and the readiness with which they mode-lock. These lasers offer a very simple design with few optical components, thus reducing the number of splices that contribute to cavity loss.

In this paper we demonstrate for the first time a self-referenced frequency comb from a carbon nanotube fiber laser (CNFL). The CNFL frequency comb shows fractional instability in the RF domain comparable to that of the phase-stabilized comb produced by a figure-eight laser (F8L). We also measured the upper limit of the comb's instability by beating it against a 1533 nm CW laser stabilized to the P(13) $\nu_1 + \nu_3$ overtone transition of an acetylene-filled kagome photonic crystal fiber infrared reference [21]. Simultaneously, the same CW laser is beat against a Cr:Forsterite laser-based frequency comb, when both combs are referenced to a GPS disciplined Rb clock (Rb/GPS). Comparison of these heterodyne signals confirms that the stability of the Rb/GPS is transferred to the optical domain of the comb for averaging times of 1-100 s. Furthermore, the upper limit on the relative frequency stability of the two combs is nearly an order of magnitude below that of the Rb/GPS. Thus, the noise created by the nanotube saturable absorber does not limit the comb's performance.

2. Phase stabilization of the carbon nanotube fiber laser comb

The phase stabilization of a mode-locked laser requires the simultaneous measurement and control of the carrier-envelope offset frequency (f_0) and repetition frequency (f_{rep}). The fiber frequency comb (Fig. 1(a)) consists of the CNFL oscillator, an amplifier to create high energy pulses, a low nonlinearity compression fiber to generate high peak power pulses after amplification, a nonlinear fiber for supercontinuum generation, and an f-to-2f interferometer for detection of f_0. The comb is generated by a CNFL that has single-walled carbon nanotubes on the end of an FC/APC connector. The performance of the nanotube saturable absorber is extremely robust; the laser's performance and ability to self-start did not change over the course of a year. The CNFL self-starts when pumped at 25 mW by a 980 nm diode laser, and is fundamentally mode-locked between 25 mW and 40 mW. The CNFL produces pulses at a repetition frequency of 167 MHz with 1 mW average power at a pump power of 40 mW. At this pump power the laser produces nearly transform-limited 250 fs sech^2 pulses that have a bandwidth of 10.5 nm centered at 1555 nm.

In order to generate the supercontinuum required for the detection of f_0 using the f-to-2f self-referencing method [1,10] the pulses were amplified and temporally compressed using a parabolic pulse erbium doped fiber amplifier [22]. The parabolic amplifier produces high average power thus allowing for more power per comb tooth, which gives higher signal-to-noise ratio on the beatnote measurement. In this design, the control of dispersion, nonlinearity, and gain is critical. A transform-limited sech^2 pulse is launched into two different EDFs that are bi-directionally pumped with 1480 nm laser diodes operating at 1.34 W of total power. A parabolic pulse is formed due to an interaction of self-phase modulation, gain and normal

#113025 - $15.00 USD Received 19 Jun 2009; revised 24 Jul 2009; accepted 26 Jul 2009; published 30 Jul 2009

dispersion in the 10 m combined length of EDF [23]. The positively chirped parabolic pulse is temporally compressed in a low-dispersion-slope hollow core photonic bandgap fiber (HC-PBGF) [24,25]. This fiber exhibits anomalous dispersion with a very low nonlinearity and the pulses are compressed to 100 fs FWHM at 330 mW average power. The amplified pulse is injected into 30 cm of highly nonlinear fiber (HNLF) [26] where the pulse is compressed to 30 fs by the solitonic effects in the first few centimeters. The octave spanning supercontinuum is created during propagation in the remaining length of HNLF. Obtaining a low loss splice between PBGF and HNLF is critical to obtaining high output power, though this was not directly achievable. However, low-loss splices between single mode fiber (SMF) and PBGF can be made [27]. Therefore, a small section of SMF was used as a bridge between the PBGF and HNLF. Using an electric-arc fusion splicer a loss of 1.5 dB was obtained at the SMF/HNLF splice, and a loss of 1.9 dB was obtained at the PBGF/SMF splice.

