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Iodine-stabilized 543 nm HeNe lasers

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Abstract

Internal-mirror 543 nm HeNe lasers are frequency-stabilized on the iodine hyperfine transitions. The Allen standard deviation of 1×10^{-12} is reached after a 10 second integration time. The hyperfine spectrum originating from the R(12) 26-0 and R(106) 28-0 lines of the B–X system of $^{127}I_2$ has been studied. The frequency differences between hyperfine components have been measured by beat frequency techniques, and the hyperfine coupling constants are fitted for the R(106) 28-0 line.

1. Introduction

Since the new definition of the meter was adopted in 1983 by the 17th Conférence Générale des Poids et Measures (CGPM) [1], based on a fixed value of the speed of light in vacuum (299792458 m/s), the wavelength of light radiation can be calculated when its frequency is known. In the same year, the Comité International des Poids et Measures (CIPM) recommended five stabilized laser radiations for the practical realization of the meter [2]. Four of them are lasers locked to the hyperfine transitions of the I_2 molecule using saturated absorption techniques.

In order to conveniently realize the new definition of the meter, many groups over the world are searching for new frequency-stabilized lasers and measuring their frequencies. The 543.5 nm green HeNe laser, locked to the saturated absorption of I_2 hyperfine transition, is a new potential candidate of the list of recommended radiations [3]. More recently, due to the precision wavelength measurement of the iodine-stabilized 543 nm HeNe laser [4], the International Committee on Weights and Measures has adopted this laser as a recommended wavelength standard [5]. Therefore, systematic studies of I_2-stabilized green HeNe lasers are important for metrology.

Up to now the following works about the I_2-stabilized green HeNe laser have been published in the literature:

(i) BIPM: a minimum value of the Allan standard deviation of 2.5×10^{-12} was reached after a 50 second integration time. Also a study of modulation and pressure effects was presented [6].

(ii) PTB: the sensitive FM side-band spectroscopy method was applied in their frequency stabilized lasers to improve the frequency reproducibility [7]. An Allan standard deviation of 2.7×10^{-13} was reached at a sampling time of 10000 s [4].

(iii) University of Aarhus (Denmark): the Doppler background was eliminated using differential saturated absorption technique and frequency stabil-

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ity of 5×10^{-11} was achieved using the first-derivative locking method [8].

In this paper, we report on I_2-stabilized green HeNe lasers. In our setup, laser frequency modulation was obtained using a PZT glued on the laser tube. The saturated absorption signals of the hyperfine structure (HFS) was investigated using the third-derivative technique and used to frequency-stabilize the laser. Good stability was obtained due to high laser power, long absorption length and high modulation frequency. Our preliminary measurement shows that the Allan standard deviation is lower than 1×10^{-12} after a 10 second integration time and about 2×10^{-13} at 300 second integration time. This result is better than previous works [4,6]. A scheme of measuring the frequency of I_2-stabilized green HeNe laser is also presented at the end of paper.

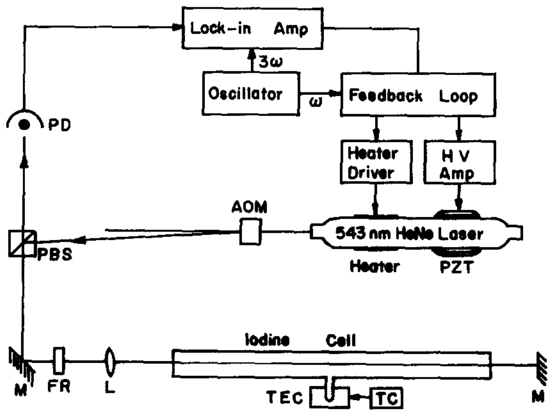

Fig. 1. A schematic diagram of the stabilized laser system. AOM: acousto-optic modulator; PBS: polarizing beam splitter; M: mirror; FR: Fresnel rhomb; L: lens (f= 1 m); PD: photo-diode; PZT: piezo-electric transducer; TEC: thermo-electric cooler; TC: temperature controller.

