COHERENT OPTICAL FREQUENCY SYNTHESIS AND DISTRIBUTION

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We demonstrate a simple optical clock based on an optical transition of iodine molecules, providing a frequency stability superior to most rf sources. Combined with a femtosecond-laser-based optical comb to provide the phase coherent clock mechanism linking the optical and microwave spectra, we derive an rf clock signal of comparable stability over an extended period. In fact, the stability (5×10^{-14} at 1 s) of the cw laser locked on the iodine transition is transferred to every comb component throughout the optical octave bandwidth (from 532 nm to 1064 nm) with a precision of 3.5×10^{-15}. Stability characterization of the optical clock is below 3×10^{-13} at 1 s (currently limited by the microwave sources). The long-term stability of this simple optical standard is demonstrated to be better than 4.6×10^{-13} over a year. To realize a genuine optical frequency synthesizer, another widely tunable single-frequency cw laser has been employed to randomly access the stabilized optical comb and lock to a desired comb component. The goal is to generate on demand a highly stable single-frequency optical signal in any part of the visible spectrum with a useful output power.

The recent revolution in the physical science brought by the beautiful merger of cw-based ultra-precision laser work and ultrafast lasers and associated nonlinear optics has enabled profound progress in both areas. Optical frequency measurements have been reduced to a simple task even while the highest level of measurement precision has been achieved [1-5]. Control of the carrier-envelope phase is now possible [6,7]. Pulse trains from independent mode-locked lasers have been synchronized below the 10 fs level and their carrier waves phase locked, leading to coherent pulse synthesis [8,9]. Arbitrary and yet phase coherent synthesis of optical spectra, either in terms of selecting desired discrete components in the frequency spectrum or by way of specifying preferred pulse shape and duration in the time domain, now appears possible.

To complement the rapid development of high performance optical frequency standards, it is important to establish an optical comb with excellent phase coherence among its individual components. The phase stability needs to exceed that of the optical standards. With this capability, we will be able to transfer the stability of a single optical oscillator to the entire comb set over its vast bandwidth, and also derive clock signals in the microwave/rf domain without any stability compromise. Optical standards based on single ions and cold atoms promising potential stability around 1×10^{-16} at 1 s [10] and potential accuracy at 1×10^{-18}

[11] may very well become future national standards, but such systems would require elaborate designs. On the other hand, excellent candidates in cell-based optical frequency standards do exist, such as the one presented in this paper, that would offer compact, simple, and less expensive system configurations, albeit at the cost of performance degradation by perhaps two decades. Along with optical combs, a competent laboratory would be able to realize a network of microwave and optical frequencies at a level of stability and reproducibility that surpasses the properties of basically all normal commercially available frequency sources, but with a reasonable cost. Easy access to the resolution and stability offered by the optical standards would greatly facilitate application of frequency metrology both to precision experiments for fundamental physics and to practical devices.

To reach that goal, it is important to understand and implement an optimized control scheme of the optical comb that avoids the limitation in phase coherence between the two ends of comb spectrum. In our previous work, an entangled control scheme could achieve only *frequency*-locking across the comb spectrum, with residual frequency noise exceeding 100 Hz at 1-s [12]. In this contribution we demonstrate that an orthogonal control of the (100 MHz fs-laser based) optical comb can lead to Hz-level ($\leq 3.5 \times 10^{-15}$) *phase*-tracking stability across the entire optical octave. Furthermore, the orthogonalization procedure permits independent control of both degrees of freedom associated with the optical comb, leading to a clock work mechanism using only one comb parameter. Recent work [13] uses a two-parameter-control scheme to transfer the stability of a cold ion based optical standard to the comb lines at the 2×10^{-16} level. Clearly, with a mature technical solution to the "gearbox problem" at hand, all future progresses in optical domain and rf domain standards can be utilized in both spectra.