As shown in Fig. 1(b), the observed carrier envelope offset frequency linewidth is about 600 kHz (FWHM) with a 25 dB signal-to-noise ratio (SNR). The sidebands move away from the center of f_0 as the 980 nm pump power is increased. If the pump power is too low, the sidebands are too close to f_0 thus creating an effectively smaller SNR that prevents locking of f_0. For a stable f_0 lock the 980 nm pump power is set to improve the SNR but at a power lower than the multi-pulsing threshold. Sidebands about the repetition frequency due to Q-switching instabilities, which can be seen in some lasers mode-locked with fast saturable absorbers [28], were not observed.

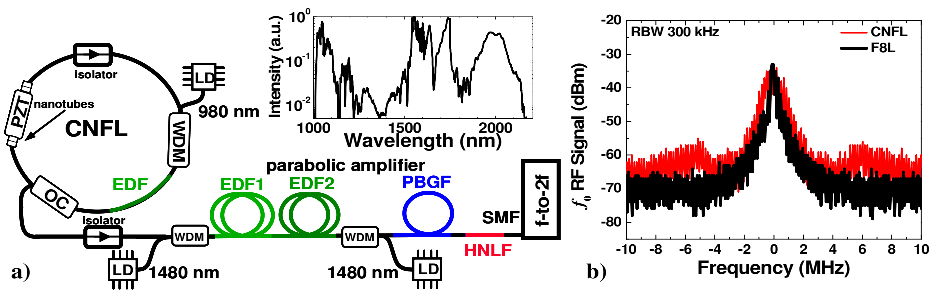

Fig. 1. (a) Schematic of the phase-stabilized CNFL frequency comb. LD: laser diode; OC: output coupler; WDM: wavelength division multiplexer; PZT: piezo-electric transducer; EDF: erbium-doped fiber; PBGF: photonic bandgap fiber; SMF: single mode fiber. Inset: the supercontinuum after the HNLF. (b) The carrier envelope offset frequency measured using an electrical spectrum analyzer with a resolution bandwidth (RBW) of 300 kHz. The carrier envelope offset frequency of the F8L laser is plotted for comparison.

The control of both f_0 and f_{rep} is accomplished in a manner similar to that reported in prior work [16,29]. The oscillator is placed in a styrofoam box for thermal isolation where the change in f_{rep} is 50 Hz over one hour. The repetition frequency is phase-locked using feedback control with a piezo-electric transducer (PZT) fiber stretcher in the laser cavity. The offset frequency is simultaneously phase-locked using feedback control to the 980 nm laser pump power. A 10 MHz signal from the Rb/GPS references all synthesizers and frequency counters. For these measurements, the CNFL frequency comb was phase-locked for 4 hours, although phase-locking for over 12 hours has been achieved when the temperature changes by less than 0.1 °C. The phase-stabilized f_{rep} and f_0 are simultaneously counted with frequency counters (Agilent 53132A) at different averaging times and their fractional frequency instabilities are calculated with a triangle deviation [30]. This deviation was measured instead of the more traditional Allan deviation due to the operation of our frequency counters. The repetition frequency has a ~0.4 mHz deviation at 1 s gate time in the RF domain, corresponding to ~400 Hz in the optical frequency domain which is below the worst-case specification for the RMS frequency resolution of the frequency counter. Measurements of the CNFL comb's in-loop phase noise on f_0 show an integrated phase error of 0.35 radians from 100 Hz to 107 kHz, compared to 0.48 radians for the F8L comb. The integrated phase error on $f_{\rm rep}$ from 100 Hz to

#113025 - $15.00 USD Received 19 Jun 2009; revised 24 Jul 2009; accepted 26 Jul 2009; published 30 Jul 2009

107 kHz was 0.023 radians for the CNFL. The measured phase noise power spectral density is plotted in Fig. 2(a).

