# DIRECT RF TO OPTICAL FREQUENCY MEASUREMENTS WITH A FEMTOSECOND LASER COMB

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*Abstract*—**By spanning an optical octave (> 300 THz) with a broadened femtosecond laser frequency comb, we directly measure optical frequency standards at 1064/532 nm, 633 nm and 778 nm in terms of the microwave frequency that controls the comb spacing.**

The pulses from a mode-locked femtosecond (fs)laser are produced in a periodic train; therefore, the required broad spectrum of the laser is actually composed of a vast array, or comb, of distinct frequency modes. The landmark experiments of Udem, *et al.* first demonstrated that the frequency-domain mode comb of a fs laser is controllable and extremely uniform, making it a valuable precision "frequency scale" to measure across gaps of many tens of THz.[1] Recently, we have used the spectrally broadened output of a 10 fs laser to measure the 104 THz gap between two CW stabilized lasers at 778 nm and 1064 nm.[2] Here we report our use of novel silica microstructure optical fiber[3] to further broaden the fs laser frequency comb to span an entire optical octave. This has enabled us to make an absolute measurement of the optical frequency of a stabilized Nd:YAG laser by measuring the gap between its fundamental $f_{1064}$ and second harmonic $2f_{1064}$. Furthermore, with knowledge of $f_{1064}$ we have subsequently used the same broadband comb to measure existing optical standards at 633 nm (HeNe/$I_2$) and 778 nm (Rb 2-photon). To our knowledge, these are the first ever direct rf to optical frequency measurements using a single optical frequency comb and they illustrate a great simplification to the longstanding problem of determining optical frequencies in terms of the cesium primary standard.

Our experiments employ a Kerr-lens mode-locked Ti:Sapphire laser spectrally centered at 800 nm. A portion of the pulse train is detected with a fast diode and the 100th harmonic of the repetition rate is phase-locked to a microwave oscillator at ~ 9.1 GHz by changing the laser cavity length with a PZT [Fig. 1]. The internal clock of the microwave oscillator is referenced to a local rubidium microwave standard, which has its average frequency offset calibrated over several days against the NIST ensemble of cesium clocks via common view GPS reception.[4] Approximately 40 mW from the fs laser is coupled into a 10 cm piece of silica microstructure fiber with minimal group velocity dispersion near 800 nm.[3] The spectrum is broadened by self-phase modulation to cover more than an octave in the optical domain [Fig. 2(a)]. This spectrum is combined with both the fundamental ($f_{1064}$) and second harmonic ($2f_{1064}$) from a Nd:YAG laser which is locked to the $a_{10}$ component of the R(56) $32-0$ transition in $^{127}I_2$.[5] The mode-matched beams are dispersed with a grating and two PIN diodes are used to measure the rf beat frequencies between the CW fields and an adjacent fs mode at both 1064 nm and 532 nm. The optical frequency can then be expressed as

$$f_{1064} = n\Delta \pm (1064 \text{ nm beat} \pm 532 \text{ nm beat}), \quad (1)$$

where $n$ is an integer and $\Delta$ is the fs comb spacing, which is fixed by the microwave oscillator. With only

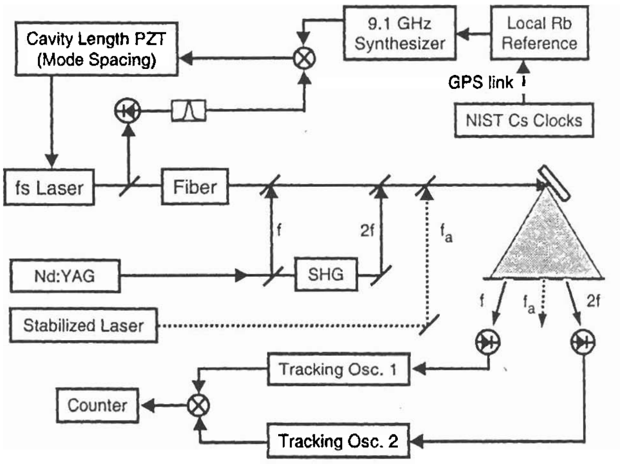

Fig. 1. Block diagram of apparatus used for direct measurement of the optical frequencies in terms of the cesium microwave standard. The stabilized laser refers to another optical frequency standard at 633 nm or 778 nm, for example.

