Frequency Comparison of $^{127}I_2$-Stabilized Nd : YAG Lasers

Feng-Lei Hong, Jun Ishikawa, Jun Yoda, Jun Ye, Long-Sheng Ma, and John L. Hall

***Abstract*— A first international comparison of I_2-stabilized Nd : YAG lasers has been made between the National Research Laboratory of Metrology (NRLM), Tsukuba, Japan, the Joint Institute for Laboratory Astrophysics JILA (formerly the Joint Institute for Laboratory Astrophysics), Boulder, CO, the National Institute of Standards and Technology (NIST), Boulder, and the University of Colorado, Boulder. The results of the comparison show that the square root Allan variance of the portable NRLM laser has reached 2×10^{-14} when the integration time is larger than 300 s. Matrix measurements were made for five hyperfine components from a_6 to a_{10} of the R(56)32-0 line. The averaged frequency difference between the NRLM and JILA lasers for four measurements made on three separate days was -4996 Hz (NRLM-JILA, at 532 nm) with a standard deviation of 88 Hz.**

***Index Terms*— Frequency control, frequency stability, laser stability, neodymium : YAG lasers, spectroscopy, standards.**

I. INTRODUCTION

IODINE-STABILIZED Nd : YAG lasers are becoming important standards of wavelength and optical frequency, and the 1997 meeting of the CCDM (now CCL) has adopted the frequency value of the radiation of I_2-stabilized Nd : YAG lasers [1], [2] for the practical realization of the meter. I_2-stabilized Nd : YAG lasers have been studied by groups at Stanford University [3], [4] and the JILA (formerly the Joint Institute for Laboratory Astrophysics) [1], [2], [5]. The absolute optical frequency of the component a_{10} in the transition R(56)32-0 has been measured by the JILA group [1], [2]. Recently, the JILA lasers have reached the unprecedented Allan frequency stability of 5×10^{-14} at 1 s, improving after 100 s toward a flicker floor at about 5×10^{-15} [6]. Research on I_2-stabilized Nd : YAG lasers is now being developed by metrological institutes in several countries.

Since many institutes conduct research on optical frequency standards, but very few have frequency chains to measure optical frequencies, it is very useful to have portable frequency-stabilized lasers, and to make comparisons between different countries. It was in this way that several unsuspected sensitivities and offsets were discovered for the 633 nm He–Ne/I_2 system. In this paper, we report the results of the frequency comparison of I_2-stabilized Nd : YAG lasers between NRLM and JILA.

Due to the strong iodine transitions in the green and the high available laser power, there is no need for an intracavity setup or external buildup cavity for the iodine in the Nd : YAG laser case. This enriches the varieties of feasible I_2-stabilized Nd : YAG laser systems. For example, to reach ultimate stability and reproducibility of the system, the JILA laser has adopted a 1.2 m-long iodine cell, while the portable NRLM laser has contained a 30 cm-long iodine cell. It is very attractive to compare these lasers with different configurations, and to get some ideas for optimizing the system as a standard.

II. LASERS AND EXPERIMENTAL CONDITIONS

The NRLM laser (NRLM-Y1) was fabricated in Japan and transported to JILA for frequency comparison. The laser control part and the final adjustment of the system are being finished at JILA. Fig. 1 shows the configuration of the portable NRLM laser. All the optical parts of the laser system were arranged on a 45 cm × 45 cm breadboard. The optical part of the system contains a source oscillator, a buildup cavity for second-harmonic generation (SHG), and an iodine spectrometer. The source oscillator of this system is a commercial diode pumped Nd : YAG laser, which emits about 700 mW at 1064 nm.

The SHG of the system is accomplished through the use of a ring buildup cavity with a nonlinear crystal of lithium triborate (LBO), which is operated at room temperature without temperature control. The cavity was controlled by two piezoelectric transducers (PZT's). One is a fast PZT with one single layer; the other is a slow PZT with multilayers. A dither at the frequency of 100 kHz was applied to the fast PZT to generate a cavity-locking signal. The fast and the slow servo signals were fed back to the fast and slow PZT, respectively. With a 7 mm-long LBO crystal, we could obtain 15 mW green light

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F.-L. Hong is with the National Research Laboratory of Metrology (NRLM), Ibaraki 305-8536, Japan. He is now with the JILA (the Joint Institute for Laboratory Astrophysics), Boulder, CO 80309, the National Institute of Standards and Technology (NIST), Boulder, CO 80309 USA, and the University of Colorado, Boulder, CO 80309 USA (e-mail: fhong@csd.net).

