# Precision tests of femtosecond laser optical frequency synthesizers

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**Abstract:** We compare the accuracy of femtosecond laser optical frequency synthesizers that employ microstructured fibers with those that directly generate a broadband output. No limitation of either system is found at fractional frequency levels of $1\times10^{-18}$.
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A femtosecond laser optical frequency synthesizer [1-3] generates a broadband comb of optical frequencies that can be phase-coherently referenced to an optical or microwave frequency standard ($f_{ref}$). Such synthesizers have found wide-spread use in optical frequency metrology [4] and emerging optical atomic clocks[5,6]. They are anticipated to play an increasingly important role in laboratory-based tests of symmetries in physics, searches for possible time-variations of fundamental constants [4,7], and the coherent control of ultrafast pulses [8]. In this context, it is important to investigate the potential limitations of diffrent types of femtosecond laser optical frequency synthesizers. When referenced to an optical frequency standard, we demonstrate that the relative frequency uncertainty in the output comb from such a synthesizer is below $1\times10^{-18}$. The reproducibility of this performance is verified by comparison of four synthesizers of significantly different construction from three laboratories.

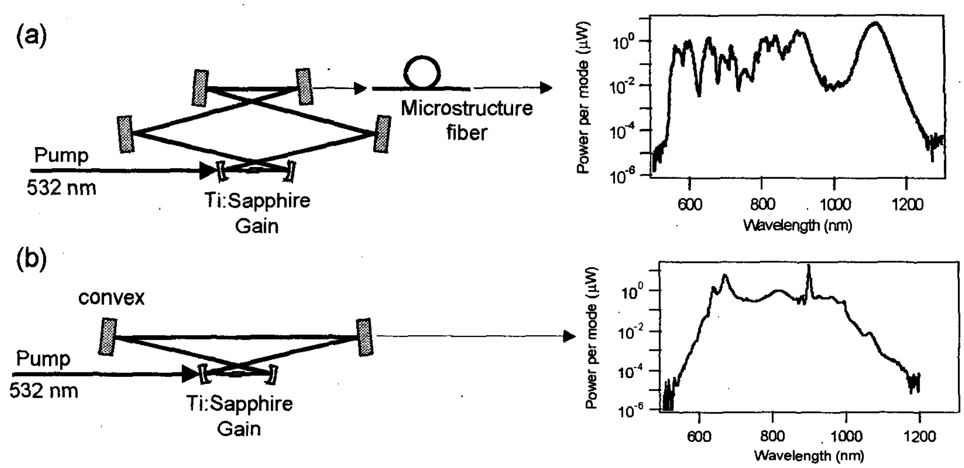


**Fig. 1.** Two different types of femtosecond laser optical frequency synthesizers that we have compared: (a) 1 GHz Ti:sapphire femtosecond laser that is spectrally broadened to more than an octave in nonlinear microstructure fiber. (b) 1 GHz Ti:sapphire femtosecond laser that directly emits a broad spectrum. For simplicity, we have not shown the control systems.

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The optical synthesizers and control techniques we employ have been described previously [5,9]. Notably, we compare synthesizers that employ nonlinear microstructured optical fibers (Fig. 1(a)) with synthesizers that directly emit a broadband spectrum (Fig. 1(b)). Each synthesizer employs a self-referencing scheme [2] to measure and phase-lock its offset frequency $f_0$. A cavity-stabilized diode laser at $f_{ref}$ = 456 THz (657 nm) is heterodyned with mode $n_0$ of the synthesizer and the resulting beat $f_b$ is used to fix the mode spacing (i.e. repetition rate) to be $f_r = (f_{ref} - f_0 - f_b)/ n_0$. The $k^{th}$ output mode of the synthesizer relative to mode $n_0$ is then given by $f_k = f_{ref} - f_b \pm \frac{k}{n_0}(f_{ref} - f_b - f_0)$.

As diagramed in Fig. 2, we employ three distinct comparisons between the synthesizers. In each of these, the noise in $f_{ref}$ is common mode so that we measure just the combined residual noise of the optical synthesizers themselves. In Fig. 2(a), direct optical heterodyne between two synthesizers has shown that the relative fractional uncertainty in the position of the modes is below $1\times10^{-18}$. This is more than a 40× improvement over earlier measurments [10]. With detectors and counters as shown in 2(b) and 2(c), we measure, for the first time to our knowledge, the uncertainty in the synthesis of 1 GHz pulse trains relative to the optical reference $f_{ref}$. In (b) this is done with optical nonlinear cross-correlation, while in (c) the comparison occurs in the microwave domain after photodetection and mixing. In case (b), we find a fractional uncertainty of $5\times10^{-18}$, while case (c), yields a fractional uncertainty of $1\times10^{-16}$. The significant increase in uncertainty in case (c) is attributed to excess noise that arises in the photodetection process.

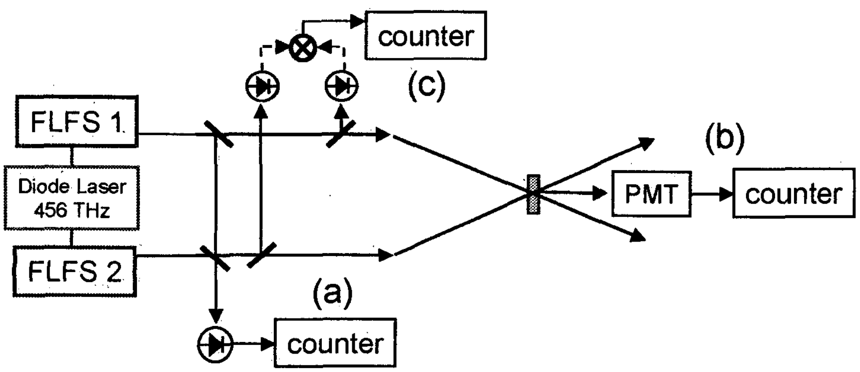


**Figure 2:** Three methods for comparing femtosecond laser optical frequency synthesizers (FLFS). (a) optical heterodyne, (b) optical nonlinear cross correlation (PMT = Photomultiplier Tube), and (c) photodetection and electronic mixing.

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