Portable national length standards designed and constructed using commercially available parts

— An advanced mechanical design for the iodine stabilized He-Ne laser —

Jun Ishikawa

[Translation from *Synthesiology*, Vol.2, No.4, p.276-287 (2009)]

The iodine stabilized He-Ne laser at 633 nm is widely used as the national length (wavelength) standards in many countries. Since the wavelength emitted by the laser is directly proportional to the cavity length of the laser, extremely high mechanical stability is necessary for the cavity of the iodine stabilized He-Ne laser. Many special parts as well as special materials are adopted to achieve a sufficiently high stability in the conventional iodine stabilized He-Ne lasers while the adoption of such special parts and materials brings difficulty in the maintenance of the lasers. I developed and constructed a new iodine stabilized He-Ne laser with a special mechanical design. The assembly and adjustment of the laser is quite easy. Although most parts and materials of the laser are commercially available, it showed better stability especially against the ambient temperature variation. The new iodine stabilized He-Ne lasers were used for a long time as the national length standards of Japan.

Keywords : Mechanical design, fine mechanism, anti-vibration mechanism, length standard, iodine stabilized He-Ne laser

1 Introduction

The length is one of the most basic physical quantities, and the technology for measuring the length is highly advanced in the fields of science and industry. The international unit for length is the meter (or metre). The International Prototype of "X" cross-section metre line-standard was used as the standard since the latter half of the 19th Century, and in the 20th Century, a definition of the metre in terms of the wavelength in vacuum of the radiation corresponding to a transition between specified energy levels of the krypton 86 atom was adopted in 1960. The current definition of the metre has been adopted since 1983, and this is based on the speed of light traveling in vacuum (light velocity)[Note 1]. Specifically, the standard is the wavelength of laser radiation under specific conditions. The most widely used standard is the helium-neon laser with its laser wavelength stabilized to the absorption line of iodine molecules[Note 2]. Currently many countries around the world including Japan use the iodine-stabilized He-Ne laser as their national standards. Figure 1 is the traceability system of length measurement using this laser as the national standard.

In general, the national standard is expected to possess the highest precision above the measurement precision required in industry and academia. Therefore, the latest, most advanced, and special technologies are summoned to achieve the highest precision in the development of the national standard. When the R&D is completed and the national standard is created, the next phase is how the standard is supplied effectively to industry and academia, and how to maintain this national standard stably. Once this supply phase is reached, the latest, most advanced, and special technologies become barriers in supplying and maintaining the standard due to high cost and difficult availability, which are factors that cannot be neglected.

When the author started research on precision interferometry at the former National Research Laboratory for Metrology, Agency of Industrial Science and Technology (current National Metrology Institute of Japan, AIST), the iodine-stabilized He-Ne laser used as wavelength standard (this was national standard of length in Japan to 2009) faced such problems. In the beginning, although I experienced poor operability and problems in procuring the special parts, I thought they were unavoidable hardships for the upkeep of a national standard with highest precision. At that time, a researcher of Physics and Engineering Laboratory of New Zealand (the National Standards Laboratory) was visiting the standard labs of various countries and stopped at AIST to conduct an international comparison of iodine stabilized He-Ne lasers[1]. He hand-carried a self-developed laser onto the passenger cabin of the airplane. Compared to the Japanese laser that was composed of a rack full of control components and the laser body installed on a cast-iron channel bench, I was absolutely amazed by its compact size and easy operability.

Inspired by this experience, I started research on the universalization of the iodine stabilized He-Ne laser. Here, “universalization” means to carefully study and to clarify the functions and properties required for each member of the iodine stabilized He-Ne laser, and then to achieve these functions and properties using generally available parts as much as possible. In this paper, I shall describe the

Digital Manufacturing Research Center, AIST Tsukuba East, 1-2-1 Namiki, Tsukuba 305-8564, Japan E-mail : j.ishikawa@aist.go.jp

Original manuscript received May 22, 2009, Revisions received September 24, 2009, Accepted September 25, 2009

situation when I started the research, the policy for elemental technology development taken under that condition, what kind of elemental technologies were developed, and what national standard was achieved by combining the elemental technologies.