J. Ishikawa and J. Yoda are with the National Research Laboratory of Metrology (NRLM), Tsukuba 305-8536, Japan.

J. Ye was with the JILA (the Joint Institute for Laboratory Astrophysics), Boulder, CO 80309, the National Institute of Standards and Technology (NIST), Boulder, CO 80309 USA. He is now with the University of Colorado, Boulder, CO 80309. He is now with the California Institute of Technology, Pasadena, CA 91050 USA.

L.-S. Ma was with JILA (the Joint Institute for Laboratory Astrophysics), Boulder, CO 80309, of the National Institute of Standards and Technology (NIST), Boulder, CO 80309 USA, and the University of Colorado, Boulder, CO 80309 USA. He is now with the Laboratory for Quantum Optics, East China Normal University, Shanghai, China.

J. L. Hall is with JILA (the Joint Institute for Laboratory Astrophysics), Boulder, CO 80309, of the National Institute of Standards and Technology (NIST), Boulder, CO 80309 USA, and the University of Colorado, Boulder, CO 80309 USA.

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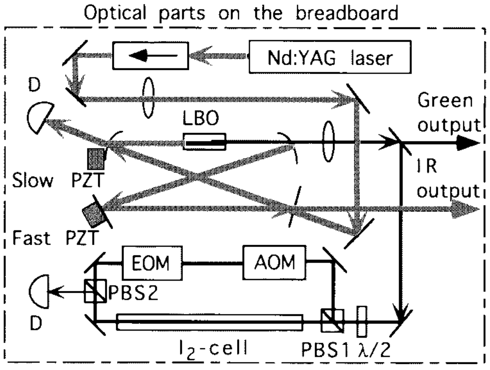


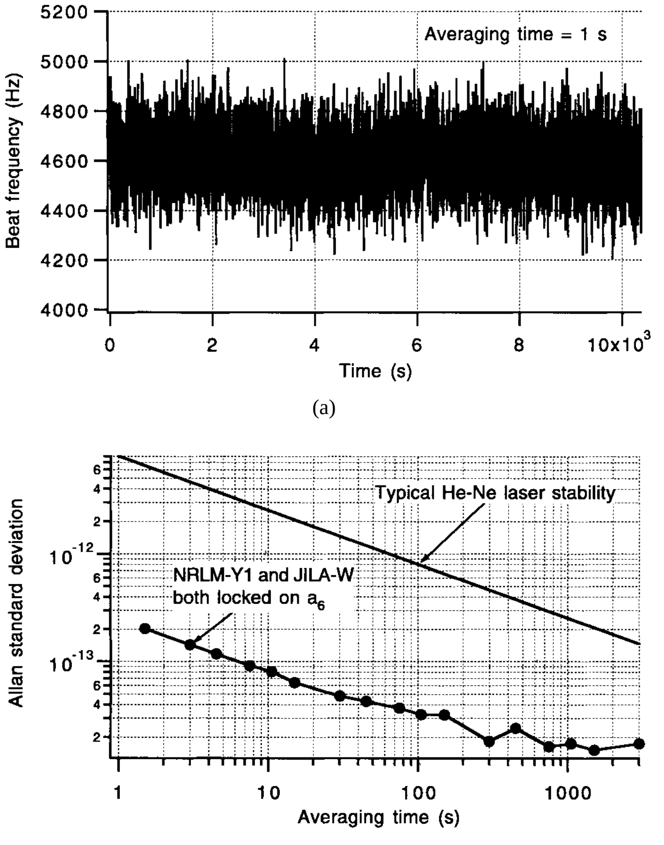
Fig. 1. Configuration of NRLM I_2-stabilized Nd : YAG laser: acoustooptic modulator (AOM); electro-optic modulator (EOM); polarization beamsplitter (PBS); and detector D.

from 525 mW IR input light, with a 20-fold cavity buildup. The reflected IR light from the cavity input coupling mirror is used as the IR output of the system.

