Search Hits Help

Frequency Comparison and Absolute Frequency Measurement of I_2-stabilized Lasers at 532 nm

A. Yu. Nevsky[1,3], R. Holzwarth[1], J. Reichert[1], Th. Udem[1], T. W. Hänsch[1], J. von Zanthier[1], H. Walther[1], H. Schnatz[2], F. Riehle[2], P. V. Pokasov[3], M. N. Skvortsov[3], and S. N. Bagayev[3]

[1] Sektion Physik der Ludwig-Maximilians-Universität München and Max-Planck-Institut für Quantenoptik, D-85748 Garching, Germany
[2] Physikalisch-Technische Bundesanstalt, D-38116 Braunschweig, Germany
[3] Institute of Laser Physics, 630090 Novosibirsk, Russia

Abstract. We present a frequency comparison and an absolute frequency measurement of two independent I_2-stabilized frequency-doubled Nd:YAG lasers at 532 nm, one set up at the Institute of Laser Physics, Novosibirsk, Russia, the other at the Physikalisch-Technische Bundesanstalt, Braunschweig, Germany. The absolute frequency of the I_2-stabilized lasers was determined using a CH_4-stabilized He-Ne laser as a reference. This laser had been calibrated prior to the measurement by an atomic cesium fountain clock. The frequency chain linking phase-coherently the two frequencies made use of the frequency comb of a Kerr-lens mode-locked Ti:sapphire femtosecond laser where the comb mode separation was controlled by a local cesium atomic clock. A new value for the R(56)32-0:a_{10} component, recommended by the Comité International des Poids et Mesures (CIPM) for the realization of the metre [1], was obtained with reduced uncertainty. Absolute frequencies of the R(56)32-0 and P(54)32-0 iodine absorp tion lines together with the hyperfine line separations were measured.

1 Introduction

Presently, twelve reference frequencies covering the visible and infrared regions of the electromagnetic spectrum are recommended by the Comité International des Poids et Mesures (CIPM) for the realization of the metre [1]. Up to now, practical length metrology is performed mainly using the red line of the iodine stabilized He-Ne laser at $\lambda = 633$ nm with a relative standard uncertainty of 2.5 $\times 10^{-11}$ [2].

A new optical frequency standard in the green part of the visible spectrum becomes possible by using a diode-pumped, frequency-doubled Nd:YAG lasers emitting at $\lambda = 532$ nm. Compact in size, these lasers exhibit low intrinsic frequency and amplitude noise, high power levels and long expected life time. A number of iodine absorption lines which are strong and narrow lie within the tuning range of the doubled frequency at 532 nm so that they can be used as reference lines and for the frequency stabilization of the laser. Presently, several groups are investigating a number of features of these laser systems, at Stanford University, the Joint Institute for Laboratory Astrophysics (JILA), Boulder, the Bureau International des Poids et Mesures (BIPM), Paris, the Institute of

Laser Physics (ILP), Novosibirsk, including different methods of frequency stabilization [3,4], measurements of hyperfine line separations or frequency intervals between absorption lines [5,6,?] and absolute optical frequency measurements [8,9,10,11]. As a result of these efforts, the Comité Consultatif des Longueurs (CCL) meeting in 1997 recommended the frequency of one particular component, the a_{10} hyperfine structure (HFS) component of the R(56)32-0 transition, for the realization of the metre with a relative standard uncertainty of 7×10^{-11} [1].

We present a frequency comparison of two independent I_2-stabilized Nd:YAG lasers at 532 nm and an absolute frequency measurement of the laser frequencies which were locked to different HFS components of the R(56)32-0 and P(54)32-0 iodine absorption line. The absolute frequencies have been determinded using a phase-coherent frequency chain which links the I_2-stabilized laser frequency to a CH_4-stabilized He-Ne laser at 3.39 μm. This laser had been calibrated before the measurements against an atomic cesium fountain clock.

2 Laser Systems

The PTB Nd:YAG laser system [12], based on model 142 of Lightwave Electronics Co. [13], is shown in Fig. 1.

