

# Optical and microwave frequency synthesis with an integrated fiber frequency comb

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**Abstract:** We demonstrate optical coherence over a broad spectral range of two independent fiber frequency combs. Additionally, we demonstrate microwave stability of better than  $2 \times 10^{-14}$  in 1 second for an optically integrated fiber frequency comb.

Fiber based frequency combs [1-3] have attracted much attention due to their performance characteristics which are amenable to a broad range of applications in both industry and in fundamental research. Here we work to characterize the short-term (averaging times  $< 1$ s) performance of fiber frequency combs (FFC) for use in high-precision frequency metrology and low-noise optical and microwave frequency synthesis. We measure the relative optical linewidth between two modelocked fiber frequency combs independently phase-locked to a common optical reference and demonstrate substantial coherence over a broad spectral range. Additionally, we show excellent short term stability of a microwave signal generated by an integrated fiber laser frequency comb as measured against an established high stability frequency comb based on a modelocked Ti:S laser.

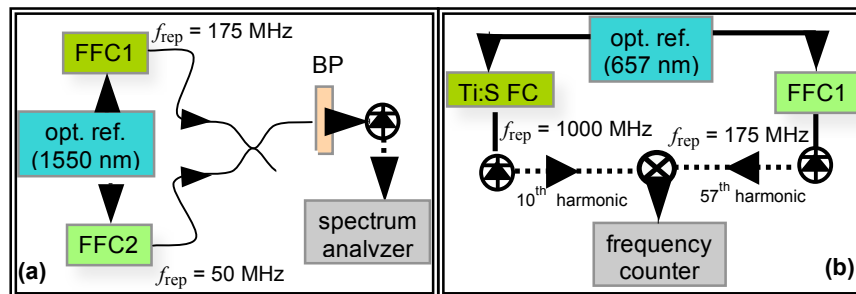


Fig. 1. (a) Configuration for the measurement of relative optical coherence of a fiber frequency combs (FFC). The bandpass filter (BP) allows for selection of different spectral ranges. (b) Configuration for the measurement of microwave stability between an integrated fiber frequency comb (FFC) and a Ti:S laser frequency comb (Ti:S FC).

Our first set of measurements involves comparisons between two FFC's of different design. One FFC was developed at NIST and is based on a ring cavity design with 50 MHz repetition rate [1] while the other FFC uses a fully optically integrated design developed at IMRA using a linear cavity with 175 MHz repetition rate [2]. In order to observe the relative linewidth between the two FFC's, we separately phase-locked their offset frequencies  $f_0$  to an RF reference and then phase-locked each FFC to a common 1550 nm optical reference (a narrow linewidth fiber laser) where the heterodyned RF beat between FFC and the reference oscillator is  $f_{beat}$  [Fig. 1 (a)]. Both FFC's use spectral broadening in UV irradiated highly nonlinear fiber [5] and the f-2f self-referencing technique for stabilizing  $f_0$ . The phase locked offset frequencies are separated by 8 MHz causing a rigid 8 MHz offset between the two FFC's. The repetition rate of the laser is given by  $f_{rep} = (f_{ref} \pm f_{beat} \pm f_0)/N$ , where  $N$  is the frequency mode number. We choose our  $f_{beat}$  and  $f_0$  locking frequencies to ensure that the repetition rates are matched such that  $f_{rep\_FFC1} = 7/2 \times f_{rep\_FFC2}$ . With our scheme, we can demonstrate coherence across a substantial portion of the optical spectrum including that generated outside the fiber laser bandwidth [Fig. 2(a)]. We observed the detected RF heterodyned beat signals between the two FFCs in  $\sim 0.5$  nm wide portions of the optical spectrum centered at 1250 nm, 1500 nm, 1550

nm and 1620 nm [Fig. 2]. Also shown in Fig. 2 are the self-referenced  $f_0$  beat note and  $f_{beat}$  heterodyned beat note of both FFC's. We suspect that limiting factors to the linewidth arise from contributions which are not common mode to the optical reference such as disparities in the phase locks. However, the broad spectral coherence demonstrates that the performance of either FFC is indeed potentially suited for rigorous application of frequency comb technology.

