

# Continuously tunable, precise, single frequency optical signal generator

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**Abstract:** To realize a genuine CW optical frequency synthesizer, a continuously tunable single-frequency CW laser has been employed to track precisely any arbitrary component of a wide bandwidth phase-stabilized optical comb. We demonstrate experimentally two fundamental aspects of optical frequency synthesis, namely, precise setting of the laser frequency at an arbitrary pre-determined value, and continuous tuning of the laser frequency with the digital precision known in radio frequency synthesis. A typical computer-automated search-and-lock procedure finishes on one-minute time scale.

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**OCIS codes:** (140.2020) Diode lasers; (140.3600) Tunable lasers; (320.7090) Ultrafast lasers; (120.0120) Instrumentation, measurement, and metrology

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## 1. Introduction

The wide-reaching field of control of coherent light is entering a qualitatively new era owing to the successful merger of ultrafast laser techniques with precision frequency metrology. Phase coherent optical frequency measurement [1,2], optical atomic clocks [3,4], and carrier-envelope phase stabilization [5,6] have been demonstrated experimentally. Combined time/frequency active stabilization now allows one to tightly synchronize separate femtosecond (fs) lasers [7], and phase lock their respective carrier waves to enable coherent optical pulse synthesis [8]. A future goal would be to demonstrate in the time domain arbitrary pulse synthesis, with the capability of phase-coherent stitching of distinct optical bandwidths. Complementary to this time domain capability, it is desirable to construct an optical frequency synthesizer that would allow one to access in the frequency domain any optical spectral feature of interest with a well-defined single-frequency optical carrier wave. Such a capability would allow great simplification in precision laser spectroscopy [9,10].

An optical frequency grid with stable lines repeating every 100 MHz or 1 GHz (i.e., the repetition rate of a mode-locked femtosecond laser) over a large optical bandwidth is useful for a number of applications. However, often times we desire a single-frequency optical-“delta”-function (of reasonable power) that can be tuned to any preferred frequency position on demand. Realization of such an optical frequency synthesizer (analogous to its radio-frequency counterpart) will add a tremendously useful tool for modern laser-based experiments. One could foresee an array of diode lasers, each covering a successive tuning range of  $\sim 10 - 20$  nanometers and emitting some reasonably useful power, that would collectively cover most part of the visible spectrum. Each diode laser frequency may be controlled by the stabilized optical comb, and therefore be directly related to the absolute time/frequency standard in a phase coherent fashion, while the setting of the optical frequency will be accomplished to any desired value via computer control. We have constructed such a system that allows a widely tunable diode laser to tune through a targeted spectral region with a desired frequency step size, while maintaining reference to the stabilized optical comb. A self-adaptive searching algorithm first tunes the laser to within a specified wavelength region with the aid of a wavelength measurement device (100 MHz resolution). A heterodyne beat signal between the diode laser’s frequency and that of a corresponding comb line is then detected and suitably processed. To deal with the fine tuning issue, an auxiliary rf source provides a tunable frequency offset for the optical beat. Frequency-tuning of the diode laser is then accomplished in a controlled fashion where the optical beat is locked to the tunable radio frequency. Once the laser frequency tuning exceeds one comb spacing, we reset the radio frequency offset back to the original value to start the process all over again. The laser frequency can thus be tuned smoothly in an “inch-worm” manner along the comb structure. Experimentally we verify this tuning process by using the modes of an independent optical cavity to monitor the diode laser frequency. When the entire optical comb is stabilized to an ultra-stable optical frequency standard [11,3,4], such stability can be faithfully transferred to another CW laser located hundreds of THz away.

In this paper we demonstrate two fundamental aspects of an optical frequency synthesizer; namely the capabilities of continuous, precise frequency tuning and arbitrary frequency setting on demand. The wide bandwidth optical comb is based on a Kerr-lens mode-locked femtosecond (fs) laser with a repetition frequency of 100 MHz. The comb bandwidth is broadened to span an optical octave (520 to 1100 nm) via a microstructure fiber with the power of each comb component in the range of nW to a few tens of nW. This power level is more than sufficient to produce a beat signal against a mW-level optical field from a laser diode, with a typical signal-to-noise ratio ( $S/N$ ) of about 40 dB in a 100 kHz detection bandwidth.

