Portable I_2-Stabilized Nd:YAG Laser for International Comparisons

Feng-Lei Hong, Jun Ishikawa, Zhi-Yi Bi, Jing Zhang, Katuo Seta, Atsushi Onae, Jun Yoda, and Hirokazu Matsumoto

***Abstract*—We have established a compact and transportable I_2-stabilized Nd:YAG laser for international comparisons of laser frequency. The root Allan variance of the portable laser has reached 3.9×10^{-14} when the integration time is longer than 200 s. The results of an international comparison between the National Research Laboratory of Metrology (NRLM), Tsukuba, Japan and the JILA (formerly the Joint Institute for Laboratory Astrophysics), Boulder, CO, USA show that the frequency difference of the portable laser NRLM-Y1 and the JILA laser JILA-W $(f_{\mathrm{NRLM\text{-}Y1}} - f_{\mathrm{JILA\text{-}W}})$ was -2.5 kHz, when the cold-finger temperatures of NRLM-Y1 and JILA-W were kept at -10°C and -15°C, respectively. The averaged frequency offset between two NRLM lasers $(f_{\mathrm{NRLM\text{-}Y1}} - f_{\mathrm{NRLM\text{-}Y2}})$ was -1.1 kHz. A frequency variation of about 1.2 kHz was found for the frequency offset between two NRLM lasers, after NRLM-Y1 was taken for a round trip to Sydney for a comparison organized by the National Measurement Laboratory, (NML), Australia.**

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

I. Introduction

IODINE-STABILIZED Nd:YAG lasers are becoming important standards of wavelength and optical frequency, and the 1997 meeting of the CCL (the Comité Consultatif des Longueurs) has adopted the frequency value of the radiation of I_2-stabilized Nd:YAG lasers [1], [2] as one practical realization of the meter [3]. The relative standard uncertainty of the recommended frequency value is 7×10^{-11} (corresponding to a frequency uncertainty of about ± 40 kHz), which is determined by both the uncertainty of the absolute optical frequency measurement and the reproducibility of the frequency stabilized lasers.

The main contribution to the uncertainty of the recommended frequency value comes from the absolute frequency measurement, where the measurement uncertainty was determined by the uncertainties of the optical frequency standards used as frequency references. Recently, a femtosecond mode-locked laser has been developed to produce a comb of optical frequencies for precision measurements of large frequency gaps [4], [5]. A direct link between microwave and optical frequencies with a femtosecond laser comb has been realized [6], where the measured frequency uncertainty of the I_2-stabilized Nd:YAG laser was only 1.1 kHz, and is determined dominated by the uncertainty of the microwave source. At the present stage, the reproducibility of frequency stabilized lasers is the main contribution to the frequency uncertainty of I_2-stabilized Nd:YAG lasers.

To verify the reproducibility of these laser systems, an international comparison of I_2-stabilized Nd:YAG lasers was carried out between the NRLM and JILA groups [7], [8]. A 5 kHz frequency offset was found between the two lasers. The excellent frequency stability (5×10^{-15} after a 100 s integration time) obtained by the JILA group [2], raises hopes that the reproducibility of the I_2-stabilized green lasers will reach a level well below 1 kHz.

In this paper, we report on a compact I_2-stabilized Nd:YAG laser system which is suitable for transporting to other laboratories for international comparisons. The frequency stability of this portable laser has reached 3.9×10^{-14} for integration times longer than 200 s. The results of a second international comparison between this laser and the JILA laser showed a frequency offset of only 2.5 kHz. We also report the frequency offset between two NRLM lasers, including the observation of the frequency variation due to a round trip of the portable laser for an intercomparison.

We may need to reconsider the role of international comparisons in the near future, since the rapid development of the femtosecond frequency comb has greatly simplified direct optical frequency measurements. However, a direct comparison of frequency stabilized lasers allows us to separate the contributions from frequency measurements, iodine cells, and spectroscopic or electronic methods which affect the laser frequency offset. Furthermore, direct communications between researchers during the international comparison provide effective feedback on the development of frequency stabilized lasers. It is in this way that several sensitivities and offsets were discovered during our international comparisons.

