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A diode laser spectrometer at 634 nm and absolute frequency measurements using optical frequency comb*

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This paper reports that two identical external-cavity-diode-laser (ECDL) based spectrometers are constructed at 634 nm referencing on the hyperfine B-X transition R(80)8-4 of $^{127}I_2$. The lasers are stabilized on the Doppler-free absorption signals using the third-harmonic detection technique. The instability of the stabilized laser is measured to be 2.8×10^{-12} (after 1000 s) by counting the beat note between the two lasers. The absolute optical frequency of the transition is, for the first time, determined to be 472851936189.5 kHz by using an optical frequency comb referenced on the microwave caesium atomic clock. The uncertainty of the measurement is less than 4.9 kHz.

Keywords: frequency standard, optical frequency comb, absolute frequency measurement, atomic clock
PACC: 0765, 3320K, 4262E

1. Introduction

Absolute frequency measurements in the optical region[1,2] have become much less complex than before[3] after the emergence of the optical frequency comb (OFC),[4] which bridges the microwave domain and the optical domain. The development of optical frequency synthesizing techniques greatly enhances the research in optical metrology,[5] optical atomic clock,[6] and test of fine structure constant invariance[7] in general physics. Recently,[8–10] the frequency comparisons between the primary microwave frequency standards and the widely used iodine stabilized He–Ne lasers at 633 nm using the OFCs, have drawn a lot attention in the field of metrology. In the same wavelength, the iodine stabilized external-cavity-diode-lasers (ECDLs) provide better stability and much wider frequency tuning range.[11]

In our previous work on the ECDL based $^{127}I_2$ spectrometer,[12] we have measured the hyperfine splittings of the R(80)8-4 at 634 nm using a Fabry–Perot interferometer and compared the data with our theoretical calculations. Error signal shows that the relative instability of the spectrometer is estimated to be 2.0×10^{-11} at 1 s integration time. In the subsequent comparison[13] with an iodine based He–Ne laser at 633 nm while the ECDL is referenced on the P(33)6-3 transition, the calculated allan variance[14] shows that the instability is 6.0×10^{-11} at 1 s integration time and reduces to 7.7×10^{-12} at 500 s.

In our present work, two identical $^{127}I_2$ stabilized ECDLs are constructed using the third derivative harmonic detection and saturated absorption spectroscopy. The instability calculated from the result of the beating is 3.7×10^{-11} at 1 s integration time and reaches the flicker noise floor of 2.8×10^{-12} at 1000 s. The absolute frequency is determined to be 472851936189.5(±4.9) kHz by comparing the ECDL with an OFC referenced on the microwave caesium atomic clock. This is, as far as we know, the first precise absolute frequency measurement of the optical transition R(80)8-4 of $^{127}I_2$ at 634 nm, whose frequency is hundreds of gigahertz away from the He–Ne laser. The ECDL based spectrometer can benefit much from its compactness, low cost and wide tuning range in the fields of atom–molecule spectroscopy,[16] metrology[17,18] and cold atomic physics,[19] etc.

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2. Experimental setup

The experimental scheme for the instability measurement is shown in Fig.1. The output power of the Littman ECDL (NewFocus 6304) is 3 mW and the line-width is below 300 kHz. The wavelength tuning range of the laser is from 632 nm to 637 nm. A polarized-beam-splitter (PBS) after the ECDL is used to separate the horizontal polarized beam power for optical frequency beating. The left vertical polarized power is used for the subsequent spectroscopy. The Faraday rotators and PBSs provide a two-stage optical isolation up to 55 dB. Before the iodine vapour cell, a half wave-plate and a PBS are used to adjust the saturating power. The cold fingers of the two identical iodine vapour cells are temperature-controlled to $15 \pm 0.05\,^{\circ}$C. A quarter wave-plate and a high reflection mirror are used to rotate the polarization of the backward detection light to reach the low noise photodiode. The power of each laser for the optical beating is around 0.1 mW before entering the avalanche photodiode (APD). The signal-to-noise ratio (SNR) of the beat note is over 40 dB (300 kHz resolution bandwidth through this paper if not specified) at a power level of –17 dBm before entering the commercial frequency counter (Agilent 53131A) referenced on the caesium atomic clock (HP5071A, instability: better than 10^{-12} after 100 s). All the optical components and the temperature controlling electronics are placed in an alloy box on a vibration-isolated optical table. The temperature of the environment is controlled to $25 \pm 1\,^{\circ}$C by the air-conditioning system.

