Optical Oscillators with High Stability and Low Timing Jitter*

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Abstract
Frequency stabilized cw lasers achieve exceptional frequency stability using high finesse Fabry-Perot cavities. That stability can be transferred to other optical frequencies with mode-locked lasers and provides optical and electronic pulses with ultra-low timing jitter.

This presentation will discuss advantages and disadvantages of stabilized optical systems that can provide extremely low timing-jitter and low phase-noise. The focus will be on some fundamental optical and electronic processes that limit the ultimate performance in terms of precise timing.

The past 10 years have shown dramatic improvement in the spectral purity and frequency-stability of cw and mode-locked lasers, and several laboratories now report laser linewidths near, and even below, 1 Hz for visible frequencies of about 500 THz. The corresponding oscillator quality factors $Q = \nu_0/\Delta\nu \sim 10^{15}$ and fractional frequency stabilities have not been achievable with other types of optical or electronic sources. Laboratory systems have demonstrated unprecedented frequency stability, low phase-noise microwaves, and sub-femtosecond absolute timing jitter. The results are certainly exceptional, and the technology is enabling rapid progress in precision spectroscopy, optical atomic clocks, tests of fundamental physics, and in some advanced timing applications. These achievements result from high quality optical reference cavities (evacuated and environmentally isolated), combined with cw and mode-locked lasers, and with many years of development of frequency control techniques such as the well-known Pound-Drever-Hall method.

However, the performance achieved to date is not good enough for some demanding applications (for example, to support the next generation of optical atomic clocks, advanced gravity wave detectors and uses of low phase-noise microwaves). Optical frequency references have significant advantages of extremely high Q, low loss materials, very high frequencies and bandwidths, but also bring with them other limitations due to optical shot noise and in ways enhanced sensitivity to thermal noise.

The basic system we use is diagramed in fig. 1 and consists of an optical frequency reference based on a cw laser locked to a stable Fabry-Perot cavity combined with an optical frequency synthesizer based on a mode-locked laser. The mode-locked laser optical synthesizer translates the optical reference frequency across the spectrum and also divides it coherently to provide electronic output pulses at microwave frequencies.

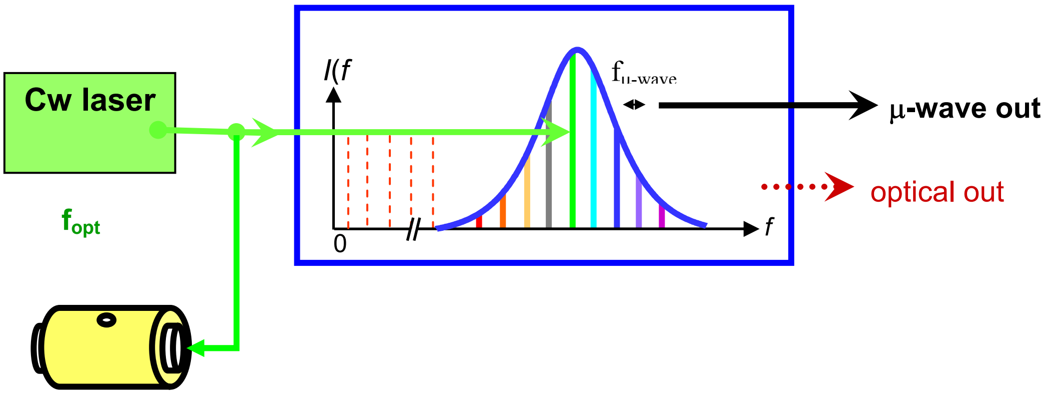

Figure 1. Simplified diagram showing a stable Fabry-Perot reference cavity that controls the frequency of a cw laser, which in turn controls the frequency of one mode of an optical frequency comb. The femtosecond-optical-frequency-comb is generated by a self-referenced mode-locked laser and produces an array of about 10^5 stable optical frequencies spanning the visible spectrum. A photodiode detects the repetitive train of ultra-short pulses from the mode-locked laser and produces a train of electrical pulses that are coherent with the optical frequency reference.

There are a large number of technical and environmental effects that limit the timing precision that can be achieved with this type of system, but we will ignore those for now under the assumption and they could be mostly eliminated with proper engineering. However, some effects limit the performance in more fundamental ways, these include:

- Optical shot noise in locking laser to reference cavity
- Thermal noise in physical spacers and optics used in the Fabry Perot cavities,
- The achievable power in each optical comb mode
- Photo-detection shot noise in the detection of the optical pulses

These processes each affect the optical and microwave spectrum in different ways, but they put fairly stiff constraints on timing-jitter and phase noise that can be achieved with practical systems.