II. Configuration of a Portable Laser System

Fig. 1 shows the configuration of the portable I_2-stabilized Nd:YAG laser (NRLM-Y1). All the optical parts of the laser were arranged on a 30 cm $\times$ 45 cm breadboard. Fig. 2 shows a picture photograph of the optical part of the laser system. A thick breadboard of 1.9 cm was used to reduce any bending of the breadboard surface. Three feet were used to give the breadboard stable support independent of the surface it stands on. The optical beam height was lowered to 5 cm above the breadboard to reduce the vibration of optical mounts and also to reduce the dimensions of the laser system.

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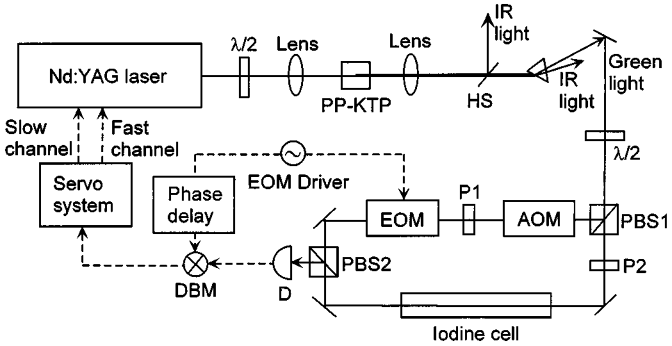

Fig. 1. Configuration of the portable NRLM I_2-stabilized Nd:YAG laser. PP-KTP is a periodically poled KTP crystal, HS is a harmonic separator, PBS1 and PBS2 are polarization beamsplitters, AOM is an acousto-optic modulator, EOM is an electro-optic modulator, P1 and P2 are polarizers, D is a photodetector, and DMB is a doubly-balanced mixer.

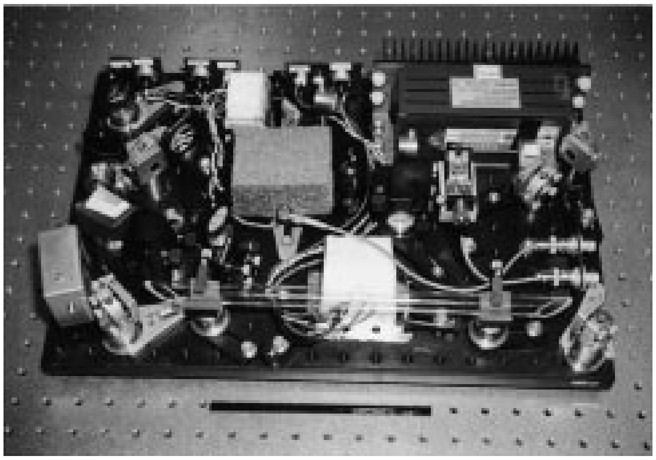

Fig. 2. Photograph of the portable I_2-stabilized Nd:YAG laser (optical part). All the optical parts of the laser were arranged on a 30 cm $\times$ 45 cm breadboard.

The stabilized laser is built from a source oscillator, a second-harmonic generation (SHG) unit, and an iodine spectrometer. The source oscillator of the system is a diode-pumped monolithic-cavity Nd:YAG laser. The SHG used a single pass scheme with a nonlinear crystal of periodically poled $KTiOPO_4$ (PP-KTP). The single pass design of the SHG simplified the system of the frequency stabilized laser and also increased the reliability of the system especially for a long running times. Periodically poled Lithium Niobate (PPLN) and PP-KTP are two possible candidates for the SHG crystal in the present experiment. While PPLN has a larger nonlinear conversion efficiency compared to that of PP-KTP, it has a narrower temperature acceptance in the phase-matching curve and a higher phase-matching temperature. This means that the temperature control is simpler and more stable for the PP-KTP crystal. With a 20 mm long PP-KTP crystal, we could obtain about 4 mW green light from about 500 mW IR input light.

Since the power ratio of the IR and green lights was extremely high after a single-pass SHG crystal, a single harmonic separator was not sufficient to completely separate the two beams. Residual IR light in the green beam will prevent an accurate measurement of the green optical power, and hence cause an error in the power shift correction. In the present laser, adequate separation of the IR and green lights was accomplished by using both a harmonic separator and a prism.

