Transferring the stability of iodine-stabilized diode laser at 634 nm to radio frequency by an optical frequency comb

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An optical frequency comb phase-locked on an iodine frequency stabilized diode laser at 634 nm is constructed to transfer the accuracy and stability from the optical domain to the radio frequency domain. An external-cavity diode laser is frequency-stabilized on the Doppler-free absorption signals of the hyperfine transition R(80)8-4 using the third-harmonic detection technique. The instability of the ultra-stable optical oscillator is determined to be 7×10^{-12} by a cesium atomic clock via the optical frequency comb's mass frequency dividing technique.

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Optical frequency comb (OFC) has been proved to be an important instrument in the field of measurement and metrology. On one hand, OFC greatly simplifies the procedure of absolute optical frequency measurements[1−3], which is exceptionally critical for the development of new optical atomic clocks[4] and the tests of basic quantum theory[5−8]. On the other hand, the practical realization of the definition of meter also benefits a lot from the recently comparisons between the iodine-stabilized He-Ne lasers and the current primary microwave cesium atomic clocks via OFC[9−11]. However, the He-Ne lasers cannot provide sufficient optical power (less than 100 μW) and wide enough tuning range (less than 1 GHz), which seriously restrains their applications. The external-cavity diode laser (ECDL) holds the virtues of wider tuning range and larger optical power, which can thus substitute the He-Ne laser in the iodine-stabilized frequency standards[12].

The frequency of the mth comb tooth (f_m) of the OFC is determined as $f_m = mf_{\rm r} + f_0$, where m is the comb index with an order of 10^5, $f_{\rm r}$ is the mode spacing or the so-called repetition rate, and f_0 is the frequency shift of all the comb modes. $f_{\rm r}$ and f_0 are in the microwave region, and f_m is in the optical frequency region. Because of this mass-frequency-multiplying (m times) property of OFC, the absolute optical frequency measurements of the atom/molecule transitions could take great advantages, making the frequency comparisons between the primary microwave atomic clock and the atom/molecule stabilized lasers much easier than before[13]. In the mean time, the OFC, which is phase-locked on the laser with ultra-stable frequency, can transfer the precision and stability of the optical transition to the microwave region or the other optical wavelengths. The precision spectroscopy[14] and optical atomic clockwork[15] would benefit much from this mass-dividing technique.

In this letter, we stabilize the ECDL on the Doppler-free absorption signals of the hyperfine transition R(80)8-4 using the third-harmonic detection technique. The wavelength of the stabilized laser is 634 nm, which is hundreds of gigahertzs from the widely used iodine-stabilized He-Ne laser at 633 nm. An OFC stabilized on the ECDL divides the optical frequency of the order 10^5 to a few megahertzs to be measured by the microwave cesium atomic clock. The instability of the microwave output signal from the OFC is measured to be 7×10^{-12} at 300-s integration time, which fits well with our previous result by comparing two identical ECDLs[16]. This is, as far as we know, the first time to stabilize OFC on this transition and to down-convert this optical frequency to the microwave region.

The experimental system is shown in Fig. 1. The I_2 stabilized diode laser consists of an ECDL, an I_2 gas reference cell, and some necessary optics. The ECDL (New Focus 6304) of Littman configuration is used as the optical oscillator. The output power is 3 mW and the tuning range is 5 nm with a mode-hopping-free range of 70 GHz. After a 55-dB optical isolator, about 2 mW of the

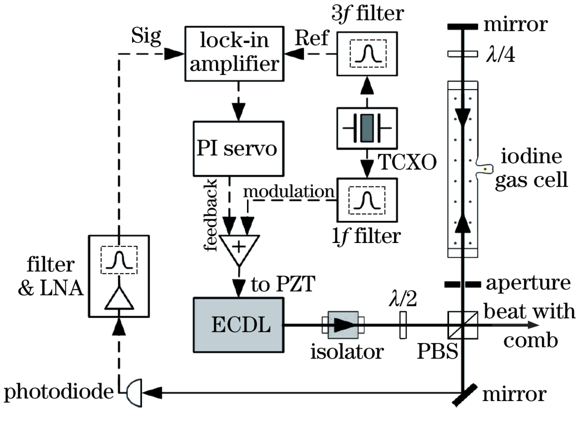

Fig. 1. Iodine-stabilized diode laser. PBS: polarization beam splitter; TCXO: temperature compensated crystal oscillator; LNA: low noise amplifier; PI: proportion and integration; $1f$: modulation frequency; $3f$: the third harmonic of modulation frequency; Sig: signal from photodiode; Ref: reference signal from TCXO; $\lambda/2$: half-wave plate; $\lambda/4$: quarter-wave plate.