3. Comparisons between the CNFL and the F8L based frequency combs

To investigate this relatively wide f_0 linewidth and the sidebands, the CNFL's amplitude response to pump power amplitude modulation (AM) is measured and compared to that of the F8L [16,31]. The F8L's pulsewidth was 220 fs with an average output of 10 mW. As shown in Fig. 2(b), the measured roll-off frequency (ν_{3dB}) is 32 kHz for the CNFL, while that of the F8L is 5.3 kHz, where 5-17 kHz is typical for an EDF laser that uses fiber nonlinearities for the saturable absorber. Therefore the CNFL seems to be susceptible to higher frequency noise which may cause the relatively wide f_0 linewidth and sidebands. The CNFL fixed points associated with pump power and cavity length changes [14] are 13.8 THz and 3.24 THz respectively, compared to 150 THz and 2.6 THz for the F8L.

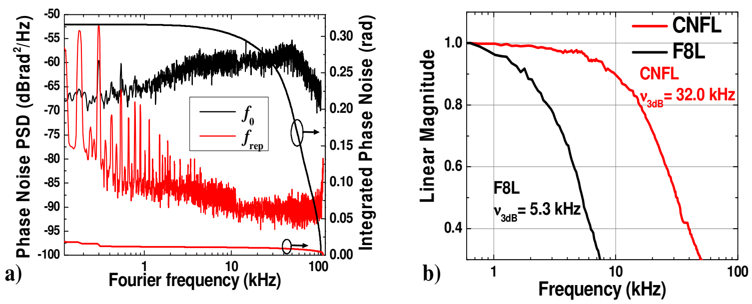

Fig. 2. (a) Phase noise power spectral density (PSD) and integrated phase noise measured for the locked CNFL f_{rep} and f_0. (b) Comparison of the AM response roll-off frequency.

The CNFL comb's fractional frequency instability of f_{rep} and f_0 was measured in-loop and compared to that of the F8L comb. Both combs were referenced to the same Rb/GPS. For both combs the measurement of the f_{rep} instability is below the counter's resolution. Figure 3 below illustrates that at low gate times the f_0 instabilities of the combs are similar, and contribute negligible uncertainty. Although the CNFL comb exhibits a wider beatnote than the F8L comb, the CNFL comb's fractional frequency instability was not adversely affected.

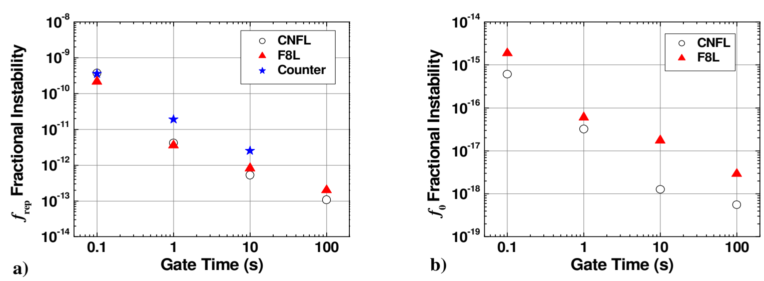

Fig. 3. The fractional frequency instability referenced to the optical domain of (a) f_{rep} (σ_{frep}/f_{rep}) and (b) f_0 (σ_{f0}/195 THz) for both the CNFL frequency comb and a F8L based frequency comb. Counter indicates the worst case counter frequency instability.