The iodine spectrometer (Fig. 1) was built with a 30 cm long iodine cell. The spectroscopy of molecular iodine was based on the sub-Doppler technique of modulation transfer [9], [10], which gives a nearly flat baseline and is therefore very attractive for laser spectroscopy and frequency stabilization. A $\lambda/2$ plate was used to rotate the plane of polarization of the input beam so that a polarization beamsplitter (PBS1) divided the beam into the required power ratio between the pump and probe beams used for modulation transfer spectroscopy. The pump beam was frequency-shifted by an acousto-optic modulator (AOM) and phase-modulated by an electro-optic modulator (EOM).

The EOM was temperature stabilized to a temperature several Kelvin above the room temperature to reduce the residual amplitude modulation (RAM) effect in the electro-optic (EO) phase modulator. In practice, pure phase modulation is difficult to achieve, and the phase modulated beam was already amplitude modulated to some extent before it entered the iodine cell. This RAM results in a dc offset of the spectral signal. The RAM in the phase modulation is mainly caused by an interference effect in the EOM [11], and by the misalignment of the laser polarization with respect to the crystal axis [11]. Tuning the temperature changes the index of refraction of the EO crystal, and a temperature can normally be found where the fringe effect of the Fabry-Perot (formed by two surfaces of the crystal) is minimized. Temperature control of the EOM can also stabilize the RAM caused by the misalignment of the polarization. We have introduced an extra polarizer (P1) (extinction ratio of 1×10^{-5}) in front of the EOM which is angled to reduce the misalignment of the laser polarization with respect to the crystal axis.

A description of the detection system and other details is given in [7], [8].

III. Frequency Stability and Reproducibility

A. Frequency Stability

Frequency stabilization of the Nd:YAG laser was achieved using the observed modulation transfer signal to drive a feedback control. The fast control signal was fed back to the laser PZT actuator, while the slow signal was fed back to the laser temperature control. The frequency stability was calculated by using the Allan variance [12]

$$\sigma^2(\tau) = \frac{1}{2\nu^2(M-1)} \sum_{i=1}^{M-1} (y_{i+1} - y_i)^2 \qquad (1)$$

where

τ	integration time for successive frequency measurements;
ν	mean optical frequency;
M	number of measurements;
y_i	ith measurement.

Fig. 3 shows the square root of the Allan variance of the measured beat note between two laser systems (NRLM-Y1 and NRLM-Y2), when both lasers were locked on the a_{10} component of the R(56)32-0 line. The stability of our lasers was 3.7×10^{-13} per laser for a 1 s averaging time, improving

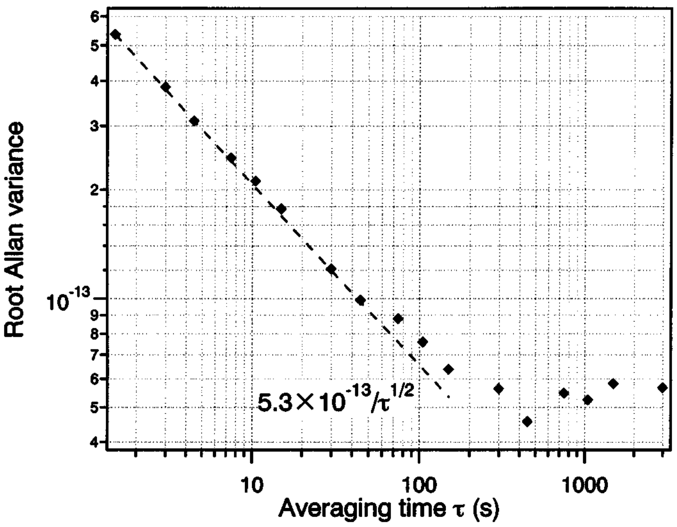

Fig. 3. Root Allan variance of the beat frequency measured between two NRLM lasers. The minimum value of about 3.9×10^{-14} per laser is reached after averaging time $\tau = 200$ s. The stability per laser is calculated using the Allan variance divided by $\sqrt{2}$.