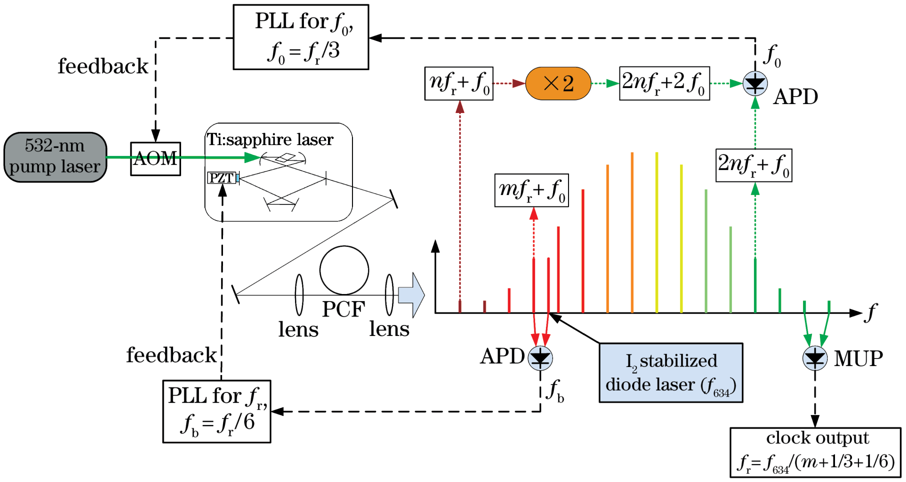

Fig. 2. Optical scheme for the OFC stabilized on the ECDL. AOM: acousto-optic modulator; n: the number index of the comb component used to acquire f_0; PLL: phase-locked loop.

continuous-wave (CW) laser enters the iodine gas cell for the absorption spectroscopy via the third-harmonic detection technique. The length of cell is 40 cm and its cold finger is temperature-controlled to 15.00 ± 0.05 °C. The error signal from the spectroscopy is then fed back to the piezoelectric transducer (PZT) on the back of the grating in the ECDL. According to our previous work[13], the instability of the stabilized ECDL is about 10^{-11} at 1-s integration time. Part of the CW power is beam split after the isolator for optical beating with the OFC. The wavelength of the frequency f_{634} was calculated to be 634.009 nm by our previous work[16].

The optical scheme for the OFC stabilized on the ECDL is shown in Fig. 2. The OFC is constituted by a 532-nm pump laser (Coherent Verdi V6), a Ti:sapphire ring cavity femtosecond oscillator (Gigajet20), and a $(f-2f)$ nonlinear spectrometer utilizing the photonic crystal fiber (PCF, Crystal Fiber NL-740-2.0) to acquire an octave spectrum. The output power of the femtosecond oscillator is about 600 mW under 4.5-W pump power. The repetition rate f_r is around 760 MHz and the pulse width is 25 fs. The signal of f_r is acquired by injecting the laser into a metal-semiconductor-metal ultrafast photodiode (MUP). The supercontinuum generated by the PCF covers the region from 560 to 1120 nm. A 5-mm-long KTiOPO$_4$ (KTP) crystal in room temperature is used to double the spectrum from the infrared to the green visible light to acquire the carrier-envelop offset (f_0). The signal-to-noise ratio (SNR) of the frequency f_0 is over 40 dB (300-kHz resolution bandwidth through this letter if not specified). f_0 is phase-locked to one third of f_r by feeding back the phase error to the acoustic optical modulator (AOM), which changes the intensity of the pump laser and thus can change f_0. The beat note (f_b) between the CW laser and one component of the OFC is acquired by an avalanche photodiode (APD) with a SNR of 30 dB. f_b is phase-locked to one sixth of f_r by feeding back the error signal to the PZT attached on the cavity mirror to change f_r. A digital frequency divider is used to divide f_r by 3, 6, and 32. The output of the entire optical frequency referenced OFC is f_r, which is an ultra-stable microwave signal that can be calculated as