## 2. Experimental setup

Figure 1 depicts the experimental setup and the basic operation principle.  $f_{cw}$  indicates the optical frequency of the cw laser that is under control by the fs comb.  $f_{rep}$  and  $f_{ceo}$  represent

respectively the frequency spacing and the carrier-envelope frequency offset of the comb [12]. They collectively define the absolute frequency of any comb components. The wavelength meter provides a coarse tuning guide for the diode laser, with a  $<100$  MHz resolution capable of identifying the individual comb component that is closest to the diode laser. In practice, we find that within the frequency range of 300 to 400 MHz we achieve the best  $S/N$  in the heterodyne beat between the diode laser and a corresponding comb component. A combination of electronic bandpass and high-Q notch filters help to suppress the repetition and other beat signals outside the frequency range of 300 – 400 MHz. As there are two nearby comb lines, we have two beat signals left to deal with, their positions conjugate and movements exactly opposite to each other within the 300 – 400 MHz beat frequency range.

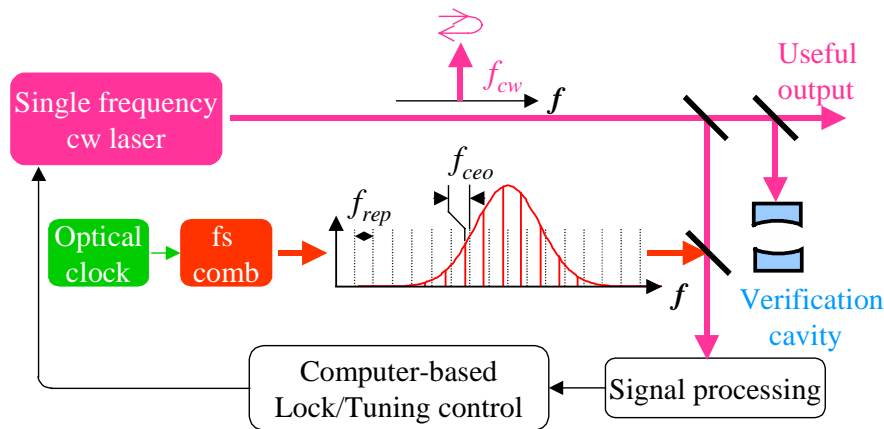


Fig. 1. Experimental schematic and the basic operation principle of a fs-comb-guided optical frequency synthesizer. Heterodyne beat between the cw laser and the fs comb is used for frequency control.

Figure 2 shows the beat signal between the cw laser diode (LD) and one of the comb components, under the condition of (a) LD free running and (b) LD frequency locked. We mix the optical beat down to a few MHz using a Voltage-Controlled Oscillator (VCO) phase-locked and tunable from 300 to 400 MHz. The processed beat signal is fed into a precision frequency-to-voltage (F/V) converter to generate a servo error signal for the LD. We use both diode current and a piezo-activated mirror in the LD external cavity as servo transducers. When stabilized, the beat signal linewidth (full-width-half-maximum) is 200 kHz, according to the Lorentzian fit shown in Fig. 2 (b). This beat linewidth is adequate for the present experiment, as each component of the fs comb, while stabilized by a single iodine-stabilized Nd:YAG laser to a fractional instability below  $5 \times 10^{-14}$  at 1 s [4], still possesses a fast linewidth of about 100 kHz at short time scales. For future experiments the fast linewidth of the comb can be further reduced using a cavity stabilization approach [13]. The feedback loop for the LD is computer-activated to lock the beat signal, and hence the LD frequency, to the VCO, which is itself phase locked to a direct-digital-synthesis (DDS) RF frequency source. This arrangement allows precision tuning of the LD as its beat frequency with a comb-line will be following the programmable DDS.