2 Objective of research

2.1 Universalized national standard

The specifications and performances required for any standard, including the iodine stabilized He-Ne laser, and its member parts may be special compared to general products. In the basic development phase, because the priority is to realize the required performance, special and expensive materials, parts, and processing methods are used generously.

In the beginning, the author was not in the position to develop the standard, but was involved in the iodine stabilized He-Ne laser as a user, and came across the opportunity of seeing the New Zealand laser. From that experience, I was convinced that the basic development phase was only half of the entire course of development of the standard, and universalization was essential to accomplish the development completely. As mentioned earlier, universalization is to carefully study and to clarify the performances and properties required and to establish the design and technology that achieve those performances and properties using universally available parts. I consider universalization as an attempt at conversion from special parts (hardware) to design and technology (software).

The operating principle of the iodine stabilized He-Ne laser is based on the quantum mechanical property of the iodine molecule. Since the quantum mechanical property of the iodine molecule is consistent, there is no difference in principle among the iodines used, unlike the International Prototype of metre that uses artifacts. However, flaws arise in the mechanism, which are artificial, for extracting the stable laser wavelength based on the quantum mechanical property of the iodine molecule, and this manifests as differences and uncertainties in laser wavelengths by different devices. The author thinks that possession and maintenance of the standard is not merely possessing the iodine stabilized He-Ne laser (hardware), but is the possession of the technology to extract the laser wavelength from the iodine molecule. For universalization, careful investigation and deep understanding of the laser wavelength extraction are necessary. The possession of technology gained through universalization is none other than the possession and maintenance of the standard.

It is expected that there will be many advantages in universalizing the national standard. The main advantages are the increased mutual reliability of the length standard among countries, and dramatic improvement of the precision of fine measurement of length in Japan.

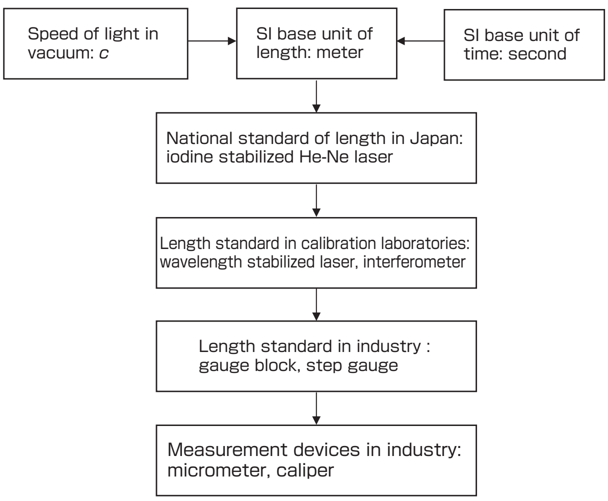

Fig. 1 Traceability system of the length measurement using the iodine stabilized He-Ne laser as the national standard.

2.2 Increased international mutual reliability

Except for some of the advanced nations, most national standard labs purchase commercially available iodine stabilized He-Ne laser as their national standard. In such cases, they must depend on the laser manufacturer for repairs other than simple adjustments. In other words, the national standard labs simply possess the hardware, and the maintenance of the standard is entirely dependent on the manufacturer. There will be no major problem as long as the product has a high degree of perfection and there are no delays in supply and maintenance services. However, because a national standard device like the iodine stabilized He-Ne laser requires high technology and its demand is extremely limited, it is not easy to develop, manufacture, and maintain it as profitable business. In fact, the business is fraught with difficulties.

The author considers the universalization of iodine stabilized He-Ne laser to be the realization of a laser with excellent performance, operability, economy, and ease of maintenance as a standard, and at the same time to disclose the detailed technological information to the laser users. The essence of wavelength standard is the technology to obtain stable laser wavelength from the unchanging quantum mechanical property of the iodine molecule. If the technology can be shared among the countries through universalization, it can become the foundation for establishing the mutual reliability to confirm the equivalencies of the national standards among the nations.

2.3 Advancement of mid-tier traceability in Japan

There are several companies that provide calibration service for wavelength standard as business in the middle tier of traceability in Japan, and their technological level is almost par to the national standard labs except for some advanced nations. The employment of the universalized iodine stabilized He-Ne laser as the standard of the calibration service providers means the possession of the standard as a technology, as explained in the previous section.