The iodine spectrometer (Fig. 1) contains a 30 cm-long iodine cell. The spectroscopy of molecular iodine was based on the sub-Doppler technique of modulation transfer [7], [8], which gives a nearly flat baseline and is therefore very attractive for laser spectroscopy and frequency stabilization. The pump beam was frequency-shifted by an acoustooptic modulator (AOM) and phase-modulated by an electrooptic modulator (EOM). The AOM worked as an optical isolator to prevent interferometric baseline noise problems in the iodine spectrometer. As shown in Fig. 1, the combination of a $\lambda/2$ plate and a polarization beamsplitter (PBS1) was used to generate a proper power ratio for the pump and probe beams. To further reduce the interference between the linearly-polarized pump and probe beams, a crossed-polarization configuration was used allowing pump and probe beams to be separated by PBS2. Inside the iodine cell, both beams were overlapped with crossed polarization. The beams have a common waist near the cell's center and the Rayleigh range is 21 m.

A more detailed description of NRLM-Y1 is given in [9].

The frequency comparison was made between NRLM-Y1 and JILA-W lasers. To have both systems operated under the same conditions, the pressure of iodine in NRLM-Y1 was also adjusted to 0.79 Pa. This corresponds to a cold-finger temperature of the iodine cell of -15°C. The pump beam power and the probe beam power of both lasers were 2.5 and 0.4 mW, respectively. The EOM modulation frequencies were 660 and 350 kHz for NRLM-Y1 and JILA-W, respectively. The AOM offset frequency of both lasers were near 80 MHz but slightly different one from the other. The AOM of JILA-W was adjusted to use the -1 order diffracted beam, while the AOM of NRLM-Y1 was adjusted to use the $+1$ order diffracted beam. This configuration is effective to avoid zero beating while both lasers are locked on the same hyperfine line. The heterodyne beat-note signal between the lasers was measured at 1064 nm (IR light) by using an avalanche photodetector. All the measured frequencies are converted to green light frequencies in this paper.



(a)

(b)

Fig. 2. (a) Variation of the measured beat-note frequency as a function of time. Drift of the optical frequency difference is <5 mHz/s and (b) Allan standard deviation of the beat note between NRLM-Y1 and JILA-W (dot and solid line).

III. Comparison Results

A. Frequency Stability

Fig. 2(a) shows the time variation of the beat note between NRLM-Y1 and JILA-W when both lasers are locked on the a_6 component of the R(56)32-0 line. Since the stability of JILA-W is fourfold better than that of NRLM-Y1 [6], the measurement results mainly indicate the stability of NRLM-Y1. The maximum frequency excursion of NRLM-Y1 in 10 000 s was about 600 Hz. For application as an optical frequency transfer standard, the absence of long term drift [<5 mHz/s for the data of Fig. 2(a)] is particularly welcome. Fig. 2(b) shows the Allan standard deviation of the measured beat frequency. The stability of NRLM-Y1 is 2×10^{-13} at 1 s, improving after 300 s toward the 2×10^{-14} level. Compared to typical I_2-stabilized He–Ne lasers, the portable I_2-stabilized Nd : YAG laser has reached a stability of about a factor of 35 better in the short-term region, and about one order of magnitude better in the long-term region.

B. Frequency Reproducibility and Repeatability

To determine the reproducibility and repeatability of frequency differences between the compared lasers, each laser in turn was stabilized to one of the hyperfine components a_6, a_7, a_8, a_9, and a_{10} so that finally a five × five matrix of measured frequency differences was obtained. These five

TABLE I

MATRIX MEASUREMENT (RUN #3). EACH BEAT RESULTS Bf (CORRESPONDING TO ONE ELEMENT IN THE MATRIX) CONSISTS OF THE AVERAGE OF TEN BEAT FREQUENCY DATA, WHERE EACH BEAT FREQUENCY DATA WAS MEASURED WITH A 10 s GATE TIME BY THE FREQUENCY COUNTER. $Sdev$ IS THE STANDARD DEVIATION OF THE MEAN OF THE TEN MEASURED BEAT FREQUENCIES. δf IS THE FREQUENCY DIFFERENCE (NRLM-YI – JILA-W) WHEN EACH LASER WAS LOCKED ON THE SAME HYPERFINE COMPONENT OR WHEN THE HPYERFINE COMPONENT WAS EXCHANGED FOR EACH LASER