Of course complications arise when the beat signal is tuned near the harmonics of the repetition frequency, i.e., near 300 and 400 MHz. Furthermore, near 350 MHz, the two beat signals will cross their paths as one moves in the increasing and the other one in the decreasing frequency directions. The presence of both beat signals in the region of 345 – 355 MHz makes it hard to process the servo error properly and we therefore could call this region a dead zone. As a first solution, when the beat signal is tuned near this region, we apply a holding command to the feedback loop so that its control signal to the LD is frozen. We then sum in an independent signal with an appropriate amplitude step to guide the LD frequency to

jump over this region. After the jump is completed, usually in a few hundred microseconds, the feedback loop is re-activated immediately. When the beat signal is tuned to near either end of the pre-selected frequency range (300 and 400 MHz), we program the DDS synthesizer and thus the VCO frequency to make a simultaneous jump corresponding to that in the feedforward drive to the LD frequency servo loop. For example, when the optical beat frequency is pulled to near 400 MHz by the VCO, we would apply a holding signal to the laser feedback loop. A quick switching signal is then applied, both to the VCO to make its frequency jump back near 300 MHz, and to the LD so that the original beat signal will move just beyond 400 MHz. Of course the periodic nature of the comb system leads to a new beat signal actually appearing again near the 300 MHz. We can then re-activate the laser feedback loop to stabilize the beat note on the VCO signal again. This process can be repeated as many times as desired, until the LD's maximum tuning range is reached.

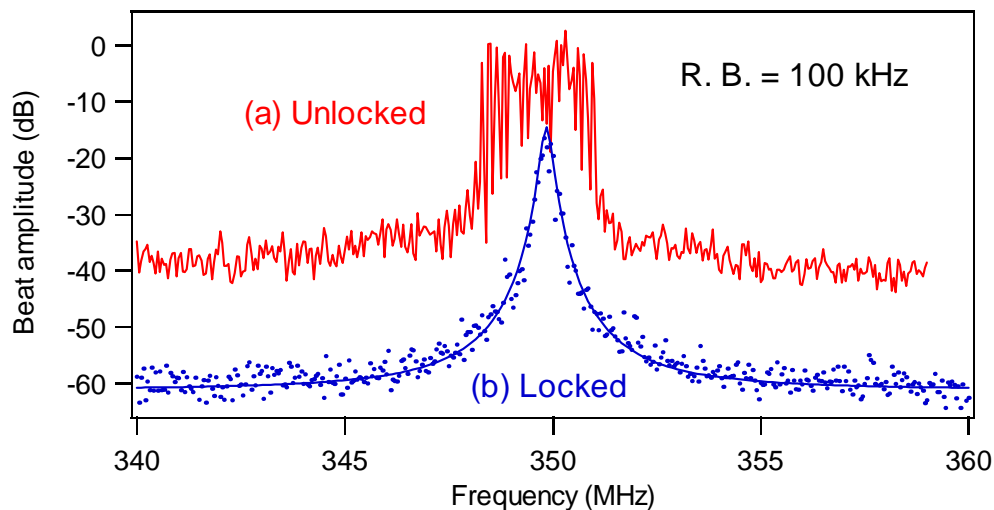


Fig. 2 (a) Heterodyne beat signal between the free-running cw laser and one of the comb components. (b) Beat signal after the cw laser is stabilized by the comb. Experimental data are in dots, and the associated Lorentzian fit is in solid line.

