Comparison of Independent Optical Frequency Measurements Using a Portable Iodine-Stabilized Nd:YAG Laser

Feng-Lei Hong, Jun Ishikawa, Kazuhiko Sugiyama, Atsushi Onae, Hirokazu Matsumoto, Jun Ye, and John L. Hall

***Abstract*—A comparison of two independent absolute optical frequency measurements has been carried out between the National Metrology Institute of Japan/National Institute of Advanced Industrial Science and Technology (NMIJ/AIST), Tsukuba, Japan and the JILA (formerly the Joint Institute for Laboratory Astrophysics), Boulder, CO, using a portable iodine-stabilized Nd:YAG laser. The agreement between the two absolute measurements is better than the measurement uncertainty of 6.7×10^{-13} that can be attributed to the reproducibility limitations of the portable laser. This comparison is used to confirm the measured absolute frequency of an iodine-stabilized Nd:YAG laser at NMIJ/AIST (Y3), which is reported to the Consultative Committee for Length (CCL) for the determination of the absolute frequency value of iodine-stabilized Nd:YAG lasers.**

***Index Terms*—International comparison, molecular iodine, Nd:YAG laser, optical frequency measurement, stabilization, standard.**

I. Introduction

RECENTLY, a femtosecond (fs) mode-locked laser has been developed to produce a comb of optical frequencies for precision measurements of absolute optical frequencies [1], [2]. A direct link between microwave and optical frequencies with a fs laser comb has been realized [3], [4] and employed by several laboratories [5]–[9]. The precision of an fs comb is usually limited by the frequency uncertainty of the microwave source used to stabilize the fs comb. In a frequency measurement of an iodine-stabilized Nd:YAG laser using an fs comb [10], the measured frequency uncertainty was about 100 Hz in the optical frequency domain.

On the other hand, frequency offset of several kHz can be observed between optical frequency standards, especially for those standards using gas cells. In the case of iodine-stabilized He–Ne lasers, the frequency uncertainty of a group of lasers was obtained to be 12 kHz [11]. During previous international comparisons of iodine-stabilized Nd:YAG lasers [12], we also observed similar frequency offsets of a few kHz. From a metrological point of view, it is always important to confirm such differences, using a different method if possible. An example of such confirmation is a comparison between absolute optical frequency measurements carried out with a traditional harmonic-generation synthesis chain and fs comb, using an iodine-stabilized He–Ne laser as a transfer oscillator [13]. The agreement between the two methods, both linked to the Cs standard, was better than 1.6×10^{-12}.

A recent optical frequency measurement of the iodine-stabilized Nd:YAG laser at NMIJ/AIST [9] using fs comb revealed a frequency difference of about 4 kHz between the NMIJ and JILA lasers. To confirm this frequency difference, we have carried out a laser frequency comparison between the NMIJ and the JILA standards using a portable iodine-stabilized Nd:YAG laser. In both cases, the frequencies of the stationary lasers in the two Institutes were independently measured against the frequency of the Cs standard. In this way, we have made a direct comparison of independent optical frequency measurements in two different institutes using a transportable laser. The frequency stability of an iodine-stabilized Nd:YAG laser is about two orders of magnitude better than that of an iodine-stabilized He–Ne laser [14], [15]. Therefore, one could expect that an iodine-stabilized Nd:YAG laser gives a better reproducibility compared to that of the portable He–Ne laser [13]. In this paper, we report the results of the direct frequency comparison and the agreement between the frequency value obtained from the direct comparison and that from the absolute frequency measurement for the NMIJ-Y3 laser. The confirmed frequency of the NMIJ laser was reported to the CCL for the determination of the frequency value of iodine-stabilized Nd:YAG lasers.

II. Laser Systems

Fig. 1 shows the laser systems involved in the frequency measurements. Each of the JILA-W and JILA-E lasers contains a 1.2-m-long iodine cell, operated at a cold-finger temperature of $-15\ ^\circ$C, corresponding to a vapor pressure of 0.78 Pa. The heterodyne beat measurements between the JILA-W and JILA-E lasers shows that the lasers have reached a relative frequency stability of 5×10^{-14} at 1 s, that reaches $\sim 5 \times 10^{-15}$ after 300 s [14], [15]. The measured absolute frequency of JILA-W, stabilized on the a_{10} component of the R(56)32-0 transition in $^{127}I_2$, is [10]

$$f_{\text{JILA-W}(-15^\circ\text{C})} = 563\ 260\ 223\ 514.48\ (24)\ \text{kHz}. \quad (1)$$