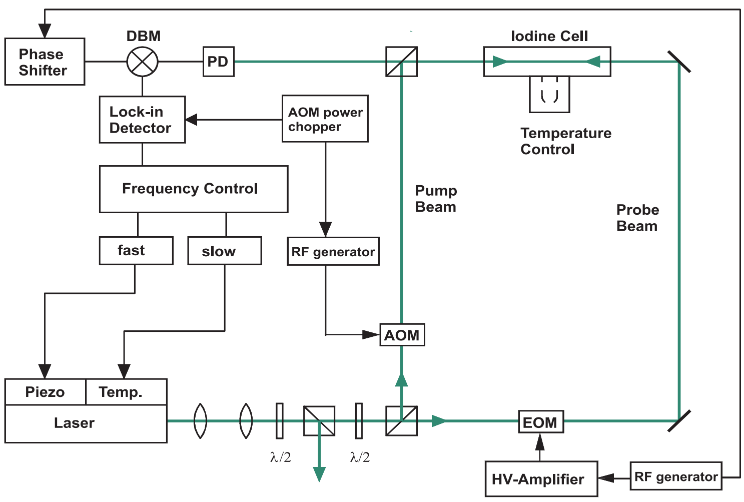

Fig. 1. Set-up of the PTB laser system. The Nd:YAG laser is frequency stabilized onto a selected iodine absorption line using the phase modulation method. The probe beam is modulated at 2.05 MHz by an electro-optic modulator (EOM), the pumb beam is frequency shifted by an acousto-optical modulator (AOM). The driving AOM rf power is chopped in order to cancel frequency offsets introduced by the Doppler background using a lock-in detection scheme. The transmitted probe beam signal is detected by a photodiode (PD) and mixed with the EOM rf in a double balanced mixer (DBM)

Within the frequency tuning range of this laser the two iodine lines R(57)32-0 and P(54)32-0 can be addressed. Two servo-loops are used to stabilize the laser frequency onto a selected I_2 line: a slow thermal and a fast piezo-mounted transducer (PZT) with bandwidths of approximately 10 Hz and 10 kHz, respectively. For the frequency lock the phase modulation method is employed [14]. The pumping beam is frequency shifted by an acousto-optical modulator (AOM) where the driving AOM rf-power is chopped in order to cancel - in combination with a lock-in detection scheme - frequency offsets introduced by the Doppler background. The frequency stability of the laser was analyzed at PTB by locking two equal systems to independent iodine cells and observing the beat frequency between them. The root Allan variance of the beat follows a $2 \times 10^{-13}/\sqrt{\tau}$ dependence for measurement times $\tau \leq 100$ sec reaching a minimum value of 3×10^{-14} at $\tau = 100$ s.

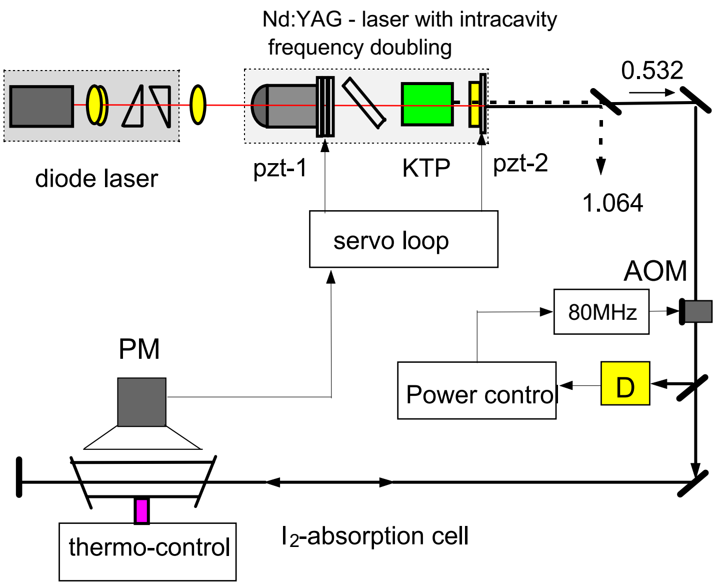

Fig. 2. Set-up of the ILP laser system. Intracavity frequency-doubling is realized with a KTP crystal which, together with a Brewster plate, serves as a Lyot filter. This allows to frequency tune the laser by more than 500 GHz by changing the temperature of the KTP crystal. The 532 nm laser radiation, after passing an acousto-optical modulator (AOM), is directed into an external I_2 fluorescence cell. A photomultiplier (PM) detects the fluorescence signal over a solid angle of almost 0.2 π. The photodiode D is used to detect a fraction of the 532 nm laser beam to power stabilize the 532 nm light via the AOM