### 3. Demonstration of frequency synthesis

Figure 3 shows continuous tuning of the single frequency laser in precision steps referenced to the phase stabilized optical comb, as evidenced by the transmission signal of an independent, stable optical cavity. The cavity free-spectral-range is 5 GHz. We have purposely degraded the spatial mode coupling between the laser and the cavity such that higher order transverse modes can be shown with reasonable amplitudes. It is evident that tuning of the laser frequency at an rf precision over an extensive frequency range is easily possible. The frequency tuning dead zones can be avoided using several different approaches. For example, the method we use is to employ an acousto-optic modulator (AOM) in the beam path of the useful LD output. As the beat signal tunes near the dead zones, we disable the VCO guiding. The useful optical frequency output can then be simply shifted through the interesting but troubling region via precision tuning of the AOM drive frequency. After this process is completed, we make a step jump in the LD frequency so that the beat note will pass through the dead zone, while an equal but opposite jump of the AOM frequency is made simultaneously to preserve the useful output frequency. This action resets the AOM frequency to its original value, making it ready for the next round of action. A corresponding jump in the VCO frequency will also be made so that the feedback loop again locks the beat note to the VCO for resuming the guided tuning.

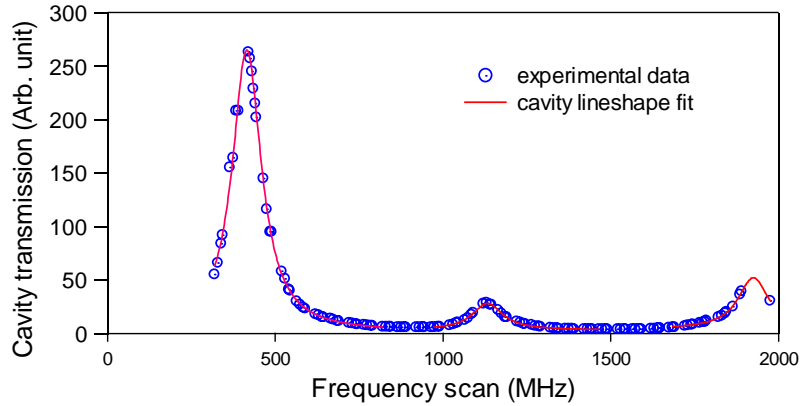


Fig. 3 Continuous tuning of the single frequency laser in precision steps guided by the phase stabilized optical comb. An independent optical cavity provides the frequency marks for reference.