$$f_r = f_{634}/(m+1/3+1/6), \tag{1}$$

where f_{634} is the frequency of the CW laser and m is the number index of the comb component used for optical beating. The down-converted frequency is further divided by 32 to approximately 23.65 MHz and is mixed with a signal coming from a signal generator (HP3325B) referenced on the cesium atomic clock (HP5071A). The frequency of the signal after the double-balanced mixer (DBM) is at the level of tens of kilohertzs, which can be measured by a commercial frequency counter (Agilent 53131A) with sufficient precision.

Figure 3 shows the free-running frequency fluctuation of the output microwave signal ($f_r/32$). We use the Allan variance[17] to describe the frequency fluctuation and instability. The data show that the free-running output has an instability of 10^{-9} at 1-s integration time and deteriorates in the long term. This is mainly due to the temperature changing of the environment (±1 °C). The short-term frequency noise is mainly due to the acoustic vibration from the air flow.

We measured the instability of the output microwave frequency while the OFC is locked on the CW laser, as shown in Fig. 4. The microwave output signal has an instability of 7×10^{-11} at 1-s integration time and reduces to 7×10^{-12} at 300-s integration time. The bandwidth

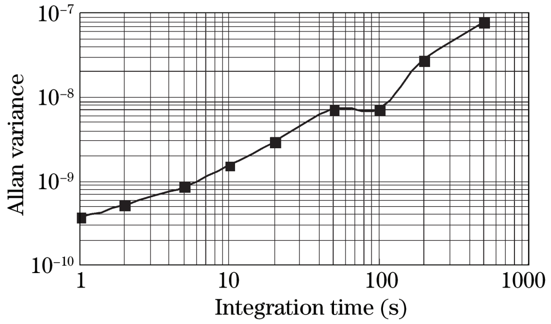

Fig. 3. Instability represented in Allan variance when the OFC is free running.

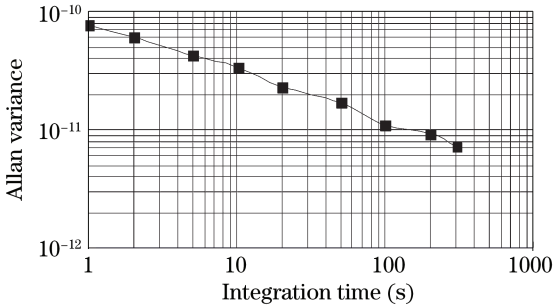

Fig. 4. Instability represented in Allan variance when the OFC is phase-locked on the iodine-stabilized laser at 634 nm.

of the loop filter is optimized to the order of hundreds of hertzs to suppress the short-term frequency noise caused by the acoustic vibrations. An integration servo is useful to control the long-term frequency fluctuation of the system. The measured result shows that the performance of the OFC referenced on optical transition has been achieved to the same level of the optical reference proposed in Ref. [13]. The result also shows that the frequency fluctuation of the OFC is below 4 kHz throughout the visible and infrared spectrum, from 560 to 1120 nm.

In conclusion, a phase-locked OFC referenced on the optical transition R(80)8-4 of iodine is constructed. The output signal of 23.65 MHz is compared with the commercial cesium atomic clock. The instability of the microwave output of the OFC is 7×10^{-12} at 300-s integration time. With the absolute frequency of the f_{634} determined and the introduction of the fiber optical comb in the future, the OFC phase-locked to the I_2 stabilized diode laser with the instability of 10^{-12} provides moderate performance and could serve as a portable molecular optical clock, which is convenient for applications in the field of metrology and measurements.