The ILP iodine spectrometer (Fig. 2) is based on a home-made diode-pumped Nd:YAG laser at 1064 nm with intracavity frequency doubling. The surface of the Nd:YAG crystal is spherical and dichroically coated to serve as resonator mirror and input mirror for the pumping beam. It is mounted on a PZT for fast frequency control. The flat output mirror is also mounted on a PZT and used for the probe frequency modulation. For intracavity frequency-doubling a KTP crystal is used which, together with a Brewster plate, serves as a Lyot filter. This provides single-frequency operation and the possibility to frequency tune the laser by more than 500 GHz by changing the temperature of the KTP crystal. Within this extremely wide tuning range it is possible to perform spectroscopy of any Iodine absorption line between 1080 and 1135 (for notation of the I_2 lines see [15]). The length of the laser resonator is about 18 mm so that the whole system remains compact and stable. With 700 mW of pumping po wer, 30 mW in the fundamental beam at 1064 nm and up to 20 mW in the second harmonic at 532 nm are generated. The 532 nm laser radiation, after passing an acousto-optical modulator, is directed into an external I_2 fluorescence cell. The iodine pressure in the cell is controlled via the temperature of a cold finger. A photomultiplier detects the fluorescence signal over a solid angle of almost 0.2 π. In order to lock the laser to an I_2 resonance, a third harmonic synchronous detection scheme is employed minimizing the influence of Doppler background. The frequency stability of the laser was investigated at ILP with two equal systems locked to two different iodine cells. The root Allan variance of the beat between the two lasers reaches a minimum of 5×10^{-14} at $\tau \simeq 300$ s.

In order to investigate the reproducibility of the two iodine spectrometers, a frequency comparison of the ILP and the PTB laser was made. The frequency intervals between hyperfine components of the P(54)32-0 line for the three best isolated components were measured, using both lasers and the matrix method [16]: one laser was stabilized to a selected component of this line while the other was successively stabilized to the a_1, a_{10}, and a_{15} component. All frequency intervals were measured several times at different days.

In order to check for systematic errors on the measured frequencies due to iodine cell impurities we used three different iodine cells in the ILP system (cells 16/89PTB, 13/97PTB, and 5/98PTB, respectively). The PTB laser system used a 50 cm cell 2/89PTB throughout the measurements. The result was: $(\nu_{16/89} - \nu_{13/97}) = 1.6$ (0.4) kHz, $(\nu_{16/89} - \nu_{5/98}) = 2.7$ (0.8) kHz and $(\nu_{2/89} - \nu_{13/97}) = 1.0$ (0.7) kHz. For most measurements, iodine cell 13/97PTB was used. In addition, we checked for systematic frequency shifts due to variation of laser power, probe modulation amplitude, beam alignment and iodine pressure. The temperature of the cells could be changed between -20 °C and +10 °C, with a stability of better than 0.05 K and an accuracy of better than 1 K. Again, one system was operated under unchanged conditions to serve as a reference while the parameters of the other laser were varied. In Tables 1 and 2 the most significant contributio ns to the estimated standard uncertainty of the stabilized PTB and ILP lasers are listed. The PTB laser is sensitive to geometrical alignment of the counter-propagating pump and probe beams and to residual amplitude modulation resulting in a total standard uncertainty of about 2 kHz. Due to the fluorescence detection technique the ILP laser is less sensitive to geometrical effects which shift the line center. At present the estimated total standard uncertainty of 1.1 kHz of this laser is limited by the uncertainty to which the absolute temperature of the cold finger of the iodine cell is known.

Taking into account all available data of frequency differences obtained during the course of the matrix measurements, and correcting for different iodine pressures, different iodine cells and different HFS-separations, we derive a combined frequency reproducibility of the two laser systems in the experiment of better than 1.5 ± 0.7 kHz. This is a notable result, given the fundamental differences between the two iodine spectrometers as far as saturated absorption signal detection, laser frequency stabilization and laser set-ups are concerned.

Table 1. Most significant contributions to the estimated frequency standard uncertainty of the iodine stabilized Nd:YAG laser of PTB

effect	**standard uncertainty**	**sensitivity coefficient**	**contribution to uncertainty**
res. first order Doppler effect			< 300 Hz
alignment of probe + pump	< 150 μrad	10 Hz/mrad	< 1500 Hz
tension of breadboard	0.5 K	0.5 kHz/K	250 Hz
pointing stability	15 μrad	10 Hz/μrad	150 Hz
residual amplitude modulation	0,5 mV	2 kHz/mV	< 1000 Hz
servo electronics offset	0.005 mV	10 kHz/mV	50 Hz
exchange of servo electronics	< 100 Hz		< 100 Hz
EOM phase adjust	0.01 rad	10 kHz/rad	100 Hz
power shift	25 μW	3.6 kHz/mW	90 Hz
pressure shift	< 0.5 K @ -5 $^\circ$ C	-4.2 kHz/Pa	< 440 Hz
total uncertainty $\delta\nu$			< 2.0 kHz
relative uncertainty $\delta\nu/\nu$			$< 3.5 \times 10^{-12}$