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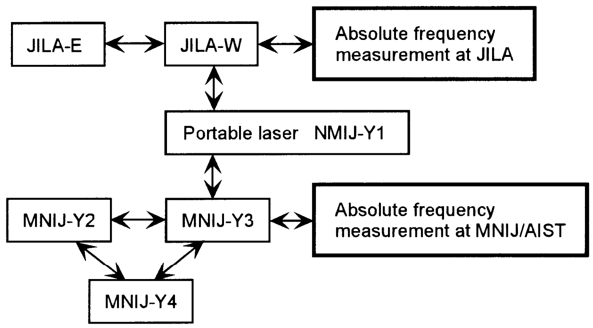

Fig. 1. Laser systems involved in the frequency measurements. NMIJ-Y1 is a portable laser traveled between the NMIJ/AIST and the JILA.

where the uncertainty is indicated within parentheses. The indicated uncertainty (0.24 kHz, relatively 4.3×10^{-13}) represents the upper limit of reproducibility over one year of the Nd:YAG laser.

In NMIJ/AIST, we have established four iodine-stabilized Nd:YAG lasers to verify the frequency reproducibility of the laser system [16]. NMIJ-Y1 and Y4 use 30-cm-long iodine cells, while Y2 and Y3 contain 45-cm-long cells. The cold-finger-temperature of the iodine cells was typically -10 °C in the NMIJ lasers, corresponding to 1.38 Pa. The observed Allan standard deviation of the four lasers was between 9×10^{-14} and 3×10^{-13} for a 1.5-s integration time, depending on the obtained signal-to-noise ratio (S/N) of the spectra, improving to $1–4 \times 10^{-14}$ after 300 s . The observed frequency reproducibility of each laser was in the range from 9.1×10^{-14} to 1.5×10^{-13}, corresponding to frequency uncertainties from 51–87 Hz. The frequency differences within a group of lasers (four NMIJ lasers) were evaluated to be 8.2×10^{-13}, corresponding to a frequency difference up to 640 Hz.

One of the four NMIJ lasers (NMIJ-Y1) is a compact iodine-stabilized Nd:YAG laser which is suitable to be transported to other laboratories for international frequency comparisons [12]. This laser was transported to JILA in August 2001 for a round-trip intercomparison for the purpose of establishing a direct link of independent absolute optical frequency measurements in the two institutes.

III. Frequency Comparison

As reported in [16], before the round-trip intercomparison, the frequency difference between Y1 and Y3 was measured over several weeks to be

$$f_{Y1(-10^\circ\mathrm{C})} - f_{Y3(-10^\circ\mathrm{C})} = 0.84\,(11)\ \text{kHz}. \quad (2)$$

The day-to-day frequency repeatability of Y1 and Y3 was 87 Hz and 59 Hz, respectively. This frequency difference is indicated at the left hand side in Fig. 2.

During the intercomparison at JILA, the portable laser Y1 was compared with JILA-W. Fig. 3 shows the measured frequency difference between JILA-W and Y1 over several days. The cold-finger temperature of the iodine cell of JILA-W was set to -15 °C, while that of Y1 was set to -10 and -15 °C. Each frequency data indicated in the figure is an average of 100 beat-frequency measurements, where each beat frequency was measured with a 1 s gate time by a frequency counter. The standard deviation of the 100 beat-frequency measurements, which depend on the S/N of the observed spectra, was typically 160 and 270 Hz for the -10 and -15 °C cold-finger temperature of Y1. The uncertainties are given as one standard deviation in the figure. By averaging 15 and 13 measurements for the -10 and -15 °C cold-finger temperature of Y1, respectively, we obtain

$$f_{\mathrm{JILA-W}(-15^\circ\mathrm{C})} - f_{Y1(-10^\circ\mathrm{C})} = 5.74\,(21)\ \text{kHz} \quad (3)$$

and

$$f_{\mathrm{JILA-W}(-15^\circ\mathrm{C})} - f_{Y1(-15^\circ\mathrm{C})} = 3.90\,(35)\ \text{kHz}. \quad (4)$$

The variation of the frequency data between different measurements depended mainly on the beam adjustment in Y1; an adjustment was necessary as the beam overlapping slightly changed during the transportation. The repeatability of Y1 without the adjustment of the beam overlapping was about 87 Hz.