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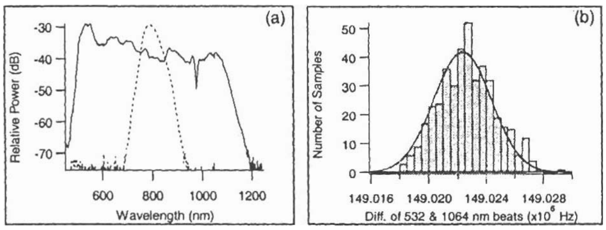

Fig. 2. (a) Output spectrum from the silica microstructure fiber (solid line). The spectrum directly from the laser is indicated by the dashed line (b) Histogram of difference of the rf beat frequencies between the fs laser comb and CW fields at 1064 nm and 532 nm.

the mode spacing of the fs comb fixed, the variations of the beats at 1064 and 532 nm are correlated as the comb position shifts. This correlated noise is removed before counting by preparing either the difference or sum of the two beats with a balanced mixer—thus eliminating two of the possible solutions to Eq. (1). The frequency $f_{1064}$ is already known to better than 1 MHz, so the remaining ambiguous sign of Eq. (1) is removed by incrementing/decrementing $n$. Fig. 2(b) shows the histogram of the difference between the rf beats at 532 and 1064 nm for a representative data set. When known shifts from acousto-optic modualators in the Nd : YAG/$I_2$ system are accounted for, we arrive at $f_{1064} = 281,630,111,760$ kHz with a statistical uncertainty of $\pm 1.9$ kHz for a 1 second measurement. In terms of the 532 nm light, this yields $2f_{1064} = 563,260,223,520$ kHz, which is +40 kHz with respect to the CIPM recommendation for the $a_{10}$ frequency. Measurements over a two-week period show this +40 kHz offset is firm at $< 1$ kHz [Fig. 3], but we emphasize that many tests of systematic effects remain to be investigated. The predominant known sources of uncertainty at this point are the short term (1 s) instability of the microwave oscillator that controls the repetition rate $\Delta$ and variations in the offset of the local rubidium microwave standard at the $10^{-12}$ level over several hours.

Confidence in this fs comb approach to optical frequency metrology can be enhanced by internal tests and measuring some known lasers. With the value of $f_{1064}$ provisionally determined as described above, we can then use the same broadened fs comb to measure the gap between $f_{1064}$ and other optical standards that exist in our lab. This is diagramed in Fig. 1, where $f_a$ is the frequency of the additional optical frequency to be measured. In this way, we have measured both HeNe/$I_2$ at 633 nm and Rb 2-photon at 778 nm. We will present our results for these measured frequencies after additional examination of the involved systematic effects. However, we can report

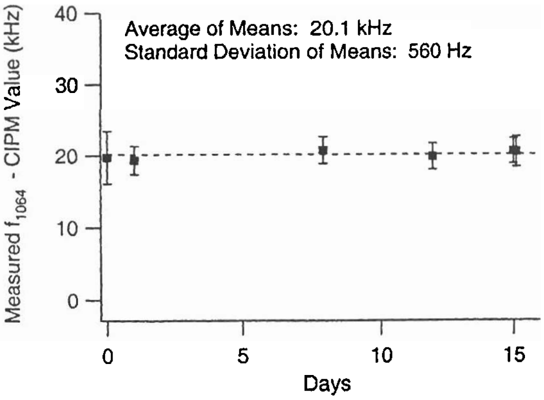

Fig. 3. Summary of measured YAG fundamental $f_{1064}$ over a two week period. The error bars are those of a single one-second measurement.

that in both cases our preliminary measurements fall well within the accepted uncertainties. As a first-order check of the properties of the extremely broad fs comb, we have established that the phases of the comb frequency ($\Delta$) at the green and infrared ends of the spectrum are mutually stable to $< 30$ mrad over a minute time scale. This places a 0.1 mHz upper limit on the variation of $\Delta$ in the two spectral regions. If the mode spacing were assumed to vary linearly, this 0.1 mHz difference would accumulate to a frequency offset of a few hundred hertz across the 280 THz gap. Other confirmation tests are underway.

We will report further on these measurements, the involved systematic effects and limitations, and our work to verify the precision of the broadened fs laser comb using a phase-coherent optical frequency bisector.

## REFERENCES

[1] Th. Udem, J. Reichert, R. Holzwarth and T. W. Hänsch, Phys. Rev. Lett. **82**, 3568 (1999). Th. Udem, J. Reichert, R. Holzwarth and T. W. Hänsch, Opt. Lett. **24**, 881 (1999).

[2] S. A. Diddams, D. J. Jones, L.-S. Ma, S. T. Cundiff and J. L. Hall, Opt. Lett. (in press).

[3] J. Ranka, R. Windeler and A. Stentz, Opt. Lett. (in press).

[4] J. Levine, in Proceedings of 1998 IEEE International Frequency Control Symposium (IEEE, 1998) pp. 284-291.

[5] J. L. Hall, L-S. Ma, M. Taubman, B. Tiemann, F-L. Hong, O. Pfister, and J. Ye, IEEE Trans. Instrum. & Meas. **48**, 583 (1999).