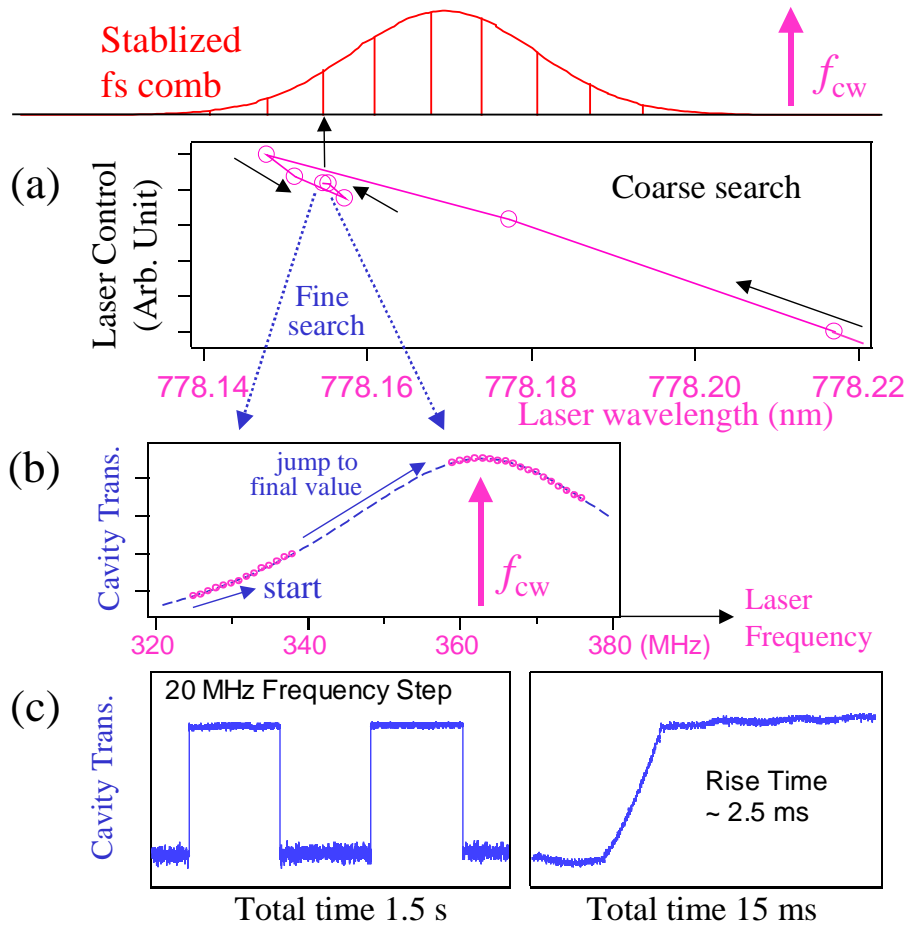


Fig. 4 Random search of and stabilization to the targeted comb position by a single frequency cw laser, with an initial coarse guiding given by a wavelength meter (a), followed by a controlled frequency seeking (b). The entire searching procedure within a 0.5 nm spectral region finishes on one-minute time scale. Also shown is controlled fast switching of the laser diode frequency (c).

The other aspect of frequency synthesis is the capability of reaching a certain desired value of frequency on demand. In the present implementation, we achieve this goal in two steps and we demonstrate this capability by setting the LD frequency to any arbitrary, but pre-determined, cavity modes within its tuning range. Coarse steering of the LD frequency to within the range of a desired comb component is accomplished by a wavelength based self-adaptive software control. Once near the target wavelength, the software searches for the cavity transmission signal and compares it against the expected value. The heterodyne beat signal between the LD and the comb is detected at the same time and the VCO frequency is adjusted automatically to enable the lock between the VCO and the optical beat. The VCO servo will then guide the search through the interesting region of the cavity modes until the desired position has been reached. Figure 4 shows the self-adaptive random search capability of any targeted comb position by the single frequency CW laser, with part (a) showing the LD coarse tuning under the guidance of the wavelength meter. Once the LD is tuned to within the desired spectral range (limited by the resolution of the wavelength meter), the frequency servo is turned on and the VCO will take over the guiding responsibility. The VCO will set precisely the LD frequency to a pre-specified position according to the cavity transmission signal and stabilize the laser there until further notice, as shown in Fig. 4 (b). Clearly this same procedure can be applied when a natural atomic or molecular resonance is the intended target. The total search time is on the order of a minute, basically independent of the size of the wavelength jump. Finally, in Fig. 4 (c) we show that controlled, rapid switching of the LD frequency can be implemented, within a reasonable frequency gap. The typical settling time is 2.5 ms, limited by a mechanical resonance in the piezo transducer used for LD servo. An improved servo using combined piezo and LD current transducers should shorten the settling time to a few tens of microsecond.

#### **4. Summary and future outlook**

In the future we will explore multiple CW lasers locked to the same fs comb, each of its own tuning but capable of being controlled by the common underlying reference comb. We also plan to use two fs combs with different repetition frequencies, such as one at 100 MHz and the other at 750 MHz, such that the entire search and stabilization process can be accomplished without the aid of a wavelength measurement device. A second strategy uses a stabilization step of the LD to a suitable reference (cavity) along with a fs laser of variable repetition rate. Measurement of the beat frequency shift compared with the repetition rate shift can give adequate knowledge of the approximate wavelength.

The powerful utility of this new kind of frequency synthesizer will be helpful in precision atomic and molecular spectroscopy and for generation of flexible light source in different optical spectral regions. One interesting experiment that we are preparing to study is coherent Raman spectroscopy using phase coherent light sources separated by large wavelength gaps. For example, certain molecular fundamental vibration transitions may be hard to reach because suitable laser sources are not available. We consider using two lasers in the visible or near IR spectral regions that are both phase-locked to the comb. The frequency difference of the two lasers can be tuned to match with the fundamental vibration frequency while each laser could also be tuned close to higher-order overtone transitions for a resonant enhancement if so desired. True phase locking between the two lasers will provide the capability of high-resolution investigation of the fundamental vibration resonance.

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