3 Frequency Chain

In order to measure the absolute frequencies of the iodine spectrometers, we employed a frequency chain which links the Nd:YAG laser frequencies to a CH_4 stabilized He-Ne laser at 3.39 μm (Fig. 3). This laser was set up at the Institute of Laser Physics in Novosibirsk, Russia [17], and has been calibrated previously (1996) for a measurement of the hydrogen 1S - 2S absolute frequency [18]. In

Table 2. Most significant contributions to the estimated frequency standard uncertainty of the iodine stabilized Nd:YAG laser of ILP

effect	**standard uncertainty**	**sensitivity coefficient**	**contribution to uncertainty**
res. first order Doppler effect			$<$ 100 Hz
alignment of probe + pump	$<$ 1mrad	10 Hz/mrad	10 Hz
servo electronics offset	0.01 mV	1 kHz/mV	10 Hz
change of modulation index	5 kHz	6.2 Hz/kHz	30 Hz
power shift	100 μW	-340 Hz/mW	30 Hz
pressure shift	$<$ 1 K @ -5 ° C	-4.2 kHz/Pa	1.1 kHz
total uncertainty $\delta\nu$			$<$ 1.1 kHz
relative uncertainty $\delta\nu/\nu$			$< 2.0 \times 10^{-12}$

the present experiment we used the result of a more recent calibration [19] that was obtained 4 month ealier from a direct comparison with a cesium fountain clock in our lab, with $f_{He-Ne} = 88\,376\,182\,599\,976\ (10)$ Hz [20,11]. This value deviates from the previous one by 39 Hz (1.6 combined standard deviations), most likely because the operating parameters were not exactly maintained over the years in the two experiments. Unlike in the previous calibration, the laser was not moved between its calibration and the measurement.

The frequency chain works as follows: to the second harmonic of the He-Ne laser at 3.39 μm a NaCl:OH^- color center laser at 1.70 μm is phase locked. To the second harmonic of the color center laser a laser diode at 848 nm is then phase locked. This is accomplished by first locking the laser diode to a selected mode of the frequency comb of a Kerr-lens mode-locked Ti:sapphire femtosecond laser (Coherent model Mira 900), frequency-broadened in a standard single-mode silica fiber (Newport FS-F), and then controlling the position of the comb in frequency space [21,11]. At the same time the combs mode separation of 76 MHz is controlled by a local cesium atomic clock [22]. With one mode locked to the 4th harmonic of the CH_4 standard and at the same time the pulse repetition rate (i.e. the mode separation) fixed [22], the femtosecond frequency comb provides a dense grid of reference frequencies known with the same fractional precision as the He-Ne S tandard [23,21,11]. With this tool a frequency interval of about 37 THz is bridged to lock a laser diode at 946 nm to the frequency comb, positioned $n = 482\,285$ modes to lower frequencies from the initial mode at 848 nm.

This part of the chain was simultaneously used for an absolute frequency measurement of the In^+ $^1S_0$ - $^3P_0$ clock transition [24]. In that case, the fourth