The octave-spanning optical comb and the associated control scheme are shown in Figure 1. A Kerr-lens mode-locked (KLM) femtosecond (fs) laser [14] generates a repetitive (~ 10 ns repetition interval) pulse train, with a corresponding rigorous periodicity in the spectral domain. To permit the coverage of an entire optical octave, the bandwidth of the comb emitted from the laser is further broadened by launching the pulse train into a microstructure fiber [15]. There are two degrees of freedom associated with the comb frequencies. The interval between adjacent frequencies in this periodically spaced "comb" is directly defined by the laser pulse repetition-rate. The other degree of freedom is the rate of slipping of the carrier-envelope phase of these short pulses. The generation of ultrashort pulses requires that the group velocity (v_g) dispersion inside the laser cavity is minimized across the pulse's frequency spectrum. This criterion is not directly related to the frequency comb spacing, since the individual mode frequencies correspond to eigenmodes of the phase-velocity (v_p) of the light, and in general we have $v_g \neq v_p$. With these considerations, each optical comb frequency is therefore effectively given by

$f_n = nf_{rep} + f_{ceo}$. Here n represents the integer (~ 3×10^6) harmonic number of the optical comb line relative to the repetition rate, f_{rep} ; and f_{ceo} is the comb offset frequency from the exact harmonics of f_{rep} [16].

The two variables of the comb can be expressed as: $f_{rep} = v_g/l_c$ and $f_{ceo} = v_0(1-v_g/v_p)$, where v_0 is the laser carrier frequency and l_c the cavity length. If one is interested only in a stable f_{rep} , for example to generate a clock signal in microwave, then control of l_c seems to be a natural choice and is sufficient. Only when the entire comb spectrum needs to be stabilized do we then need another control freedom, either the pump laser power to influence both v_g and v_p, or a swivel mirror reflecting the dispersed spectrum inside the laser cavity to control v_g [1]. Therefore some degree of signal mixing/feedforward is attractive. We would use a fast servo loop acting on l_c to stabilize f_{rep} , with use of the second control loop to influence mainly f_{ceo} . The inevitable variation in v_g caused by the second loop is then compensated by a properly scaled and opposite-sign feedforward signal to the first loop.

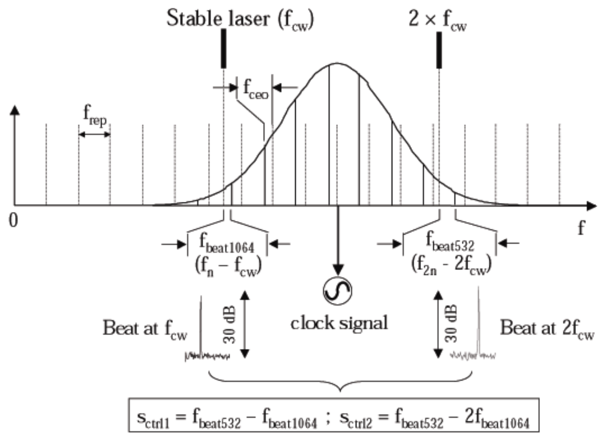

Figure 1. The schematics of the octave-bandwidth optical comb and the stabilized cw laser used for control of the comb. The beat notes of the cw laser and its second harmonic against the corresponding comb components located respectively at the two comb ends are shown. The two beat signals serves as the two observed variables that are used to derive the orthogonal control signals for the comb.

The remaining question is how to have two experimental observables to recover the information relating to f_{rep} and f_{ceo} . In our case we use two beat signals between a cw stabilized laser and its second harmonic against two respective comb components near the two ends of the comb spectrum. The cw reference laser is a Nd:YAG laser (frequency f_{cw}) with its second harmonic ($2f_{cw}$) locked on an iodine transition near 532 nm: this system offers the stability of 5×10^{-14} at 1-s [17]. Both beat signals, $f_{beat1064} = \text{n} \times f_{rep} + f_{ceo} - f_{cw}$ and $f_{beat532} = 2\text{n} \times f_{rep} + f_{ceo} - 2f_{cw}$, are recovered with about 30 dB signal-to-noise ratio at 100 kHz bandwidth, as shown in Fig. 1. These beat signals are regenerated electronically using the rf tracking-oscillator/filter approach, then mixed in the following way to produce control signals related to f_{rep} and f_{ceo} , namely $s_{ctrl1} = f_{beat532} - f_{beat1064} = n \times f_{rep} - f_{cw}$ and $s_{ctrl2} = f_{beat532} - 2f_{beat1064} = -f_{ceo}$. Therefore the frequency/phase variations arising in both f_{rep} and f_{ceo} are now directly manifested in the two control variables s_{ctrl1} and s_{ctrl2} and are linked to the optical frequency standard f_{cw} . These two signals can then drive the two servo transducers mentioned above to close the feedback loops.