4. Stability measurement using an acetylene-filled kagome fiber reference

To characterize the CNFL frequency comb in the optical domain, we beat it against a 1533 nm CW laser locked to a sub-Doppler P(13) $\nu_1 + \nu_3$ overtone transition in $^{12}C_2H_2$ inside kagome-structured photonic crystal fiber [21]. Simultaneously the stabilized CW laser beats against a Rb/GPS referenced Cr:Forsterite laser comb [32]. In this way, the fluctuations of both the optical reference and the Rb/GPS reference are common to both beats, and the difference in

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the beats gives the relative instability of the two combs. The layout of this experiment is shown in Fig. 4(a). A 70 µm core size kagome fiber was filled with $^{12}C_2H_2$ to a pressure of 100 mtorr. The triangle deviation of the measured beatnote frequency for both combs is shown in Fig. 4(b). Data are recorded at a 1 s gate time and averaged to give instabilities at longer gate times. The instability of the point-to-point comparison between the two heterodyne signals is nearly an order of magnitude lower than either heterodyne signal and is smaller than any fluctuations seen on either signal individually. Care was not taken to synchronize the counters precisely, so this represents an upper limit on the relative instability of the CNFL and the Cr:Forsterite comb. We conclude that the CNFL transfers the stability of the Rb/GPS to the optical domain. Therefore, the instability of the CNFL/CW laser beatnote is dominated by the Rb/GPS instability at short times and the acetylene-filled kagome fiber at longer times.

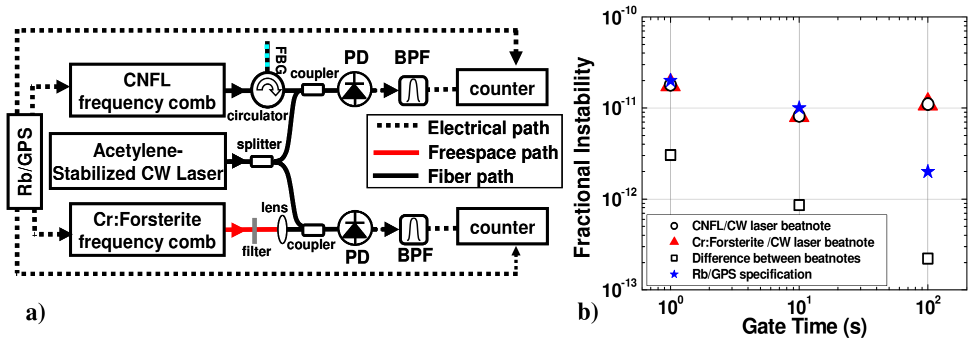

Fig. 4. (a) Experimental set-up to beat the CNFL comb and Cr:Forsterite laser comb against a 1533 nm CW laser reference. Each comb's supercontinuum is optically filtered (either by a filter or a fiber Bragg grating (FBG)) and beat against the CW laser on a fast photodiode (PD). Each PD signal is filtered by a bandpass filter (BPF) and counted. All synthesizers and frequency counters are referenced to the Rb/GPS. (b) The fractional frequency instability of the beat note between the stabilized CW laser and the CNFL and Cr:Forsterite frequency combs. The point-to-point difference shows the relative instability of the CNFL and Cr:Forsterite combs.

5. Summary

We have demonstrated for the first time a passively mode-locked carbon nanotube fiber laser that is phase-stabilized with an f_0 integrated phase error of 0.35 radians. From our comparison, the f_0 width of the CNFL frequency comb is larger than that of a F8L frequency comb, but the frequency stability of the Rb/GPS is transferred to the optical domain, and the relative stability of the CNFL comb and the Cr:Forsterite comb is $<10^{-12}$ in 1 s. The CNFL frequency comb offers much promise as a portable, reliable, robust, and inexpensive fiber frequency comb with further potential for scaling to higher repetition frequencies. These features will allow frequency combs to make the transition from laboratory instruments to portable commercial systems.

Acknowledgement

We thank Nathan Newbury for helpful discussions. The authors are grateful for the donation of the highly nonlinear fiber from OFS Fitel Denmark. This research was supported by the AFOSR under contract No. FA9950-08-1-0020, the NSF under Grant No. ECS-0449295 and PHY-0552878, and the K. C. Wong Education Foundation, Hong Kong.

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