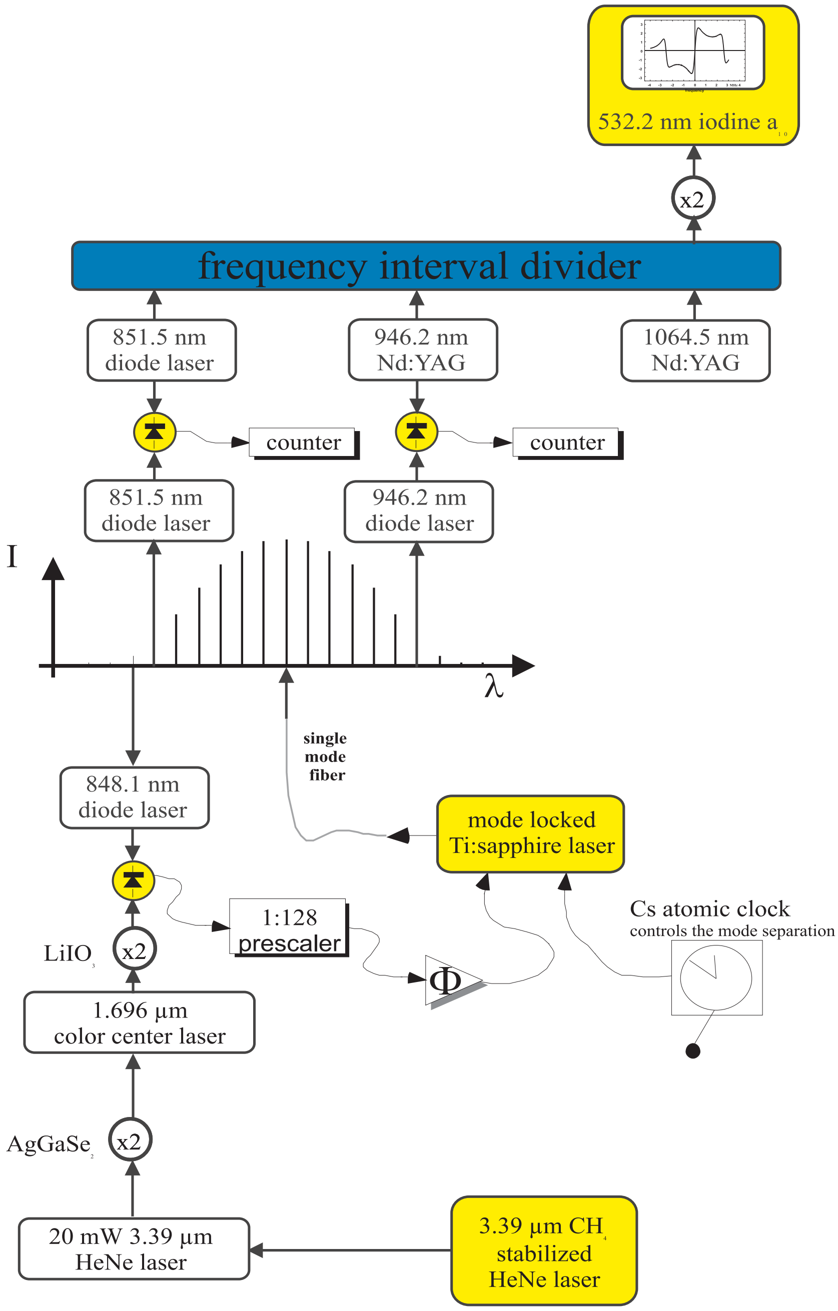

Fig. 3. Set-up of the frequency chain used to measure the absolute frequency of the two iodine spectrometers. The chain links the 532 nm radiation of the frequency doubled Nd:YAG lasers (563 THz) to a methane-stabilized He-Ne laser at 3.39 μm (88 THz). The two input frequencies of the frequency interval divider stage at 852 nm and 946 nm determine the frequency of the Nd:YAG lasers at 1064 nm. The input frequencies are phase-coherently linked to the methane-stabilized He-Ne laser at 3.39 μm by use of a frequency comb generated with a Kerr-lens mode-locked femtosecond laser

harmonic of a 946 nm Nd:YAG laser, which is heterodyned with the comb locked diode laser at 946 nm, excites the In^+ $^1S_0$ - $^3P_0$ transition at 236 nm.

In extension to this frequency chain we installed an optical frequency interval divider [23] to extrapolate to 1064 nm (see Fig. 3). The center frequency of the optical divider stage is given by the Nd:YAG laser at 946 nm laser with its frequency determined via the beat note with the comb locked laser diode at 946 nm. The higher input frequency of the divider stage is set by a diode laser at 852 nm which is heterodyned with another diode laser at 852 nm, also phase locked to the frequency comb. The lower input frequency of the divider stage is determined by the iodine stabilized Nd:YAG laser at 1064 nm. While scanning the frequency doubled 1064 nm Nd:YAG laser over the iodine line the two beat notes at 852 nm and 946 nm are measured with a rf-counter. They are then used to determine the absolute frequency of the 1064 nm Nd:YAG laser.

4 Absolute Frequency Measurements

With the frequency chain in lock the unknown frequencies f_{532} of the investigated iodine lines at 532 nm are related to the known frequency of the He-Ne standard f_{He-Ne} and the comb mode separation f_{rep} through:

$$f_{532} = 8 \cdot f_{He-Ne} - 4 \cdot \Delta f_{946} - 2 \cdot \Delta f_{852} - 4n_1 \cdot f_{rep} + 2n_2 \cdot f_{rep} - f_{LO} \quad (1)$$

Here Δf_{946} and Δf_{852} are the beat signals at 946 nm and 852 nm, respectively, n_1 and n_2 are the number of modes separating the two selected modes of the comb at 946 nm and 852 nm from the comb mode at 848 nm and f_{LO} collects the frequencies of all local oscillator employed in the phase-locks.

