Optical-to-Electrical Frequency Conversion with Attosecond Timing

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The most frequency-stable electromagnetic radiation is produced optically, with lasers locked to passive reference cavities reaching a fractional frequency instability of 10^{-16}, and optical clock instabilities approaching 10^{-18} at 10^4 s. These references can find new utility when their stability is transferred to the electronic domain, such as in microwave spectroscopy, radar, and synchronization at kilometer-scale scientific facilities, such as free-electron lasers and phased-array telescopes. High fidelity optical-to-electrical conversion is achieved by locking an optical frequency comb (OFC) to an ultrastable optical reference, transferring the frequency stability to the pulse repetition rate. Direct detection of the ultrashort optical pulse train from the OFC then generates ultrastable electrical signals at the pulse repetition rate and harmonics thereof. Using this technique, 10 GHz microwave signals have been generated with instability at one second of 8×10^{-16}, matching the stability of the optical reference (T. Fortier, et al, *Nat. Photon*., **5**, 2011, p. 425). With continued improvements to the stability of optical frequency references, extremely high fidelity photodetection across timescales ranging from less than a microsecond to hours will be required. Here we report optical-to-electrical conversion performance using modified uni-traveling carrier (MUTC) photodetectors for frequency transfer of current state-of-the-art and next-generation optical references. Our work demonstrates residual fractional frequency instability at 1 second averaging of 1.4×10^{-17} (F. Baynes et al., *arXiv:1410.7461*), and photocurrent timing noise spectral density reaching 25 zeptoseconds/√Hz (F. Quinlan, et al, *Nat. Photon*., **7**, 2013, p. 290).

Figure 1 shows the fidelity of the photodetection process, characterized in terms of added fractional frequency instability of a generated 10 GHz microwave carrier for timescales greater than 1 second, and phase noise power spectral density for shorter timescales. As shown in Fig. 1(a), for the shortest timescales, the microwave phase noise is dependent on the optical pulse width, a consequence of shot noise correlations when detecting a periodic train of ultrashort optical pulses. Fig. 1(b) displays the lowest flicker phase noise achieved by direct photodetection, with 10 GHz phase noise of -135/f dBc/Hz, corresponding to a timing noise of 4 attoseconds/√Hz at 1 Hz offset. The fractional frequency instability added in the photodetection process is shown in Fig. 1(c), reaching 5.5×10^{-20} at 10^4 seconds of averaging. State-of-the-art optical and microwave frequency references are also shown for comparison.

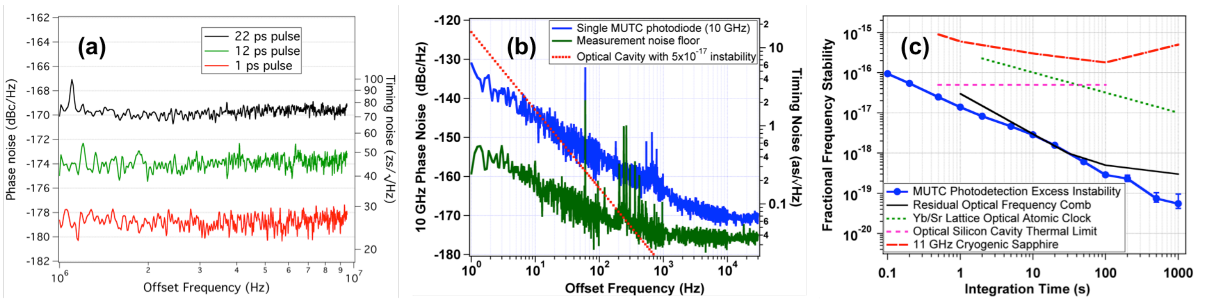

Figure 1. Characterization of the frequency, phase, and timing noise of a 10 GHz microwave generated via direct photodetection of a train of ultrastable optical pulses. (a) Phase noise floor, demonstrating the impact of the optical pulse width. (b) Close-to-carrier photodetector flicker noise, along with the scaled phase noise of an optical cavity with 5×10^{-17} fractional frequency instability at 1 second for comparison. (c) Fractional stability of direct photodetection, compared to an OFC and state-of-the-art frequency references.