The traceability of artificial standards such as gauge blocks and weights can be maintained by assessment through calibration. However, the iodine stabilized He-Ne laser is a standard that extracts wavelength based on the quantum mechanical property of the iodine molecule, and the difference by device (uncertainty) depends on the technology for extracting the wavelength. In such a standard, in addition to evaluating the wavelength, the possession of technology for extracting the wavelength and its assessment, or the "traceability of technology" is essential. Universalization of the technology will promote conversion from possession of hardware to possession of technology, and the reliability in the mid-tier traceability such as among the calibration service providers will improve.

3 Operating principle of iodine stabilized He-Ne laser

Here, I shall explain the operating principle of the iodine stabilized He-Ne laser. Figure 2 is a schematic diagram of the structure of the iodine stabilized He-Ne laser. In ordinary He-Ne laser, a laser tube containing a mixture of helium and neon gases is placed between the laser cavity composed of two plane laser mirrors (more accurately, they are slightly concave). In the iodine stabilized He-Ne laser, the "iodine cell" where highly pure iodine molecule is sealed inside is placed in the laser cavity. The relationship between the optical interval (length of laser cavity) of the two laser mirrors L and wavelength λ can be expressed as Equation (1).

$$\lambda = 2L / \mathrm{N} \tag{1}$$

Here, N is an integer. λ is proportional to L. Since the wavelength range in which the light amplification effect of the He-Ne laser tube is effective is extremely narrow, the laser wavelength λ remains at a certain limited range. When L is changed past the effective wavelength range, the integer N increases or decreases one at a time (mode hop), and remains at a certain range in which the light amplification is effective. When L is varied in the range where mode hop does not occur, the laser output I changes as shown in Fig. 3 (dashed line). I decreases at both ends where λ is close to mode hopping, and becomes highest at the center. When the iodine cell is present in the laser cavity in addition to the laser tube, the light absorption by the iodine molecules affects I, and the output curve changes as shown in Fig. 3 (solid line). Since a strong standing wave of light (10 mW) is present inside the laser resonator, the absorption by iodine molecules becomes saturated. Since the absorption weakens at the center of the absorption wavelength by saturated absorption, I increases slightly, and a spike appears on the output curve. Using this phenomenon, extremely high-resolution spectroscopy (saturated absorption spectroscopy) without the Doppler effect due to motion of the iodine molecules can be achieved. The iodine stabilized He-Ne laser uses the spike of saturated absorption that appears on the output curve as a marker, and the high precision is realized by controlling and stabilizing the laser wavelength to its center.

Differential signal by phase sensitive detection is normally used as method for detecting the peak position of the output curve. Figure 4 shows the principle of differential signal by phase sensitive detection. To accomplish the differential signal, λ is slightly modulated. The modulation of λ changes the I, but the amplitude and phase are determined by the gradient of output curve $I(\lambda)$. As shown in the figure, the first derivative $I'(\lambda)$ of $I(\lambda)$ is obtained when the DC component is extracted from the signal obtained by crossing the output signal and the demodulated signals. The laser wavelength stays at the peak position of $I(\lambda)$ by controlling the λ to keep this derivative at zero. However, in the iodine stabilized He-Ne laser, since the spike due to saturated absorption of iodine molecules is superimposed on the laser output curve $I(\lambda)$, the effect on the gradient of the baseline cannot be avoided. To remove this effect and to detect the true center of the saturated absorption by iodine molecules, the third derivative detection is done in practice. The signal $I'''(\lambda)$ of the third derivative can be obtained by using the threefold wave (frequency $3f$) of the modulated signal (frequency f) as the demodulated reference signal of the phase sensitive detection. Since the laser output curve is gentler by far compared to the spike of saturated absorption, the effect is sufficiently removed by third derivative. Figure 5 is the

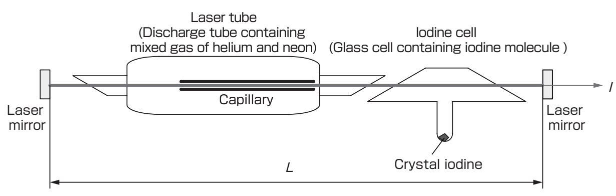

Fig. 2 Schematic diagram of iodine stabilized He-Ne laser.