In a first experiment, the frequency of the a_{10} HFS component of the R(56)32-0 iodine absorption line was measured. This line is recommended by the Comité International des Poids et Mesures (CIPM) for the realization of the metre [1]. Since the PTB laser is not tunable to this frequency, the experiment has been carried out with the ILP laser only. Using cell 13/97PTB with the parameters T = -5 °C (p = 2,42 Pa), P = 1,7 mW, I = 80 mW/cm^2 the result is:

$$f_{a10}(R56) = 563\,260\,223\,507.8\,(1.1)\,\mathrm{kHz}.$$

The contributions to the estimated standard uncertainty of this frequency are listed in Table 3. For a given cell, the frequency uncertainty is mainly determined by the limited reproducibility of the ILP standard. As the frequency uncertainty of the iodine cell is concerned, an upper limit is difficult to give since it strongly depends on the impurities of the cell and these are difficult to assess. Over the years it has been found that for a given set of iodine cells the one with the smallest impurities will lead to the highest measured transition frequency of a given iodine line. Therefore, we relate our results to PTB cell number 16/89 (see Section 2).

Table 3. Contributions to the standard uncertainty of the absolute frequency measurement. For a given cell, the uncertainty is mainly determined by the limited reproducibility of the ILP standard. For the frequency uncertainty of a given iodine cell see text

effect	**contribution to the frequency uncertainty of the**	
	PTB laser	**ILP laser**
uncertainty of spectrometer	2.0 kHz	1.1 kHz
standard deviation of the mean value of experimental data	$<$ 200 Hz	$<$ 100 Hz
uncertainty of Cs clock	15 Hz	15 Hz
CH_4 - frequency standard	80 Hz	80 Hz
total uncertainty $\delta\nu$	2.0 kHz	1.1 kHz
total relative uncertainty $\delta\nu/\nu$	3.5 $\times 10^{-12}$	2.0 $\times 10^{-12}$

To be able to compare our result for the a_{10} component of the (R56)32-0 transition with previously published data [7], we extrapolate further to an iodine pressure at -20 °C (p = 0,46 Pa) [25]. In this case we obtain:

$$f_{a10}(R56) = 563\,260\,223\,517.7\,(1.2)\,\mathrm{kHz}\,. \qquad (2)$$

This value is shifted by about 46.7 kHz to higher frequencies from the value published in [7]. However, our result is in good agreement with a more recent measurement of this transition, where an absolute frequency of $f_{a10}(R56) = 563\,260\,223\,514\,(5)$ kHz was obtained [10,11]. The result (2) agrees also within uncertainty bars with the value stated for the recommended line [1].

Note that this value and its uncertainty is valid only for this particular iodine cell (16/89PTB) and must not be confused with the value and uncertainty of the unperturbed value of this hyperfine transition. The frequencies of iodine cells from different origins may scatter more than the uncertainty of the absolute frequency measurement reported here. However, cell 16/89PTB has participated in an international comparison of iodine cells at BIPM and found to have a frequency shift of $\Delta\nu_{16/89} = +\,2.6\,(2.8)$ kHz with respect to an iodine cell used as reference in the BIPM4 He-Ne frequency standard [26].

In the same manner, using only the ILP laser, the absolute frequencies of the hyperfine components a_1, a_{10} and a_{15} of the P(54)32-0 iodine absorption line were measured. Again, extrapolating to cell 16/89PTB and an iodine pressure at -20 °C [25] we obtain:

$$f_{a1}(P54) = 563\,212\,634\,618.6\,(1.2)\,\text{kHz}\,, \tag{3}$$
$$f_{a10}(P54) = 563\,213\,206\,155.3\,(1.2)\,\text{kHz}\,, \tag{4}$$
$$f_{a15}(P54) = 563\,213\,492\,579.2\,(1.2)\,\text{kHz}\,. \tag{5}$$

As the uncertainty introduced by the use of different iodine cells is concerned we refer to the discussion above.

The results (3) - (5) were confirmed by an independent measurement using both iodine spectrometers, locked to the same HFS components of the P(54) line. While the ILP laser frequency was counted in the manner described above, the PTB laser frequency - shifted by an AOM - was determined by additionally counting the beat signal between the two oscillators. The pressure in the cells was kept equal, setting the temperature of the cold fingers of both cells to T = -5 °C. After extrapolating to cell number 16/89 and to an iodine pressure at -20 °C, the results for the PTB laser system agree with the outcomes (3) - (5) but uncertainty bars were now increased due to the lower reproducibility of the PTB laser.

The absolute frequencies of the P(54)32-0 iodine line were measured independently for the first time. We found that the frequency separations between the three HFS components are in a good agreement with previously published data [7]. However, the frequency distance between the a_{10} component of the (R56)32-0 line and the a_1, a_{10} and a_{15} components of the (P54)32-0 line were about 7 kHz higher than stated in [7] (see Fig. 4).