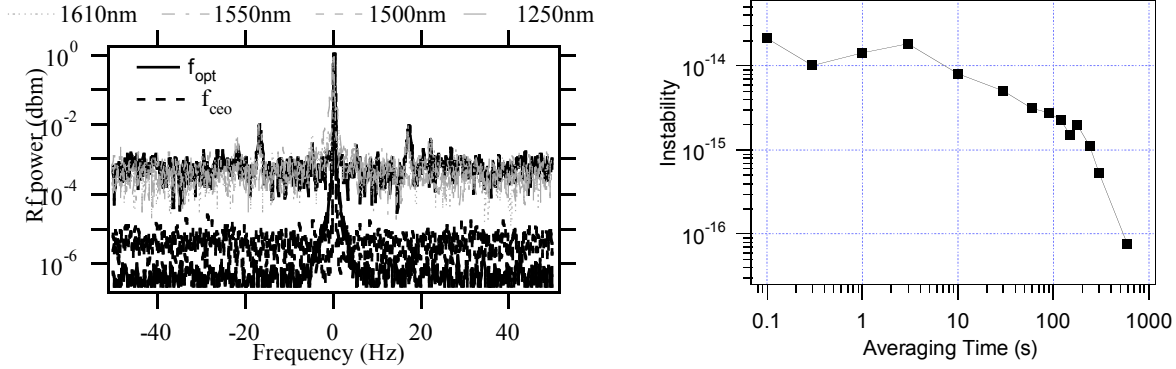


Fig. 2. (a) Demonstration of the optical coherence between the two fiber frequency combs (FFC) at different spectral regions. The data shows coherence both within the optical bandwidth of the fiber lasers as well as coherence in the externally spectrally broadened region. The linewidths of all the beat notes are instrument limited at 0.3 Hz. (b) Relative instability (i.e.  $\delta f/f$ ) of a 10GHz microwave signal derived from an integrated FFC locked to a Hz-level optical reference.

In a second set of experiments we show good short term stability of an optically integrated FFC [2] relative an established high stability frequency comb based on a 1 GHz modelocked Ti:S laser [4]. Both combs are phase locked to the same narrow-linewidth CW laser at 657 nm with established stability of around  $3 \times 10^{-15}$  in 1s. In the case of the FFC, the required 657 nm light is outside the comb spectral bandwidth. Using an in-line optically integrated scheme based on periodically poled reverse proton exchanged LiNbO<sub>3</sub> waveguide technology we generate 657 nm radiation ( $\sim 0.25$  nm bandwidth) together with doubled 2.1  $\mu$ m radiation (required for the f-2f self-referencing scheme) in a single waveguide. The LiNbO<sub>3</sub> waveguide contains single-mode sections at the input and output ends for mode filtering and to simplify coupling connected by tapers to the low mode-field area central region with two QPM grating sections (10 mm and 20mm long) for frequency conversion. This very compact and novel scheme can be easily extended to generate multiple visible spectral lines matched to optical standards (which are often in the visible spectral region). We could detect a heterodyne beat note of the FFC and the optical reference at 657nm with 30dB SNR in a 100 kHz RBW and establish a stable phase lock.

The relative stability of a 10 GHz signal derived from the FFC repetition rate is shown in Fig. 2(b). The excellent short term stability of  $2 \times 10^{-14}$  in 0.1 s averaging time is comparable to a similar measurement comparing two Ti:S combs [4]. The instability at longer averaging times may be limited by temperature- and power-driven fluctuations that are coupled to the photodetection of the FFC repetition rate.

In conclusion, we have demonstrated substantial optical coherence between the two fiber combs phase locked to a common optical reference. Additionally, we developed a novel compact and integrated scheme for generating visible spectral line output of an FFC. Using this concept we have shown a stability of better than  $2 \times 10^{-14}$  in a 1 s gate time for a 10 GHz microwave signal derived from the fiber frequency comb as measured against an established high stability frequency comb where both frequency combs are phase-locked to a common optical reference in the visible spectral region.

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## References

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