To demonstrate the effectiveness of our control scheme, we first show the stabilization of f_{rep} to the optical standard. Essentially we need to use only the information of s_{ctrl1} to control l_c and thus f_{rep} . This approach magnifies the noise of f_{rep} relative to the optical standard by a factor ~ 3×10^6. In doing so, we can leave the variable f_{ceo} free-running since it has been effectively taken out of the control equation. In practice, we use l_c to control the phase of s_{ctrl1} to that of another stable oscillator in the rf domain (which translates the optical frequency by a small offset with no degradation of stability). Figure 2 shows the time record of the frequency differences between f_{cw} and $2.813988 \times 10^6 \times f_{rep}$, with a standard deviation of 0.8 Hz at a 1-s counter gate time. Allan deviation calculated from this time record is shown in the bottom trace. The tracking capability of the comb system, at a level of 10^{-15} or better, is more than ten times better than the current optical standard itself.

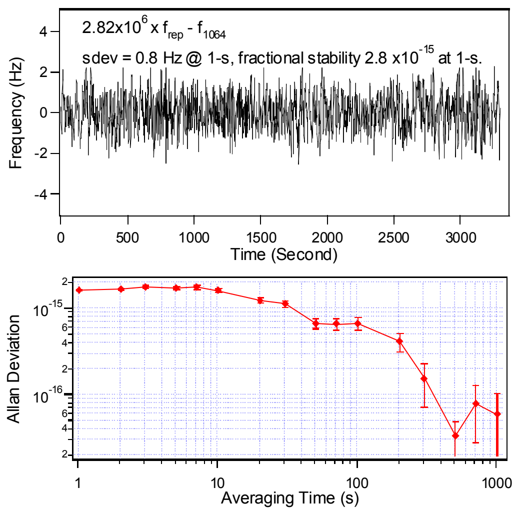

Figure 2. Tracking stability of the comb repetition frequency to the cw reference laser. (a) Time record of the frequency difference between the cw reference laser and the 2.82 millionth harmonic of frep. (b) The associated Allan deviation calculated from the time record.

With the excellent tracking property of the comb system, we expect the stability of the derived clock signal of f_{rep} to be basically that of the optical standard, namely 5×10^{-14} at 1-s. Such an optically derived clock would give its natural time stamps at the $1/f_{rep}$ interval and/or its integer multiples. To characterize the system, a reality check would be to compare the optical clock signal against other well-established microwave/rf frequency standards. The international time standard, Cs clock, should certainly be one of the references; however, the short term stability of a Cs atomic clock is only $\sim 5 \times 10^{-12}$ at 1-s. For improved short term characterization of the fs comb clock, we also use a hydrogen maser signal transmitted over a 2-km fiber, and another in-house highly stable crystal oscillators (short term stability better than 5×10^{-13} at 1-s), which is slowly slaved to the Cs reference for correcting the frequency offset and drift [18]. Figure 3 summarizes the comparison results of the optical clock against all three rf references. The upper graph shows part of the time record of the beat signal between an 8 GHz synthesized frequency from the crystal oscillator against the 80th harmonic of f_{rep} (~ 100 MHz). We use the combination of high harmonic orders and heterodyne beat to help circumvent the resolution limit of frequency counters. The standard deviation of the beat frequency at 1-s averaging time is 0.0033 Hz. The resultant Allan deviation is shown as the curve in triangles in the bottom graph of the figure. Use of a more stable hydrogen maser signal further reduces the Allan deviation of the beat, to be just below 3×10^{-13} at 1-s (shown with open circles). The beat between the optical and the Cs clock is represented by the curve in diamonds. For comparison, we also display the Allan deviation associated with the Cs atomic clock ("worst case" specification) in circles and the Allan deviation of the iodine stabilized laser in squares. The data of the optical standard itself was obtained from heterodyne experiments between two similar laser stabilization systems. We note that the superior stability of our optical clock is currently not yet revealed by the microwave-clock based tests. A microwave source with a better short term stability can be substantially more expensive, even more than our optical system. Use of two optical clocks would of course be the ultimate choice to perform thorough cross-checks of these new devices. Similar work is being pursued in other labs [13].