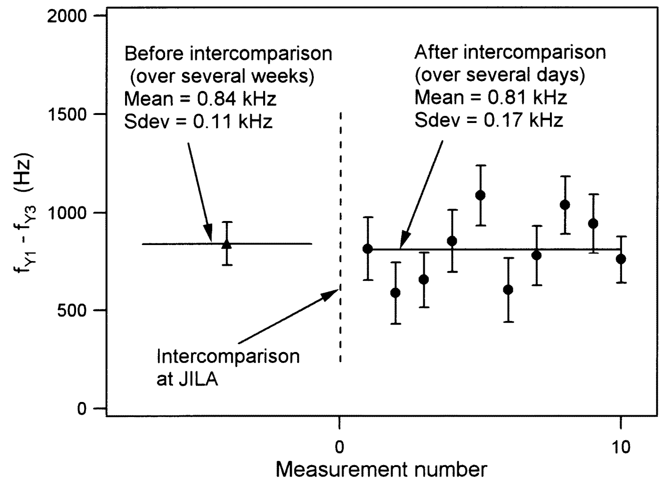

Fig. 2. Measured frequency difference between Y1 and Y3, when the cold-finger temperature of both lasers was set at -10 °C.

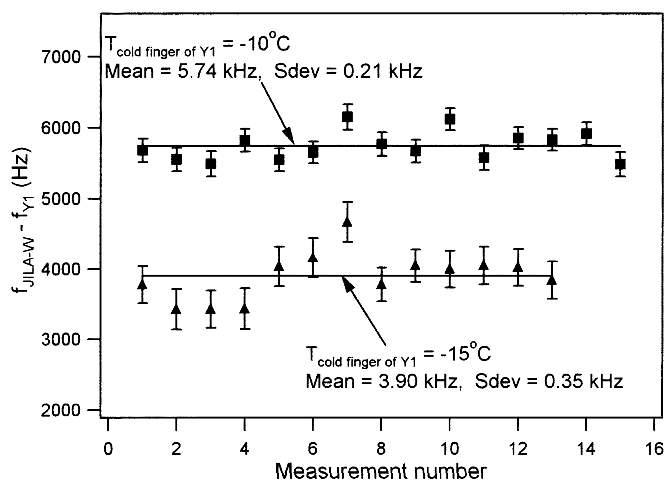

Fig. 3. Measured frequency difference between JILA-W and NMIJ-Y1 during the international comparison. The cold-finger temperature of JILA-W was set at -15 °C.

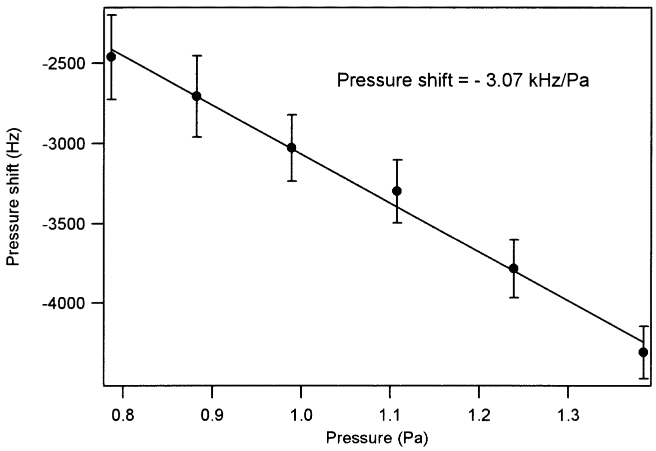

Fig. 4. Pressure shift of NMIJ-Y1.

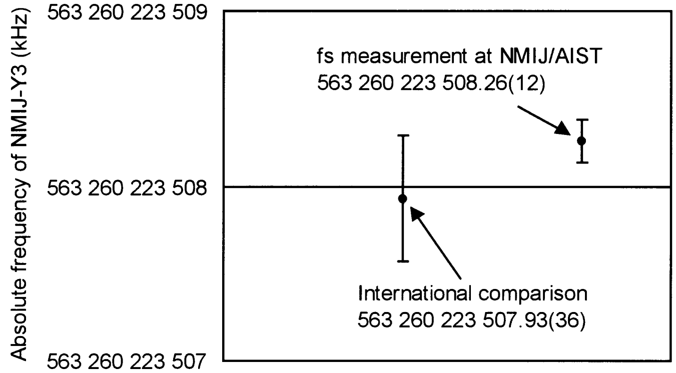

Fig. 5. Absolute frequency of NMIJ-Y3 obtained by fs measurement at NMIJ/AIST and by international comparison. The difference between the frequencies obtained from the two methods (330 Hz) is smaller than the combined uncertainty of the two methods (380 Hz).

To further confirm the working condition of NMIJ-Y1, pressure shift was measured for Y1 during the intercomparison. Fig. 4 shows the pressure dependence of the frequency of Y1. The data indicated is an average of 100 beat-frequency measurements and the uncertainty is given as one standard deviation of the average. The measured slope of the frequency shift was −3.07 kHz/Pa, which is similar to that observed at NMIJ/AIST before the round-trip. The iodine cell used in Y1 was NRLM7.