NRLM-Y1 \ JILA-W		a_6	a_7	a_8	a_9	a_{10}
a_6	*Bf* (Hz)	4714	15 520 120	38 153 410	53 869 930	170 068 720
	Sdev (Hz)	34	38	40	38	36
	δf (Hz)	- 4714	- 4602	- 5041	- 5229	- 4773
a_7	*Bf* (Hz)	15 510 916	4526	22 637 752	38 354 298	154 553 080
	Sdev (Hz)	38	38	30	40	32
	δf (Hz)		- 4526	- 4937	- 5138	- 4677
a_8	*Bf* (Hz)	38 143 328	22 627 878	5338	15 721 894	131 920 630
	Sdev (Hz)	32	46	24	36	28
	δf (Hz)			- 5338	- 5545	- 5068
a_9	*Bf* (Hz)	53 859 472	38 344 022	15 710 804	5800	116 204 492
	Sdev (Hz)	42	42	26	44	48
	δf (Hz)				- 5800	- 5271
a_{10}	*Bf* (Hz)	170 059 174	154 543 726	131 910 494	116 193 950	4782
	Sdev (Hz)	30	42	42	34	30
	δf (Hz)					- 4782

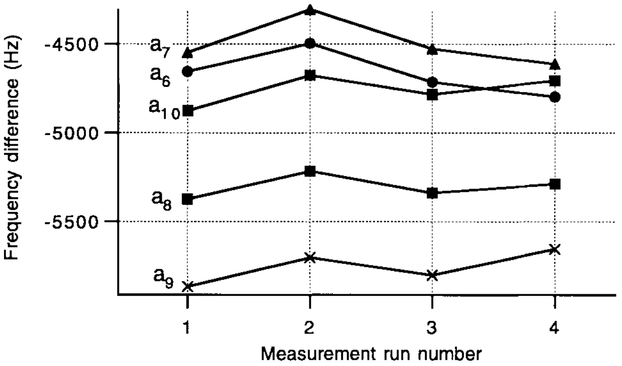


Fig. 3. Frequency differences of NRLM-Y1 and JILA-W when each laser was locked on the same hyperfine line (the diagonal components of the matrix measurements).

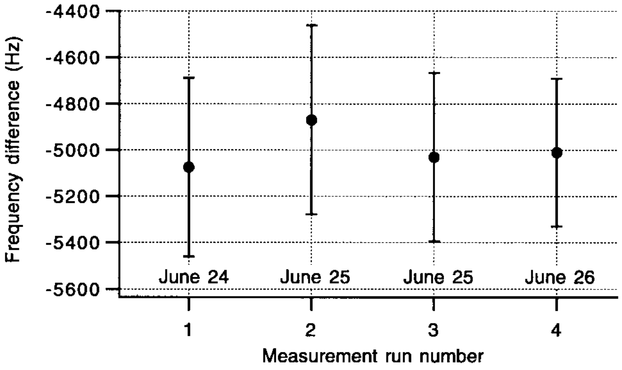


Fig. 4. Repeatability of the matrix-averaged frequency differences between lasers NRLM-Y1 and JILA-W. The uncertainties are given as one standard deviation of the matrix averaging.

lines were chosen because they are located near the Doppler center and have no strong lines nearby.

Table I shows a typical measured matrix (Run #3). Each beat result (Bf) (corresponding to one element in the matrix) consists of the average of ten beat frequency data, where each beat frequency data was measured with a 10 s gate time by the frequency counter. $Sdev$ is the standard deviation of the measured beat frequency data. The typical value of $Sdev$ is 40 Hz. δf is the frequency difference (NRLM-Y1–JILA-W) when each laser was locked on the same hyperfine component or when the hyperfine component was exchanged for each laser. The averaged δf of matrix measurement (Run #3) is -5029 Hz with a standard deviation of 365 Hz. Fig. 3 shows, for four measurements made on three different days, the frequency differences of NRLM-Y1 and JILA-W when each laser was locked on the same hyperfine line (the diagonal components of the matrix measurements). A pattern has been formed by the diagonal components, and been repeated during the four measurements. This means the two systems effectively have different hyperfine splittings at some small level. With the higher stability of these 532 nm systems, as compared to He–Ne lasers, we can now look into these issues more precisely. So, once again, this international intercomparison has turned up some otherwise unexpected physical effects.

Because of the hyperfine-structure dependencies, the frequency difference between the two systems will be calculated here using the matrix method. Fig. 4 shows the matrix-averaged results of the four frequency comparisons. This averaged frequency difference between the NRLM and JILA lasers for the four measurements was -4996 Hz with a standard deviation of 88 Hz. The origin of the observed frequency difference of the two systems may also be partly associated with the difference of the hyperfine splitting. The uncertainties in Fig. 4 are given as one standard deviation of the matrix averaging. It is important to gain a deeper understanding of the nearly tenfold ratio of the matrix-averaged standard deviation and that of each single beat measurement.