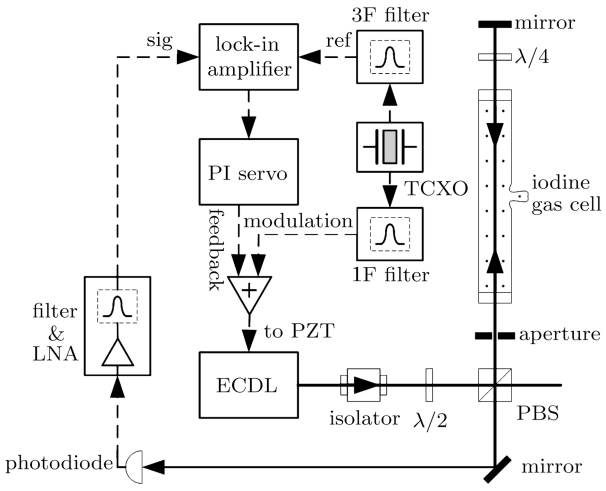


Fig.1. Iodine stabilized ECDL for optical frequency beating. ECDL: external-cavity diode laser, PBS: polarized beam splitter, TCXO: temperature compensated crystal oscillator, LNA: low noise amplifier, PI: proportion and integration, PZT: piezo transducer, 1F: modulation frequency, 3F: the third harmonic of modulation frequency.

The modulation frequency for the piezo transducer (PZT) attached on the grating of the ECDL is 2.083 kHz from a temperature-compensated-crystal-oscillator (TCXO) and the typical peak-to-peak modulation depth is 6 MHz. The second harmonic suppression and the third harmonic suppression of modulation signal are over 85 dB using notch filters. The electrical signal from the photodiode is amplified by a low noise amplifier (LNA). The third harmonic of the modulation frequency is band-pass selected and phase-detected with the reference at 6.249 kHz using lock-in amplifiers (LIA). After properly phase shifting and filtering, the SNR of the acquired error signal between the laser frequency and the transition frequency is over 100 (100 ms time constant in LIA). It is then processed with a proportional-integration (PI) servo controller to stabilize the laser's frequency via the PZT in the ECDL.

Figure 2 shows the absolute frequency measuring system. A Ti:sapphire ring cavity femto-second oscillator (Gigajet20) is pumped by a 532 nm solid state laser (Coherent Verdi V6) with an output power of about 600 mW while 4.8 W pumped. 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 f_r is phase-locked to the microwave reference signal from the caesium atomic clock (HP5071A) by feeding back the phase error to the PZT attached on the cavity mirror to change the cavity length. An f-2f nonlinear spectrometer utilizing the photonic crystal fibre (PCF, Crystal Fibre NL-740-2.0) is used to acquire an octave spectrum. The supercontinuum generated by the PCF covers the region from 560 nm to 1120 nm. A 5 mm-long KTiOPO4 (KTP) in the room temperature is used to double the spectrum from the infra-red to the green visible light to acquire the carrier-envelop offset (f_0), with an SNR of over 40 dB. The f_0 is also phase-locked to the microwave reference from the caesium atomic clock by feeding back the phase error to the acoustic optical modulator, which changes the intensity of the pump laser thus can change the f_0. To find out the index (m) of the comb tooth which is beating with the CW laser, we use a 6-digit wavelength-meter to record the wavelength of the CW laser. Another way is to use the theoretical calculated results from Ref.[12]. The wavelength of the transition is determined to be 634.0091 nm.