So far we have made an optical comb that has a well-defined frequency spacing, but the absolute frequencies are uncertain since f_{ceo} is left floating. An attractive approach to stabilize the entire comb spectrum is to transfer the stability of a single optical standard to the whole set of the comb components throughout the optical bandwidth. To accomplish this task, we need the information carried by s_{ctrl2} to exert servo action on the comb by the second control parameter, in our case, the swivel mirror. When this second loop is activated, the impact on the first loop where f_{rep} is being stabilized through l_c is small. This is partly due to the fact that the dependence of f_{rep} and f_{ceo} on their respective control variables is to a large degree already well separated. The other part of the reason is that fluctuations of f_{ceo} develop on a slower time scale compared with that of f_{rep} and therefore a correspondingly slower servo loop is sufficient for stabilization of f_{ceo}. Nevertheless we take part of the second servo signal and after appropriate signal conditioning we feedforward this information to the first servo loop. The resulting loop performance is improved by about a factor of two. (See Figure 4)

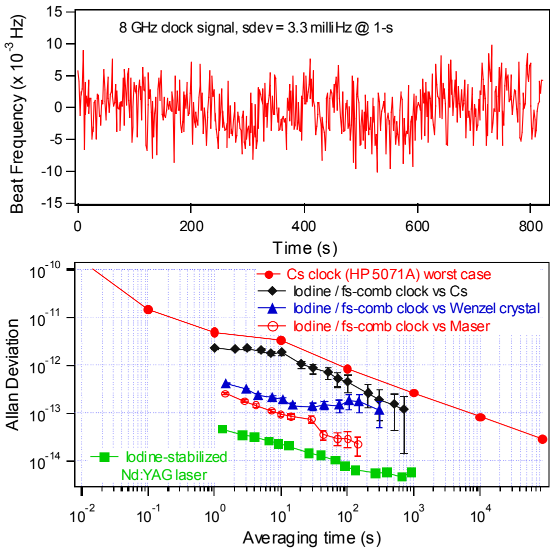

Figure 3. Characterization of the clock signal derived from the iodine stabilized laser. The upper graph shows part of the time record of the beat signal between an 8 GHz synthesized frequency of the crystal oscillator referenced to a Cs clock against the 80th harmonic of f_{rep} of the comb. The lower graph shows the relevant Allan deviations: squares for iodine stabilized laser; circles for the upper stability limit of the Cs atomic clock; triangles, open circles, and diamonds for the beat between the optical clock and the crystal oscillator, the maser, and the Cs clock, respectively.

We use the two original optical beats, namely $f_{beat1064}$ and $f_{beat532}$ that are responsible for generating the control observables but are otherwise outside the servo loops, to characterize the performance of the orthogonal control of the comb. Figure 4 shows the counting record of the two beat frequencies of $f_{beat1064}$ and $f_{beat532}$. Both signals are shown with their mean values removed but indicated in the figure. Again the counter gate time is 1 s and the standard deviations of the two beat signals are 1.7 Hz for $f_{beat532}$ and 1.5 Hz for $f_{beat1064}$. This result indicates that every comb component over the entire optical octave bandwidth is following the cw laser standard at a level of 3.5×10^{-15}, again a factor of about ten times better than the current optical standard itself. The future implication of this work is very clear: With an appropriately chosen optical standard, we can establish an optical frequency grid with lines repeating every 100 MHz over an octave optical bandwidth and with every line stable at the one Hz level.

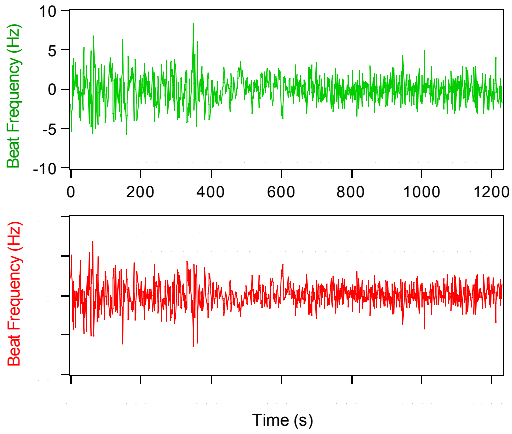

Figure 4. Orthogonal control of the entire optical comb, showing Hz-level stability for both beat signals of the cw laser against a comb component at 1064 nm (bottom trace) and the second harmonic of the cw laser against its corresponding comb line at 532 nm (upper trace). Better orthogonalization in the control loops leads to reduced noise after 400 s.