2. Experimental setup

Two internal-mirror green HeNe laser tubes [#1], type LTGR0075 manufactured by PMS (Particle Measurement System), with cavity length of 0.34 m and mode spacing of 440 MHz, were used in our experiment. A magnetic field with an 45° angle to the natural axis of the laser tube was applied in order to avoid polarization flipping [8–10]. A tuning range of about 750 MHz, and a maximum output power of 400 μW were obtained. For controlling the laser cavity length, a thin film heater and a PZT (glued by epoxy) were attached to the laser tube. In order to decrease the thermal drift, the laser were enclosed in temperature-controlled boxes.

The experimental setup we used is shown in Fig. 1. After the laser output beam was diffracted by the acousto-optic modulator (AOM, carrier frequency is 80 MHz), the −1 order beam passed through the polarizing beam splitter (PBS) to select a single frequency mode for the saturation absorption. Then it was reflected by the mirror and passed the Fresnel rhomb (FR) and lens (L, f= 1 m). Finally, it went through the I_2 cell. The returned beam transmitted the PBS and was detected by the photodiode (PD). Among those optical elements, PBS, FR and AOM played the role of optical isolator which prevented the optical feedback effect.

The I_2 cell is 120 cm long. By cooling the cold finger of I_2 cells with the thermo-electric cooler (TEC), the vapor pressure of I_2 was controlled and hence the pressure broadening was decreased. The temperature of the cold finger was kept constant at −15°C with a temperature controller (TC) and the corresponding iodine pressure is about 1 pa (or 7 mTorr).

In order to obtain an I_2 saturated absorption spectrum, the PZT tube was used to modulate the laser frequency with a modulated frequency of 25.6 kHz, which is the mechanical resonance frequency of laser tube, similar to the method of Mio and Tsubono [11]. The advantages of this method are the modulation amplitude needed is easily achieved, and the signal-to-noise ratio (SNR) is greatly increased due to high modulation frequency and low $1/f$ noise.

The third derivative signal was obtained with the third-harmonic demodulation, and it was fed into the feedback circuit to correct the cavity length of laser tube. The slow frequency drift was corrected by the film heater, and the fast frequency fluctuation was corrected by the PZT.

The beat frequencies between the HFS components were measured by mixing two iodine-stabilized laser beams into an APD (Telefunken BPW 28). The beat frequency was lowered (or raised) to about 50 MHz by mixing it with a rf signal from a frequency synthesizer (HP8656B). The final beat notes were

[#1] Our laser tubes are glass laser tubes, which are different from the metal tubes used by Chartier et al. [6].

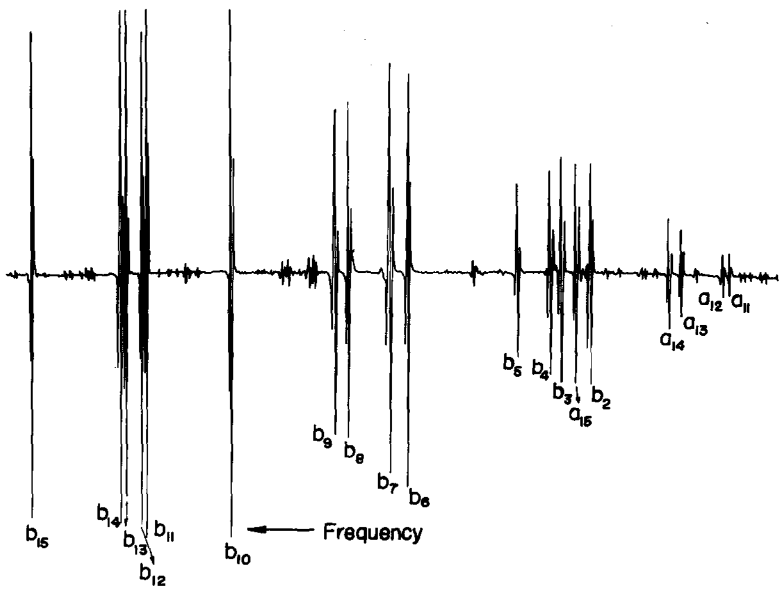

Fig. 2. The observed hyperfine spectrum of I_2. It was recorded by thermal tuning the laser cavity length. The frequency scale is not linear. Many weak and unidentified lines are seen in this figure due to the high SNR of our setup.

filtered by a bandpass filter at 50 MHz and amplified by a rf preamplifier (HP8447D) before they were counted by a frequency counter and recorded by a personal computer. The true beat frequency was obtained by adding (or substracting) the frequency or the rf signal to the counted frequency.