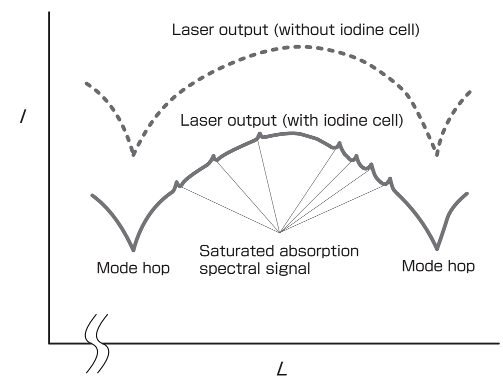

Fig. 3 Relationship between laser cavity length *L* and laser output *I* (in single axial mode).

third derivative signal $I'''(\lambda)$ around the iodine molecule absorption component in the iodine stabilized He-Ne laser output observed on the oscilloscope. The laser wavelength is controlled so this third derivative signal becomes zero and stability is achieved.

The wavelength of laser λ is proportional to the length of the laser cavity L in the range where mode hop does not occur, as mentioned earlier. Therefore, to change the laser wavelength λ for control and modulation, L may be changed. For example, 6 $MHz_{p\text{-}p}$ modulation, converted to optical frequency, is applied to the laser wavelength λ as modulation for third derivative signal detection. If L is 0.3 m, the change of L corresponding to the 6 MHz modulation is 3.8 nm. This means that if one of the laser mirrors is vibrated at amplitude 3.8 nm in the optical axis direction, modulation of λ needed for third derivative detection can be achieved. Also, the width of the third derivative signal (Fig. 5) used in the control of laser wavelength is about 5 MHz, converted to optical frequency. When the modulation range of the laser wavelength surpasses this width due to vibration or shock, control is lost (this is when “the frequency lock becomes unlocked”). To stabilize the laser wavelength, it is necessary to keep the change in L at about 1/10 of this width, or at about 500 kHz. The change of resonator length L equivalent to the change of laser frequency change of 500 kHz is 0.32 nm. This is approximately the diameter of an atom. For a stable operation of the iodine stabilized He-Ne laser, it is necessary to have the fine technology of keeping the change in the interval of the laser mirror due to vibration to about the diameter of an atom.

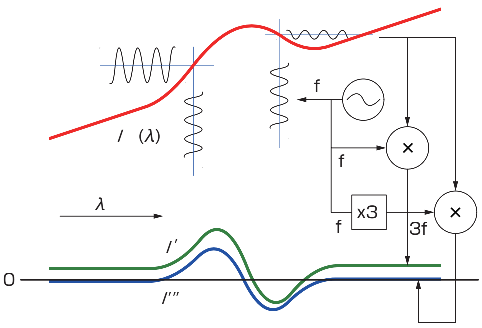

Fig. 4 Spike in laser output *I*(λ) due to saturated absorption, signal for its first derivative *I'*, and signal for third derivative *I'''*.

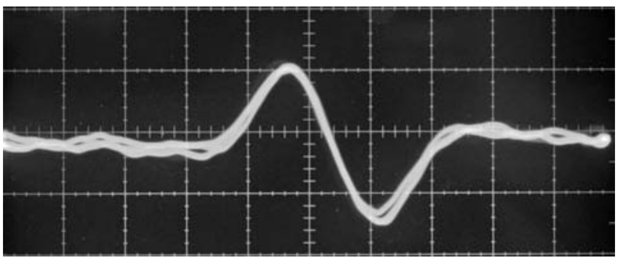

Fig. 5 Actual third derivative signal observed on the oscilloscope.

Figure 6 is the mechanism of the first resonator of the iodine stabilized He-Ne laser used by the author. One of the laser mirrors is as is, while the other one is attached to a ring-shaped stacked piezoactuator. Each mirror is supported by endplates with mechanism for precise angle adjustment. The two endplates are supported facing each other with four spacer rods made of Super Invar that has thermal expansion close to zero. A laser tube and an iodine cell are set in the resonator. In actual operation, the effect of vibration was kept within the aforementioned condition range of 500 kHz by mounting the resonator on the anti-vibration plate supported by air springs and then covering it with a soundproof case. Only one multi-layer ring piezoactuator is shown in Fig. 6, and both the demodulation and the control signals were applied to this piezoactuator to accomplish simultaneous modulation and control.