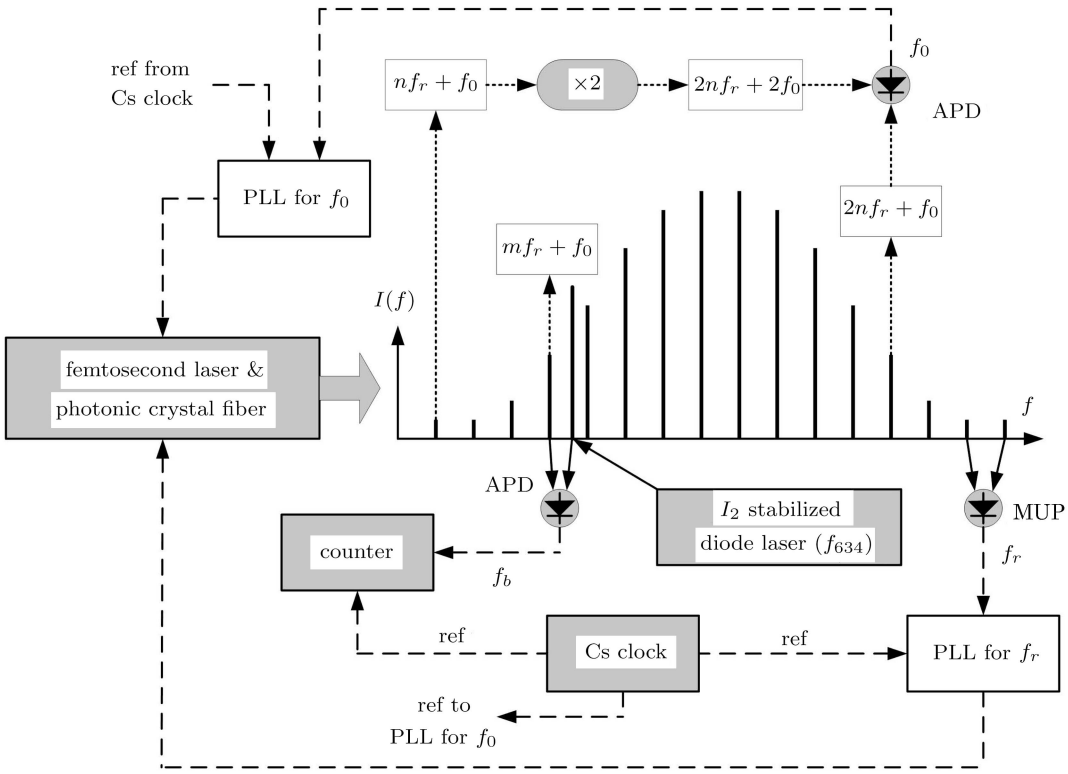


Fig.2. Optical layout for the absolute frequency measurement. APD: avalanche photodiode, MUP: metal-semiconductor-metal ultrafast photodiode, f_r: repetition rate, f_0: carrier-envelop offset, f_b: beat note, f_{634}: optical frequency, n: the number index of the comb component for $f - 2f$ interferometer, m: the number index of the comb component for optical beating, counter: frequency counter, Cs clock: caesium atomic clock.

3. Results and discussions

The instability of the stabilized spectrometer is determined by comparing the two identical systems. The ECDLs in the two systems are stabilized on two different hyperfine transitions (a and f in the inset of Fig.3) of R(80)8-4 to acquire a non-zero beat note signal. We counted the beat note for more than 12 hours. Figure 3 shows the calculated allan variance from the recorded frequency data of the beat note. The relative instability of each spectrometer is 3.7×10^{-11} at 1 s integration time and reaches the flicker noise floor of 2.8×10^{-12} at 1000 s, corresponding to a frequency fluctuation of 1.3 kHz.

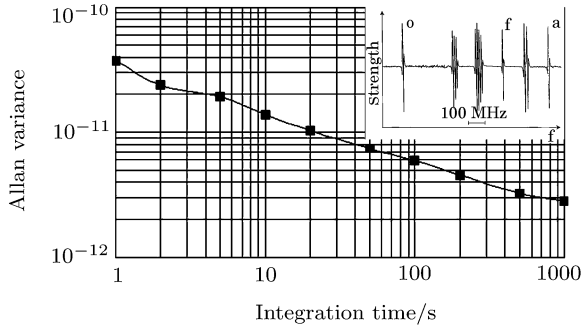


Fig.3. The Allan variance acquired by beating two identical spectrometers stabilized on different hyperfine structures of iodine R(80)8-4 transition.('a' and 'f' in the inset).

The short term instability is mainly caused by the residual air flowing in the laboratory, which is necessary for the air-conditioning to maintain the environmental temperature. The long term fluctuation is mainly due to the temperature fluctuation of the cell cold finger (0.05 °C) and cell wall (1 °C). According to the suggesting coefficients in Ref.[15], the frequency shifting caused by these two reasons are approximately 0.75 kHz and 0.5 kHz respectively in our measurements.

The absolute frequency of the highest hyperfine transition 'a' of R(80)8-4 is performed by comparing the CW laser with the adjacent comb tooth of the OFC. The SNR of the beat note is 25 dB and is bandpass filtered and amplified to 0 dBm before counting. The comparison is repeated four times on different days and the results are shown in Fig.4.

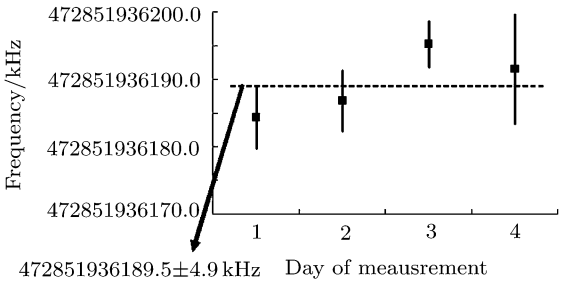


Fig.4. Absolute frequency measurement of the "a" hyperfine structure in R(80)8-4 transition of $^{127}I_2$.

The frequency of the transition is measured to be 472851936189.5 kHz with a measuring uncertainty of 4.9 kHz. This is, as far as we know, the first precise absolute frequency measurement of this transition at 634 nm.

4. Conclusion

In conclusion, two identical ECDL based spectrometers referenced on the hyperfine transition of $^{127}I_2$ R(80)8-4 are built to acquire an instability of 2.8×10^{-12} at 1000 s integration time. The absolute frequency of the highest hyperfine transition 'a' is measured to be 472851936189.5(±4.9) kHz by comparing an OFC referenced on the caesium atomic clock and the stabilized ECDL. This is, as far as we know, the first precise absolute frequency measurement of iodine transition at 634 nm, which is hundreds of gigahertz away from nearing the iodine stabilized He–Ne laser at 633 nm.

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