After the round-trip comparison, the frequency difference between Y1 and Y3 was measured again at NMIJ/AIST. The results of 10 measurements over several days after the intercomparison are shown at the right hand side in Fig. 2. The data is averaged over 100 beat-frequency measurements. We obtain

$$f_{Y1(-10^\circ\mathrm{C})} - f_{Y3(-10^\circ\mathrm{C})} = 0.81\,(17)\ \text{kHz}. \tag{5}$$

Again, the variation of the frequency difference between different measurements is mainly dependent on the beam alignment in Y1. We adjusted the beam alignment, although we observed no change of the beam overlapping in Y1 after the transportation back to Japan. The averaged frequency difference between Y1 and Y3 changed with less than 30 Hz before and after transportation.

Using (1), (3), and (5), we can determine the frequency value of Y3 from the direct frequency comparison as

$$f_{Y3(-10^\circ\mathrm{C})} = 563\,260\,223\,507.93\,(36)\ \text{kHz}. \tag{6}$$

The uncertainty listed in (6) includes all the uncertainties listed in (1), (3), and (5).

During the frequency-difference measurement of Y1 and Y3 after the intercomparison, we also carried out six absolute frequency measurements at Y3 using the fs comb at NMIJ/AIST. These measurements gave a frequency value of Y3 as [9]

$$f_{Y3(-10^\circ\mathrm{C})} = 563\,260\,223\,508.26\,(12)\ \text{kHz}. \tag{7}$$

The absolute frequencies of NMIJ-Y3 obtained from the fs measurement (7) and from the international comparison (6) are indicated in Fig. 5. The difference between the frequencies obtained from the two methods (330 Hz) is smaller than the combined uncertainty of the two methods (380 Hz). The combined uncertainty (relatively 6.7×10^{-13}) is mainly limited by the reproducibility of the portable laser Y1.

A change in the pressure of 0.60 Pa will occur when the cold-finger temperature is changed from −10 to −15 °C. Taking account of the pressure shift of −3.07 kHz/Pa, the frequency of Y3 at −15 °C is 1.8 kHz higher than it would be with the cold finger at −10 °C. The uncertainty of the fs comb measurements lasting 3 months at NMIJ/AIST was 0.3 kHz [9]. Furthermore, the frequency agreement between two methods of frequency measurement demonstrated above is also 0.3 kHz. Consequently, the frequency value of NMIJ-Y3, stabilized on the a_{10} component of the R(56)32-0 transition for a cold-finger temperature of −15 °C, was reported to the CCL as

$$f_{Y3(-15^\circ\mathrm{C})} = 563\,260\,223\,510.1\,(3)\ \text{kHz}. \tag{8}$$

This value was accepted by the CCL 2001 as one of three references for the adoption of a recommended frequency of iodine-stabilized Nd:YAG lasers.

IV. Conclusion

We have compared two optical frequency measurements made in NMIJ/AIST and JILA by using a portable Nd:YAG laser. The agreement between the two absolute frequency measurements is within 6.7×10^{-13}, a level that is equal to the observed reproducibility of the portable laser. This direct comparison has confirmed the absolute frequency of NMIJ-Y3 obtained by fs comb measurements at NMIJ/AIST.

The measurement uncertainty obtained in the present direct comparison is about 1/2 the limit obtained in the earlier comparison with a 633 nm portable He–Ne laser [13]. The improvement in the measurement uncertainty is not as large as that obtained for the frequency stability, which is more than two orders of magnitude. The frequency variation of the transportable laser Y1, provoked by deviations in the beam overlap is believed to arise from residual Doppler effects in the sub-Doppler spectroscopy method [17] and may be improved by, for example, putting the iodine cell into an optical cavity. Experiments along this field are now in progress.

As proposed at the CCL 2001 meeting, the frequency uncertainty of the 532-nm iodine-stabilized Nd:YAG laser is taken to be 5 kHz. The main contributions to this uncertainty are offsets due to the impurities in the iodine cells. One related problem is the pressure shift, which is different for different laser systems [18], [19]. It is important to separate the frequency offsets induced by different iodine cells and those associated to different spectroscopic setups, where other effects like residual amplitude modulation [20] may also contribute to the frequency offset. By exchanging iodine cells between laser systems, we can identify the frequency offset due to a particular cell, which may be caused by contamination. An efficient way of such a test is to compare iodine cells at different institutes. Work along this line is also in progress.

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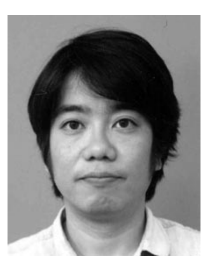

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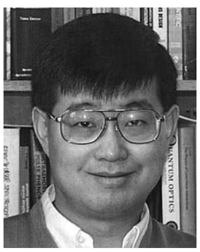

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