3. Results

A typical saturated-absorption spectrum obtained by thermal tuning, is shown in Fig. 2. The result shows good SNR (some greater than 200) and the Doppler background is removed. The transition lines with $\Delta F = \Delta J = +1$ were easily observed. We have observed 19 transitions, a_{11} to a_{15} and b_2 to b_{15}. Among them, b_{11} to b_{15} are first observed using a green HeNe laser. Here, a and b refer to R (12) 26-0 and R (106) 28-0 hyperfine lines, respectively, following the nomenclature proposed by Gläser [12]. In addition, many unidentified lines are clearly seen in Fig. 2, and an analysis of these lines is still under investigation.

The lasers can be locked to each of the 19 lines. Fig. 3 shows the plot of the two sample standard deviation $\sigma(2, \tau)$ of b_8 for the integration time from 0.1 to 1000 s with both lasers locked to the b_8 component.

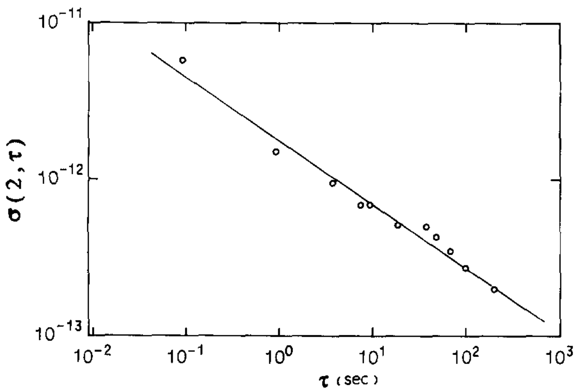

Fig. 3. The Allan standard deviation $\sigma(2, \tau)$ of b_8 as a function of the integration time τ.

The preliminary beat frequency measurement shows that the Allan standard deviation is smaller than 10^{-12} at 10 s and is down to 2×10^{-13} at about 300 s. By far this is the best result and it is well comparable to the iodine-stabilized red HeNe laser.

The measured hyperfine frequency intervals with respect to b_8 component are listed in Table 1, and compared with other results [4,13]. Each component is obtained and averaged with 20 measurements. Our results compare very well to Brand's re-

Table 1
The measured and fitted hyperfine frequency intervals with respect to b_8 compared with that of Brand [4] and Gläser et al. [13] The estimated standard uncertainty is in last digits within parenthesis.

HFS Comp	Measured [this work] (MHz)	Fitted (MHz)	Measured [4] (MHz)	Measured [13] (MHz)
R(12)26-0				
a_6	–		−668.152(11)	−668.156(10)
a_7	–		−624.616(9)	−624.649(9)
a_8	–		−605.370(8)	−605.389(3)
a_9	–		−551.657(8)	−551.664
a_{10}	–		−468.368(8)	−468.383(12)
a_{11}	−357.784(7)		−357.847(17)	−357.903(17)
a_{12}	−348.641(19)		−348.589(16)	−348.615(17)
a_{13}	−295.473(1)		−295.463(11)	−295.482(17)
a_{14}	−282.251(3)		−282.256(11)	−282.278(18)
a_{15}	−178.158(1)		−178.143(10)	−178.167(19)
R(106)28-0				
b_1	–	−446.003	−445.996(8)	−446.033(15)
b_2	−192.704(1)	−192.704	−192.699(10)	−192.743(19)
b_3	−163.840(1)	−163.839	−163.822(17)	−163.854(19)
b_4	−154.382(1)	−154.384	−154.379(18)	−154.413(19)
b_5	−125.916(1)	−125.917	−125.912(16)	−125.933(19)
b_6	−44.936(1)	−44.934	−44.929(12)	−44.943(19)
b_7	−31.672(1)	−31.673	−31.664(13)	−31.664(19)
b_8	0.000	0.000	0.000(17)	0.000(19)
b_9	13.181(2)	13.176	13.190(20)	13.185(19)
b_{10}	127.761(1)	127.757	127.763(11)	127.759(20)
b_{11}	252.586(7)	252.592	–	–
b_{12}	260.073(2)	260.072	–	–
b_{13}	282.272(1)	282.272	–	–
b_{14}	290.414(3)	290.418	–	–
b_{15}	415.004(1)	415.004	–	–