4 Road map for achieving the goals

As mentioned in the earlier chapters, the performances and properties required from each mechanism of the iodine stabilized He-Ne laser are quite special. Special requirements cannot be achieved by using universal members. To achieve special performances and properties using universal parts, it is necessary to devise new and special usage. As for special usage, methods that cause danger or ones that significantly reduce the lifespan cannot be employed. By devising and realizing ways to achieve the required performances and properties within reasonable and feasible range, the employability of the universal parts can be widened even if they are used unconventionally.

As an example, I shall explain the new bias adjustment circuit of the control mechanism. In the iodine stabilized He-Ne laser, it is necessary to smoothly change the voltage applied to the piezoactuator to search and select the absorption line. Conventionally, this change was done using the potentiometer, but there is no potentiometer that has sufficient voltage resolution over the entire range. Therefore, the range of change was limited to a narrow voltage range, and this made the operability poor. Figure 7 shows the voltage adjustment circuit that achieves extremely high voltage resolution using the DC gear motor and integrator circuit instead of a potentiometer. The DC gear motor is an actuator that rotates at rate proportional to the input

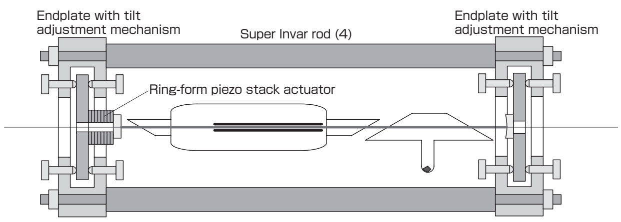

Fig. 6 Resonator mechanism of the iodine stabilized He-Ne laser (conventional type).

voltage, but when it is rotated by external force, it also functions as a generator and produces voltage proportional to the angular velocity ($2\pi \times$ number of rotations). When the generated voltage is input to the integrator circuit, the output is voltage proportional to the rotational angle of the gear motor. The constant of proportion of the rotational angle and the integrator circuit output voltage can be set arbitrarily by selecting the input resistance of the integrator circuit and the capacitor. Moreover, this gear motor can be rotated without limit, unlike a potentiometer, and the voltage can be adjusted throughout the process. For example, it can be set at a rotation of 100 times or more.

Achievement of special functions using universal parts was not conducted in a planned or systematic manner. While the development of parts directly affecting the laser performance as well as parts that may be difficult to procure or to maintain should be priority, the order at which ideas arose and problems were solved did not necessarily correspond to the priorities. Therefore, in conducting this development, there was no planned or systematic scenario in the beginning. After I succeeded at several universalizations, I became capable of seeing the bottleneck accurately. By recognizing the importance of the issue and then placing it somewhere in the corner of my mind, I was able to engage in improvements and developments whenever a solution came up while doing some other work. Under such situations, the set of universalizations was completed in about 10 years.

The example of the above voltage adjustment circuit improved the operability, and it was possible to improve the basic performance (uncertainty and stability) by using the new mechanism with universal parts. The following chapters explain the control mechanism of the laser cavity length that determines the basic performance of the laser.

5 Universalization of laser cavity length control mechanism

The laser resonator length control mechanism is the most important part that determines the basic performance of the iodine stabilized He-Ne laser. Conventionally, special parts such as ultra-low heat expansion materials and piezoactuators were used. The resonator length control mechanism is composed of the linear movement mechanism to control the wavelength and the modulation mechanism to obtain

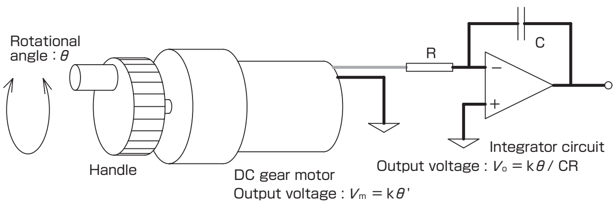

Fig. 7 Wide-range voltage micro-adjustment circuit using DC gear motor and integrator circuit.