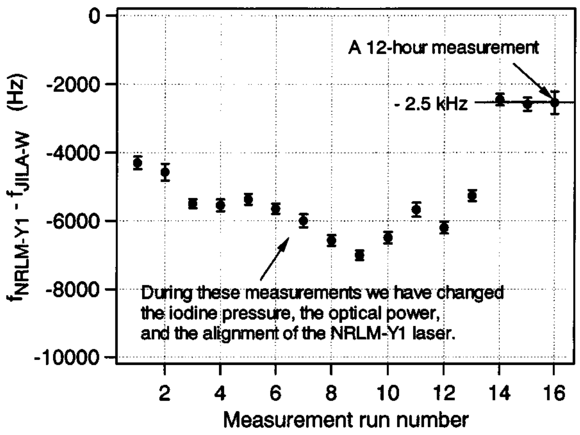

Fig. 4. Frequency differences between NRLM-Y1 and JILA-W. During measurement 1 and 13, we changed the iodine pressure, the optical power, and the alignment of NRLM-Y1 to investigate the origin of the frequency offset. In between measurements 13 and 14, we found that there was a small back reflected signal from the pump beam which contained a RAM signal. By introducing an extra polarizer into the probe beam, we could reduce the frequency difference to -2.5 kHz.

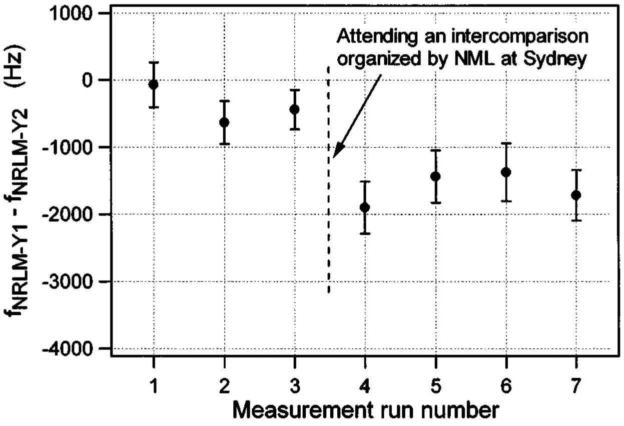

Fig. 5. Frequency differences between NRLM-Y1 and NRLM-Y2. The first three measurements were made after NRLM-Y1 returned from JILA. The averaged frequency offset of these three measurements was -0.4 kHz with a standard deviation of 0.3 kHz. The last four measurements were made after the NML intercomparison when the laser had been returned to NRLM. The average frequency offset of these four measurements was -1.6 kHz with a standard deviation of 0.2 kHz. The average of all seven measurements was -1.1 kHz with a standard deviation of 0.7 kHz.

after a 200 s averaging time toward 3.9×10^{-14}. (Since we have similar laser systems, the stability per laser is calculated using the Allan variance divided by $\sqrt{2}$.) The low long term frequency drift in the present system is particularly welcome for applications such as an optical frequency transfer standard.

B. Frequency Reproducibility

The portable laser system NRLM-Y1 was transported to JILA for a comparison in March 2000. Frequency differences between NRLM-Y1 and JILA-W are shown in Fig. 4. Sixteen measurements were made on several different days with each laser locked on the a_{10} component of the R(56)32-0 line. At the beginning of the comparison, we found that the frequency of NRLM-Y1 was about 6 kHz below JILA-W. During the first thirteen measurements we changed the iodine pressure, the optical power, and the alignment of NRLM-Y1 to investigate the origin of this frequency offset. The laser frequency variation caused by these changes (within about a 3 kHz frequency range) is a rough indication of the reproducibility of NRLM-Y1 due to the variation of sensitive parameters.

Eventually we found that there was a small back reflected signal from the pump beam which contained a RAM signal. By introducing an extra polarizer into the probe beam (P2 in Fig. 1) we could reduce this significantly and therefore reduce the frequency offset to -2.5 kHz $(f_{\text{NRLM-Y1}} - f_{\text{JILA-W}})$ as shown in the last three measurements in Fig. 4. The last measurement was over a 12-h period and had a standard deviation of about 300 Hz for a 1 s integration time. During the last three measurements, the cold-finger temperature of NRLM-Y1 was kept at -10°C, while that of JILA-W was kept at -15°C.