In order to verify this result, we measured the frequency gap using a different technique: while one ILP laser was locked to the R(56)32-0:a_{10} transition another ILP Nd:YAG laser with slightly worse characteristics was first locked to the same transition to subtract frequency shifts due to the use of different iodine cells and then alternately locked to the a_1, a_{10} and a_{15} component of the P(54)32-0 line. The beat frequency between the two lasers of about 47 GHz was detected by a fast photodetector (New Focus model 1006) and measured by mixing the signal down with a Rb-clock synchronized high-frequency synthesizer. Within the uncertainty of the two measurements, the results of the absolute frequency measurement using the frequency chain were confirmed (see Fig. 4). According to this measurement, the frequency differences between the a_{10} HFS component of the (R56)32-0 line and the a_1, a_{10} and a_{15} HFS component of the (P54)32-0 line are:

$$\Delta f_{a10:(R56)-a1:(P54)} = 47\,588\,898\,(2)\,\text{kHz}\,, \tag{6}$$
$$\Delta f_{a10:(R56)-a10:(P54)} = 47\,017\,360\,(2)\,\text{kHz}\,, \tag{7}$$
$$\Delta f_{a10:(R56)-a15:(P54)} = 46\,730\,937\,(2)\,\text{kHz}\,. \tag{8}$$

Since systematic frequency shifts due to the use of different iodine cells can be neglected in this measurement, the total uncertainty is given by the combined uncertainty of the two ILP standards corresponding to about 2 kHz.

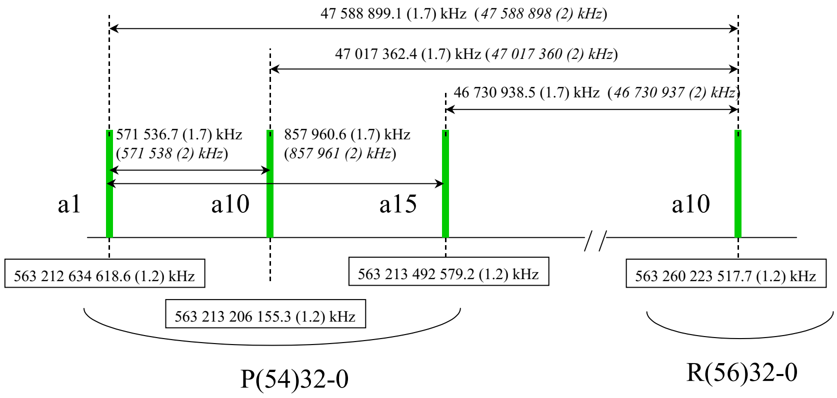

Fig. 4. Results of the absolute frequency measurements: shown are the absolute frequencies and hyperfine line separation of the hyperfine components a_1, a_{10} and a_{15} of the P(54)32-0 and the hyperfine component a_{10} of the R(56)32−0 iodine absorption line. Numbers in brackets correspond to an independent heterodyne frequency measurement where the beat between two ILP lasers, locked to corresponding HFS components of the P(54)32-0 and the R(56)32-0 line, were observed (for details see text)

This result was again confirmed by a measurement at PTB using two Nd:YAG lasers from Innolight GmbH [13] with dual wavelength output. In the experiment the two lasers were stabilized to the I_2 transitions R(56)32-0 and P(54)32-0 in the manner described above but the beat signal between them was now measured in the infrared. The 23.5 GHz signal was detected using an IR photo detector. Evaluating the data, it was found that both measurements agree to within 0.3 kHz.

5 Conclusion

In conclusion we presented an absolute frequency measurement and a frequency comparison of two iodine stabilized frequency-doubled Nd:YAG laser systems, one set up at the Institute of Laser Physics, Novosibirsk, Russia, the other at the Physikalisch-Technische Bundesanstalt, Braunschweig, Germany. The individual frequency stability and the reproducibility of the two laser systems were characterized. It was found that despite fundamental differences as far as frequency generation, signal detection and frequency stabilization techniques are concerned the combined frequency reproducibility of the two laser systems was better than 1.5 ± 0.7 kHz. In a further experiment the absolute frequencies of HFS components of the R(56)32-0 and P(54)32-0 transitions in I_2 were determined using a phase-coherent frequency chain. This chain links the frequency of the I_2-stabilized Nd:YAG laser to a CH_4-stabilized He-Ne laser at 3.39 μm. The He-Ne reference was calibrated before the measurement against an atomic cesium fountain clock. In this measurement a new value for the R(56)32-0:a_{10} component was obtained with reduced uncertainty. This value coincides within uncertainty bars with the value recommended by the Comité International des Poids et Mesures (CIPM) for the realization of the metre [1]. Finally, improved absolute frequency values of several HFS components of the P(54)32-0 iodine absorption line together with their hyperfine line separations were measured.