Table 1 Operational parameters of the iodine stabilized He-Ne laser (recommendation of the CIPM).

・Cell-wall temperature of iodine cell	(25±5)	℃
・Cold-finger temperature of iodine cell	(15±0.2)	℃
・Frequency modulation width peak-to-peak (P-P)	(6±0.3)	MHz
・One-way intracavity beam power	(10±5)	mW
＊The coefficient of one-way intracavity beam power of the optical frequency must be 1.4 kHz/mW or less.		

the third derivative signal. The universalization of the two mechanisms is explained below. Also, I shall explain the anti-vibration mechanism that is important to achieve stable resonator length control.

5.1 Linear movement mechanism of the laser mirror

The operating parameters of the iodine stabilized He-Ne laser are listed as the recommendation of the Comité International des Poids et Mesures (CIPM)[2]. Table 1 shows the operating parameters of the iodine stabilized He-Ne laser as recommended by CIPM. Of the four recommended parameters, only the depth of the modulation (6 ± 0.3 MHz converted to optical frequency) as mentioned earlier is directly related to the resonator mechanism, but since the one-directional optical intensity (10 ± 5 mW) within the resonator is affected by the laser mirror angle, it can also be considered as an issue of the resonator mechanism. In the conventional iodine stabilized He-Ne laser, the resonator length was controlled by a ring-shaped stacked piezoactuator. However, the piezoelement is not necessarily made of homogenous materials, and unevenness where the expansion and contraction may differ in places may occur even when constant voltage is applied. This causes a phenomenon where the tilt angle of the laser mirror slightly varies. When the tilt of the laser mirror changes, the loss of laser cavity changes so that the laser output also changes. The laser output is determined by the sum of the one-directional optical intensity within the resonator and the transmissivity of the laser mirror. Table 1 shows that the tolerance of change is large at ± 50 % of the designated output (one-directional optical intensity in the resonator is 10 mW), and the output change due to change in the tilt of the piezoactuator normally falls within this range.

However, from actual experiments, it was absolutely necessary to keep the change of the tilt of the laser mirror during control as small as possible, to realize the iodine stabilized He-Ne laser with excellent reproducibility and stability of laser wavelength. On this point, the recommendation of CIPM is deficient on the major parameter that affects the laser wavelength. The author has conducted measurements while maintaining the laser power I almost constant while changing the angle of the laser mirror, to assess the dependency of the laser wavelength λ on the inclination of the laser mirror[3]. As a result, it was experimentally confirmed that the laser wavelength may change in the recommended uncertainty (10 kHz converted to frequency), even when all the operating parameters of the iodine stabilized He-Ne laser are set within the recommendations of CIPM. It was learned that extremely high linearity was required for the movement mechanism of the laser mirror to ensure the stability of laser wavelength of the iodine stabilized He-Ne laser. The piezoactuator used in the control of the resonator length has excellent rigidity and micro-displacement capability, but was a bottleneck for the precision of conventional iodine stabilized He-Ne laser due to the linearity issue. I learned that it was essential to develop a movement mechanism with excellent linearity for further universalization, and employed the method of combining the piezoactuator with excellent rigidity and micro-displacement and a guide mechanism with excellent linearity in the new iodine stabilized He-Ne laser.

In general, the mechanical linear guide can be categorized into three: parallel spring, sliding, and rolling guides. The parallel spring guide has been used most commonly as the linear guide combined with the piezoactuator. Although the range of motion is limited, the parallel spring guide is considered particularly suitable for fine position control since there are no allowance, friction, or backlash. However, to realize a high degree of linearity, the parallel spring structure must be somewhat enlarged, and the weight increases when the rigidity of the system increases. Moreover, it is expensive. The sliding guide inherently has allowance and cannot be used for this purpose. In this development, I use the rolling guide because it is inexpensive and light, even though it had almost no history of being used as a guide for laser cavity length control.