C. Frequency Shifts

Pressure shift and power shift of the locking frequency were measured for NRLM-Y1 to reveal the frequency shifts due to the changing of cold-finger temperature or of laser power.

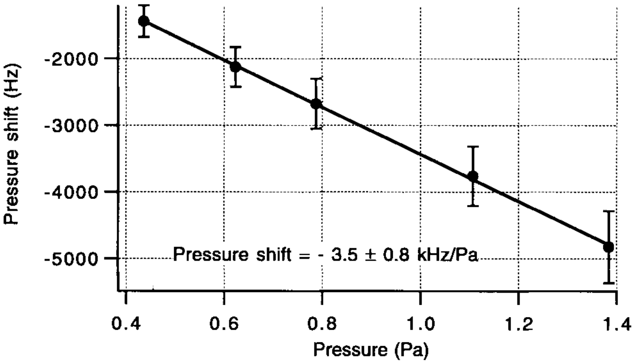


Fig. 5. Pressure shift of NRLM-Y1. Averaged value for a_6 to a_{10} hyperfine components of R(56)32-0. The uncertainties are given as one standard deviation of the averaging.

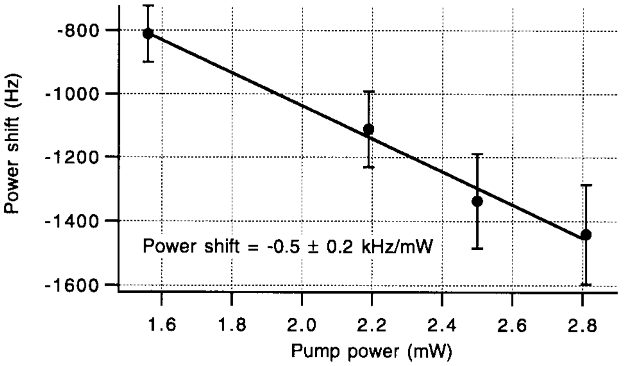


Fig. 6. Power shift of NRLM-Y1. Averaged value for a_6–a_{10} hyperfine components of R(56)32-0. The uncertainties are given as one standard deviation of the averaging.

Fig. 5 shows the measured pressure shift of NRLM-Y1 with the averaged value for a_6 to a_{10} components. The uncertainties are given as one standard deviation of the averaging. The power of the pump and probe beams of NRLM-Y1 was kept at 2.5 and 0.4 mW, respectively. The measured pressure shift slope was -3.5 ± 0.8 kHz/Pa. This is about two times larger compared to the reported pressure shift of the JILA laser [5].

Fig. 6 shows the measured power shift of NRLM-Y1 with the averaged value for a_6 to a_{10} components. The uncertainties are given as one standard deviation of the averaging. The cold-finger temperature of NRLM-Y1 was kept at -15 °C. The measured power shift slope was -0.5 ± 0.2 kHz/mW. This slope has an opposite sign compared to the reported power shift of the JILA laser [5]. The difference of the pressure and the power shifts of the NRLM and JILA lasers also are related to the observed frequency difference, since the frequency difference is taken at some convenient operating point, as opposed to being an extrapolation to zero pressure and power.

IV. CONCLUSIONS

We have fabricated a portable I_2-stabilized Nd : YAG laser for international frequency comparisons. The results of the comparison between this laser and the JILA-W standard show that the stability of the portable laser has reached 2×10^{-14} when the integration time is larger than 300 s. The matrix measurements of five hyperfine lines made on three different days show that the average frequency difference between JILA-W and the portable NRLM-Y1 was -4996 Hz (NRLM-JILA, at 532 nm) with a standard deviation of 88 Hz. The repeatability of the frequency measurement has reached 51 Hz, which is the average standard deviation for the four measurements.

Frequency differences can arise from differing saturation parameters, residual linewidths and possible (small) contamination of the I_2 reference cells. The wavefront difference of the overlapping beams inside the iodine cell may also cause frequency shifts [10]. Independent adjustment of these items will be reconfirmed. Also, frequency comparisons involving more than two I_2-stabilized Nd : YAG lasers may give us a more clear description for each system, and are now in progress.