Fig. 5 shows (seven measurements made on several different days) the frequency differences between NRLM-Y1 and NRLM-Y2 when each laser was locked to the a_{10} component of the R(56)32-0 line. The cold-finger temperature of NRLM-Y1 was kept at -10°C, while that of NRLM-Y2 was kept at -15°C. The first three measurements were made after NRLM-Y1 returned from JILA. The averaged frequency offset of these three measurements was -0.4 kHz with a standard deviation of 0.3 kHz. This standard deviation (0.3 kHz) is also an indication of the repeatability of our systems. Our portable laser system NRLM-Y1 was transported to Sydney during the CPEM conference (May 2000) to participate in an international comparison organized by NML [13]. The last four measurements in Fig. 5 show the frequency differences of NRLM-Y1 and NRLM-Y2 after the NML comparison when the laser had been returned to NRLM. The average frequency offset of these four measurements was -1.6 kHz with a standard deviation of 0.2 kHz. The average frequency offset therefore changed from -0.4 kHz to -1.6 kHz after the intercomparison. We do not have a full explanation for this 1.2 kHz variation. A slight change of the beam position in the EOM may have caused a different RAM condition. We may also have had a different wavefront distortion due to a change of the beam position in the EOM and the AOM. A wavefront difference between the overlapping beams inside the iodine cell may also cause frequency shifts [14]. The frequency of NRLM-Y2 may have changed while NRLM-Y1 was participating in the NML comparison. The average of all seven measurements in Fig. 5 was -1.1 kHz with a standard deviation of 0.7 kHz.

A change in the pressure of the iodine will result in a frequency shift due to the changing of the cold-finger temperature, and this is a dominant shift in the I_2-stabilized Nd:YAG laser. A change in the pressure of 0.6 Pa will occur when the cold-finger temperature is changed from -10°C to -15°C. Taking account of the pressure shift (-3.5 kHz/Pa [7]), the frequency of NRLM-Y1 at -15°C is 2.1 kHz higher than it would be with the cold finger at -10°C. Therefore, when the cold-finger temperatures of both NRLM-Y1 and JILA-W are -15°C, the frequency offset $(f_{\mathrm{NRLM\text{-}Y1}} - f_{\mathrm{JILA\text{-}W}})$ should be -0.4 kHz. Similar corrections due to the pressure shift can also be applied to the measurements in Fig. 5.

IV. CONCLUSIONS

We have built a portable I_2-stabilized Nd:YAG laser with proven high frequency stability for international frequency comparisons. A comparison with JILA showed that $f_{\mathrm{NRLM\text{-}Y1}} - f_{\mathrm{JILA\text{-}W}}$ was -2.5 kHz, when the cold-finger temperatures of NRLM-Y1 and JILA-W were kept at -10°C and -15°C, respectively. The averaged frequency offset between two NRLM lasers $(f_{\mathrm{NRLM\text{-}Y1}} - f_{\mathrm{NRLM\text{-}Y2}})$ was -1.1 kHz with a standard deviation of 0.7 kHz. A frequency variation of about 1.2 kHz was found for the frequency offset between two NRLM lasers, after the portable laser NRLM-Y1 experienced a round trip for a comparison.

To verify the reproducibility of the laser systems, we are now developing third and fourth I_2-stabilized Nd:YAG lasers at NRLM. In this way, we can check whether the frequency of the portable laser or the frequency of the laser remaining at NRLM is changed. Furthermore, the testing of more than three laser systems is an effective way to investigate the frequency reproducibility. An important issue is the contamination of iodine reference cells. By exchanging iodine cells between different laser systems, we can identify the frequency offset due to a particular cell, which may be caused by contamination. NRLM has built a filling apparatus for iodine cells with a mass spectrometer to check for iodine purity. International comparisons of I_2-stabilized Nd:YAG lasers has just started and should provide us with necessary information about the reproducibility of I_2-stabilized Nd:YAG lasers.

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