References

1. Recommendation adopted by the Comité International des Poids et Mesures at its 86th meeting: T. J. Quinn: Metrologia **30**, 523 (1993/1994); T. Quinn: Metrologia **36** 211 (1999)
2. H. Darnedde, W. R. C. Rowley, F. Bertinetto, Y. Millerioux, H. Haitjema, S. Wetzels, H. Piree, E. Prieto, M. Mar Perez, B. Vaucher, A. Chartier, and J.-M. Chartier: Metrologia **36**, 199 (1999)
3. M. Eickhoff and J. L. Hall: IEEE Trans. Instrum. Meas. **44**, 155 (1995)
4. R. Storz, C. Braxmeier, K. Jäck, O. Pradl, and S. Schiller: Opt. Lett. **23**, 1031 (1998)
5. A. Arie, S. Schiller, E. K. Gustafson, and R. L. Byer: Opt. Lett. **17**, 1204 (1992)
6. A. Arie and R. L. Byer: J. Opt. Soc. Am. **B 10**, 1990 (1993)
7. J. Ye, L. Robertsson, S. Picard, L.-S. Ma, and J. L. Hall: IEEE Trans. Instrum. Meas. **48**, 544 (1999)
8. P. A. Jungner, S. Swartz, M. Eickhoff, J. Ye, J. L. Hall, and S. Waltman: IEEE Trans. Instrum. Meas. **44**, 151 (1995)
9. 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)
10. S. A. Diddams, D. J. Jones, Jun Ye, S. T. Cundiff, J. L. Hall, J. K. Ranka, R. S. Windeler, R. Holzwarth, Th. Udem, T. W. Hänsch: Phys. Rev. Lett. **84**, 5102 (2000); D. J. Jones, S. A. Diddams, J. K. Ranka, A. Stentz, R. S. Windeler, J. L. Hall, St. T. Cundiff: Science **288**, 635 (2000);
11. J. L. Hall et al., *this edition*, pp. 125–144
12. P. Cordiale, G. Galzerano, and H. Schnatz: Metrologia **37**, 177 (2000)
13. The citation of a company's name is for sole purpose of technical communication and does not mean an endorsement
14. R. W. P. Drever, J. L. Hall, F. V. Kowalski, J. Hough, G. M. Ford, A. J. Munley, H. Ward: Appl. Phys. B **31**, 97 (1983)
15. S. Gerstenkorn and P. Luc: "Atlas du spectre d'absorption de la molecule d'iode 14800 – 20000 cm^{-1}". Complement: Identification des transitions du systeme (B-X), Editions du CNRS, Paris (1985)
16. F. Bayer-Helms, J. M. Chartier, J. Helmcke, and A. Wallard: PTB Bericht ME-**17**, 139 (1977)
17. S. N. Bagayev, A. K. Dmitriyev, and P. V. Pokasov: Laser Physics 7, 989 (1997)
18. Th. Udem, A. Huber, B. Gross, J. Reichert, M. Prevedelli, M. Weitz, and T. W. Hänsch: Phys. Rev. Lett. **79**, 2646 (1997)
19. P. Pokasov et al.: to be published
20. M. Niering, R. Holzwarth, J. Reichert, P. Pokasov, Th. Udem, M. Weitz, T. W. Hänsch, P. Lemonde, G. Santarelli, M. Abgrall, P. Laurent, C. Salomon, and A. Clairon: Phys. Rev. Lett. **84**, 5496 (2000)

21. J. Reichert, M. Niering, R. Holzwarth, M. Weitz, Th. Udem, and T.W. Hänsch: Phys. Rev. Lett. **84**, 3232 (2000)
22. J. Reichert, R. Holzwarth, Th. Udem, and T.W. Hänsch: Opt. Comm. **172**, 59 (1999)
23. H. R. Telle, D. Meschede, and T. W. Hänsch: Opt. Lett. **15**, 532 (1990)
24. J. von Zanthier, Th. Becker, M. Eichenseer, A. Yu. Nevsky, Ch. Schwedes, E. Peik, H. Walther, R. Holzwarth, J. Reichert, Th. Udem, T. W. Hänsch, P. V. Pokasov, M. N. Skvortsov, and S.N. Bagayev: Opt. Lett., to be published; Th. Becker, M. Eichenseer, A. Yu. Nevsky, E. Peik, Ch. Schwedes, M. N. Skvortsov, J. von Zanthier, and H. Walther: *this edition*, pp. 545–553
25. The pressure shift measured in the ILP laser system is -4.2 ± 0.2 kHz/Pa
26. J.-M. Chartier, S. Picard-Fredin, and A. Chartier: Metrologia **29**, 361 (1992)