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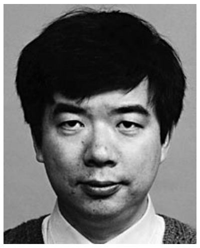
Feng-Lei Hong was born on June 8, 1963, in Shanghai, China. He received the B.S., M.S., and Ph.D. degrees in physics from the University of Tokyo, Tokyo, Japan. His dissertation was on the relationship between molecular vibrational relaxation processes and laser chaos phenomena.

After a two-year postdoctoral appointment working on laser and microwave double-resonance spectroscopy of Rydberg atoms at RIKEN, Japan, in 1994, he joined the National Research Laboratory of Metrology (NRLM), Tsukuba, Japan, where he is a Senior Researcher. His current research interests include high-resolution laser spectroscopy, laser frequency stabilization, optical frequency standards, wavelength standards, optical frequency measurement, and ultrashort optical pulse generation. As a Visiting Member, he is now with JILA (formerly the Joint Institute for Laboratory Astrophysics), Boulder, CO of the National Institute of Standards and Technology (NIST), Boulder, CO, and the University of Colorado, Boulder, CO.

Dr. Hong is a member of the Optical Society of America, the Physical Society of Japan, and the Japan Society of Applied Physics.

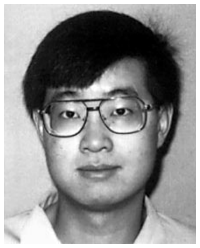


Jun Ishikawa was born in Tokyo, Japan, in 1956. He received the B.E. and M.E. degrees from the Tokyo Institute of Technology in 1980 and 1982, respectively.

Since 1982, he has been with the National Research Laboratory of Metrology, Tsukuba, Japan. His research is in the field of length standards. He is responsible for the wavelength standard in Japan.

Jun Yoda was born in 1943. He received the B.S. and M.S. degrees from Osaka University, Osaka, Japan, in 1966 and 1968, respectively, and the Ph.D. degree from the University of Tsukuba, Tsukuba, Japan, in 1993.

In 1968, he joined the National Research Laboratory of Metrology (NRLM), Ministry of International Trade and Industry, Tsukuba. From 1968 to 1981, he worked in Cs frequency standards. He was a Fellow at the Laboratoire de l'Horloge Atomique, Orsay, France, from 1982 to 1983. Since 1984, he has been engaged in research on ion trap and laser cooling.



Jun Ye was born on November 7, 1967, in Shanghai, China. He received the B.S. degree from Jiao Tong University, Shanghai, in 1989, the M.S. degree from the University of New Mexico, Albuquerque, in 1991, and the Ph.D. degree from the University of Colorado, Boulder, in 1997.

He is currently a R.A. Millikan Prize Post-Doctorate Fellow, Quantum Optics Group, California Institute of Technology, Pasadena. His research interests include high-precision measurements, high-resolution and ultrasensitive laser spectroscopy, optical frequency standards, atom trapping, and quantum dynamics in optical and atomic physics.

Long-Sheng Ma was born on June 29, 1941, in Shanghai, China. He graduated from East China Normal University, Shanghai, in 1963, majoring in electronics and physics.

He studied laser propagation in atmosphere and laser monitoring of air pollution until 1980. Since 1981, his research field has been ultrasensitive and high-resolution laser spectroscopy, laser frequency stabilization, and molecular spectroscopy. He was a Visiting Scholar at the JILA (formerly the Joint Institute for Laboratory Astrophysics), Boulder, CO, and the University of Colorado, Boulder, from 1981 to 1983, and Guest Scientist at the Institute for Laser-Physics, Hamburg University, Hamburg, Germany, from 1992 to 1993. From November 1993 to 1998 he was once again with JILA. He is now a Professor, Department of Physics, East China Normal University, Shanghai.

John L. Hall was born in 1934 in Denver, CO. He received the Ph.D. degree in physics from the Carnegie Institute of Technology, Pittsburgh, PA.

Since 1964, he has been with the JILA (Joint Institute for Laboratory Astrophysics), Boulder, CO, the University of Colorado, Boulder, and National Institute of Standards and Technology (NIST), Boulder, where he has been responsible for a number of major innovations and developments in high-resolution ultrasensitive laser spectroscopy, laser frequency stabilization, laser cooling, quantum optics, and high-precision measurements using laser technology.

Dr. Hall is a Member of the National Academy of Science, Senior Fellow of the National Institute of Standards and Technology, and a Fellow of JILA, the Optical Society of America, and the American Physical Society.