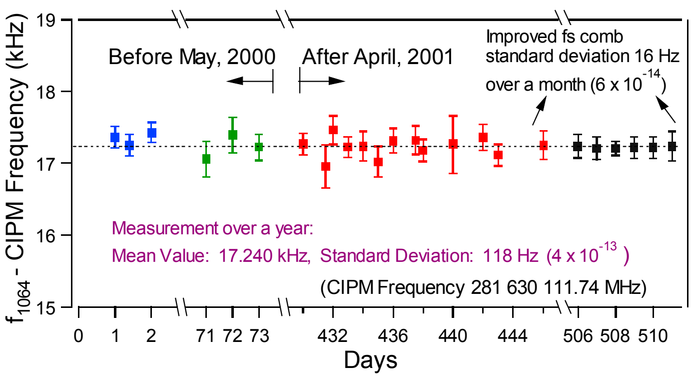

Figure 5. Long term reproducibility of intercomparison between the Cs clock and the iodine-stabilized laser. The measurement period covers more than one year with the stability level at the 4×10^{-13}. This represents the upper limit of the long-term reproducibility of our current optical standard as well as the reproducibility of the comb-based frequency transfer mechanism.

The long-term stability/reproducibility of the iodine-stabilized laser is characterized by comparison against the Cs clock over a period of more than one year. In this long-term comparison, basically we measured repeatedly the stabilized laser frequency using the Cs-referenced optical comb. During the measurement period, we changed a number of parameters associated with the comb and its generation, including f_{rep} , laser power, spectrum and pulse width, and the nonlinear fiber lengths, etc. The reference Nd:YAG laser is stabilized on the R(56) 32-0 a_{10} iodine transition via a modulation transfer technique. The iodine cell is 1.2 m long and its vapor pressure maintained by its cold finger (-15 ^{0}C) is 0.787 Pa. The pump (probe) laser power is ~ 1.0 (0.25) mW with collimated beam diameters of ~ 1.9 mm. The result of this rf – optical frequency intercomparison is shown in Figure 5 and is consistent with our previous measurement [2]. However, we are now able to show the measurement uncertainty over the entire year is about 126 Hz, or ~ 4×10^{-13}. Long-term drift is not statistically significant. During the last month of the data record, after the optical comb system was further improved, the standard deviation was reduced to 16 Hz (6×10^{-14}). While this result represents the lowest level of measurement uncertainty associated with any compact, cell-based optical frequency standards, we notice the long-term reproducibility of cold atom based optical standards has reached the 4×10^{-14} level [5].

A portable version of this iodine based optical clock would have a great impact in field applications: we will be able to make precision measurements in length and time with a single device. The frequency stability in both microwave and optical domains is exceptional, surpassing basically all common sources save only national-standards-scale massive installations. The stability (5×10^{-14} at 1 s) and reproducibility (4×10^{-13}) of the cw laser locked on the iodine transition can be further improved, possibly by another factor of ten. We fully expect such simple optical clock systems will be developed by various interested laboratories.

An optical frequency grid with stable lines repeating every 100 MHz over a large optical bandwidth is useful for a number of applications. However, often times we desire a single-frequency optical-"delta"-function 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 optics-based experiments. One can foresee an array of diode lasers, each covering a successive tuning range of ~ 10 – 20 nanometers and emitting some reasonably useful power, that would collectively cover most part of the visible spectrum. Each diode laser frequency will be controlled by the stabilized optical comb, and therefore related to the absolute time/frequency standard, while the setting of the optical frequency will be done through computer control to any desired value. For the first step, we have constructed an electronic control system that allows a widely tunable diode laser to tune through an targeted spectral region at a 10 MHz step while maintaining reference to the stabilized optical comb. A self-adaptive searching algorithm first tunes the laser to within the specified wavelength region with the aid of a LambdaMeter wavelength measurement device. The heterodyne beat between the diode laser and the comb lines is then detected and properly processed. An auxiliary rf source provides a tunable frequency offset for the optical beat. Frequency-tuning of the diode laser is accomplished by a diode-laser-servo-control that locks the optical beat to the tunable radio frequency. Once the laser frequency tuning exceeds 100 MHz (going through one comb spacing), we reset the radio frequency offset back to the original value to start the process over again. The laser frequency can thus be tuned smoothly in an "inch-worm" fashion through the comb structure. In experiment we verify this tuning process by using independent optical resonances to monitor the diode laser frequency. With improved servo bandwidth, the stability of the iodine-stabilized Nd:YAG laser will be faithfully transferred to another cw laser lying hundreds of THz away.

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18. Cs clock: HP 5071 A; Crystal oscillator: Wenzel 5/10 Blue Top Ultra Low Noise Oscillator; Hydrogen maser: ST-22, Clock-13, NIST, Boulder. We thank our NIST colleagues for the fiber-based delivery of the maser signal to JILA. Mentioning of commercial products is for technical communications only.