Table 2
The fitted hyperfine coupling constants for I_2 R(106) 28-0 transition

	This work		Ref. [4]	Ref. [13]	Ref. [14]
	with weights	without weights			
ΔeqQ(MHz)	1914.4320(69)	1914.4330(86)	1914.422(7)	1914.514(24)	1912.96(47)
ΔC(kHz)	70.267(2)	70.267(3)	70.30(1)	70.28(1)	70.71(17)
Δd(kHz)	−33.877(259)	−34.205(300)	−34.0(14)	−37.3(9)	−1.58(5)
$\Delta\delta$(kHz)	−9.632(411)	−8.953(474)	−8.6(3)	−5.1(4)	−3.66(3)
Standard deviation of the fit (kHz)	2.30	2.81	5.4	9	44

The lower level constants are following: $eqQ=-2452.5837$ MHz, $C=3.162$ kHz, $d=1.58$ kHz, $\delta=3.66$ kHz [15]. The weights used are the inverse square of estimated uncertainty of measured values. The standard deviation is in last digits within parenthesis. For comparison the results of Brand [4], Gläser [13] and Fredin-Picard et al. [14] are included. Here, *eQq*: nuclear electric quadrupole interaction, *C*: spin–rotation interaction, *d*: tensor spin–spin interaction, and δ: scalar spin–spin interaction.

sults [4] and the differences (except a_{11} and a_{12}) are under 20 kHz.

Due to the small number of the observed hyperfine lines for R (12) 26-0 transition, we have only fitted the hyperfine coupling constants for R (106) 28-0 transition. The fitting program was generously given by Dr. S. Fredin-Picard of BIPM [14]. The hyperfine coupling constants of the lower level were taken from Yokozeki and Munter [15], and were kept fixed in the fit. The fitted hyperfine coupling constants are given in Table 2. The standard deviations of the fit are 2.30 and 2.81 kHz with and without weight, respectively. The fitted results are better than others [4,13,14].

4. Proposed frequency measurement scheme

Although a precision wavelength measurement of the hfs-component a_9 has been carried out at PTB using the Michelson interferometer [4], we propose a frequency measurement scheme here, as shown in Fig. 4. The second harmonic radiation generated in the nonlinear crystal $ZnGeP_2$ of a 9P (38) CO_2 laser stabilized by saturated fluorescence [16], and the radiation from an I_2-stabilized 612 nm HeNe laser are mixed in $LiIO_3$ crystal to obtain green radiation at the sum frequency. This radiation separates from the 543 nm HeNe laser radiation by about 24.7 GHz, which can be measured by beat frequency measurement. Since th accuracy of the frequency of CO_2 laser is known to 5 kHz [17,18], and that of I_2-stabilized 612 nm HeNe laser to 180 kHz [2], the result of this measuring scheme should reach an accuracy about

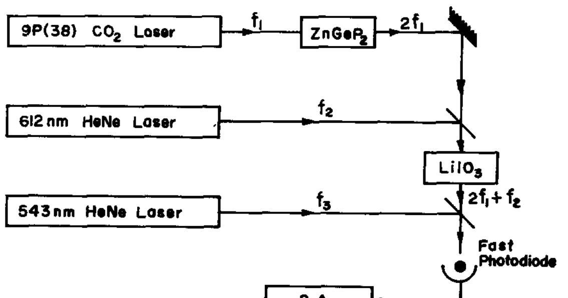

Fig. 4. The proposed frequency measurement scheme. $ZnGeP_2$ and $LiIO_3$ are nonlinear optical crystals, and SA is a spectrum analyzer.

200 kHz, i.e. $\Delta f/f \sim 3.6 \times 10^{-10}$, for the 543 nm HeNe laser. Currently, we are setting up the system and we plan to measure the frequency of our iodine-stabilized 543 nm HeNe laser in the near future.

5. Conclusions

Using the I_2 standard absorption technique, we were able to frequency stabilize two internal-mirror 543 nm HeNe lasers on the HFS transition of I_2. Our preliminary result yields an Allan standard deviation $< 10^{-12}$ at 10 s, which is better than that of Brand [4] and is comparable to that of I_2-stabilized 633 nm HeNe lasers. Hereby, the iodine-stabilized 543 nm HeNe laser can be considered as one candidate to the list of recommended wavelengths. Currently, we are improving the stability of our systems and preparing the apparatus for measuring the frequency in the near future.

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