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References

1. Th. Udem, S. A. Diddams, K. R. Vogel, C. W. Oates, E. A. Curtis, W. D. Lee, W. M. Itano, R. E. Drullinger, J. C. Bergquist, and L. Hollberg, Phys. Rev. Lett. **86,** 4996 (2001).
2. J. Stenger, C. Tamm, N. Haverkamp, S. Weyers, and H. R. Telle, Opt. Lett. **26,** 1589 (2001).
3. J. Helmcke, G. Wilpers, T. Binnewies, C. Degenhardt, U. Sterr, H. Schnatz, and F. Riehle, IEEE Trans. Instrum. Meas. **52,** 250 (2003).
4. S. A. Diddams, Th. Udem, J. C. Bergquist, E. A. Curtis, R. E. Drullinger, L. Hollberg, W. M. Itano, W. D. Lee, C. W. Oates, K. R. Vogel, and D. J. Wineland, Science **293,** 825 (2001).
5. H. Marion, F. P. Dos Santos, M. Abgrall, S. Zhang, Y. Sortais, S. Bize, I. Maksimovic, D. Calonico, J. Grünert, C. Mandache, P. Lemonde, G. Santarelli, Ph. Laurent, A. Clairon, and C. Salomon, Phys. Rev. Lett. **90,** 150801 (2003).
6. S. Bize, S. A. Diddams, U. Tanaka, C. E. Tanner, W. H. Oskay, R. E. Drullinger, T. E. Parker, T. P. Heavner, S. R. Jefferts, L. Hollberg, W. M. Itano, and J. C. Bergquist, Phys. Rev. Lett. **90,** 150802 (2003).
7. M. Fischer, N. Kolachevsky, M. Zimmermann, R. Holzwarth, Th. Udem, T. W. Hansch, M. Abgrall, J. Grünert, I. Maksimovic, S. Bize, H. Marion, F. P. Dos Santos, P. Lemonde, G. Santarelli, P. Laurent, A. Clairon, C. Salomon, M. Haas, U. D. Jentschura, and C. H. Keitel, Phys. Rev. Lett. **92,** 230802 (2004).
8. E. Peik, B. Lipphardt, H. Schnatz, T. Schneider, Chr. Tamm, and S. G. Karshenboim, Phys. Rev. Lett. **93,** 170801 (2004).
9. R. W. Fox, S. A. Diddams, A. Bartels, and L. Hollberg, Appl. Opt. **44,** 113 (2005).
10. P. Balling and P. Křen, Eur. Phys. J. D **48,** 3 (2007).
11. R. P. Smith, P. A. Roos, J. K. Wahlstrand, J. A. Pipis, M. B. Rivas, and S. T. Cundiff, J. Res. Natl. Inst. Stand. Technol. **112,** 289 (2007).
12. A. Zarka, A. Abou-Zeid, D. Chagniot, J.-M. Chartier, O. Číp, J.-F. Cliche, C. S. Edwards, F. Imkenberg, P. Jedlićka, B. Kabel, A. Lassila, J. Lazar, M. Merimaa, Y. Millerioux, H. Simonsen, M. Têtu, and J.-P. Wallerand, Metrologia **37,** 329 (2000).
13. H. Schnatz, B. Lipphardt, J. Helmcke, F. Riehle, and G. Zinner, Phys. Rev. Lett. **76,** 18 (1996).
14. W. Demtröder, *Laser Spectroscopy: Basic Concepts and Instrumentation* (Springer-Verlag, Berlin, 1981).
15. A. D. Ludlow, T. Zelevinsky, G. K. Campbell, S. Blatt, M. M. Boyd, M. H. G. de Miranda, M. J. Martin, J. W. Thomsen, S. M. Foreman, J. Ye, T. M. Fortier, J. E. Stalnaker, S. A. Diddams, Y. Le Coq, Z. W. Barber, N. Poli, N. D. Lemke, K. M. Beck, and C. W. Oates, Science **319,** 1805 (2008).
16. X. Chen, K. Zhang, E. Zang, Y. Akimoto, T. Kasahara, K. Sakamoto, and H. Inaba, Proc. SPIE **3547,** 194 (1998).
17. D. W. Allan, Proc. IEEE **54,** 221 (1966).