5.1.1 Linear motion guide by ball spline

Rolling linear motion guide includes ones with finite stroke and infinite stroke. The finite stroke rolling guide has structure where the rolling body such as balls or rollers is placed between the opposing linear guides, as shown in Fig. 8a. When the lower guide is fixed and the upper guide is moved, the rolling body in between moves halfway along the upper guide. To maintain the movement of the guide, the rolling body is arranged at the range of 50~70 % of the total length of the guide. The problem of the finite stroke rolling guide is that the support point (position of the rolling body) moves along with the movement. While it is dependent on the rigidity and load, the movement of the support point is the cause of unavoidable position shift.

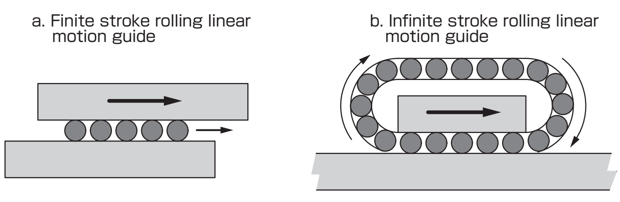

Fig. 8 Finite stroke rolling linear motion guide (a) and infinite stroke rolling linear motion guide (b).

The infinite stroke rolling guide has a mechanism to return the rolling body, which is expelled from the rear as the upper guide moves, to the position between the upper and lower guide, as shown in Fig. 8b. In addition to allowing long distance movement, the movement of the support point is small (less than the interval of the rolling bodies), and it is an excellent mechanism with little position shift.

The first mechanism I used as the rolling linear motion guide was a ball spline with a circular hollow shaft structure (THK Co., Ltd.: LF13)[4]. The ball spline is a kind of infinite stroke rolling guide, and I decided to use this because high-level linearity can be obtained. Also it was shaped similarly to the ring-form piezo stack actuator and it could be incorporated easily to the laser resonator. The spline shaft diameter of the ball spline is 13 mm, and there is a hole of 5 mm diameter in the center through which the output laser passes. Figure 9 shows the laser mirror linear movement mechanism with an incorporated ball spline. The laser mirror is set at the end of the spline, and the spline shaft is pulled out front with a preload spring in the control arm. When the adjustment mechanism for the laser mirror is installed on the laser body, the tip of the linear piezoactuator of the main body contacts the spline shaft control arm, and the spline shaft is pushed in about halfway. Control voltage is applied to the linear piezoactuator, and the mirror position is controlled by the expansion and contraction.

Unlike the sliding guide, the allowance can be removed in the rolling mechanism by applying preload. For the ball spline tested, the gap between the main body and the ball spline shaft was adjusted to less than the ball diameter by 2 ~ 6 μm, and there was no looseness. However, when the spline shaft was pushed in the side direction during laser emission, a change in laser power that was thought to arise from the mirror tilt was observed. The rigidity against the side moment of the ball spline guide is not enough. In this ball spline guide, the ball is circulated. According to the specification, since the gap between the main body and the spline shaft is smaller than the diameter of the ball (-6 ~ -2 μm), large resistance is produced when the ball enters the interval and hampers smooth movement. However, no change in resistance due to entry and exit of the ball was observed. In both ends, the interval is slightly larger to prevent resistance when the ball enters, and it is estimated that the actual

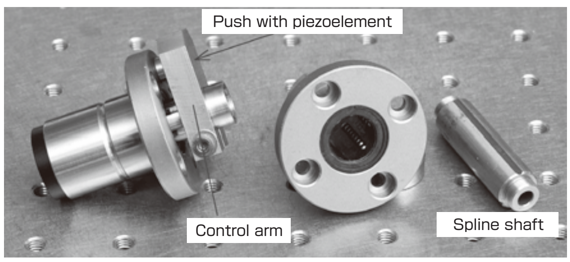

Fig. 9 Linear motion guide for laser mirror with the ball spline.

preload occurs in the central part. As a result, the rigidity against the shift can be maintained but the rigidity against the tilt is insufficient. In the manufacturer's explanation, it is recommended that two splines should be used linearly in place where there is side moment.

5.1.2 Linear movement mechanism by cross roller guide

It was mentioned earlier that the position shift accompanying the movement of the support point position couldn't be avoided in the finite stroke rolling linear motion guide. In principle, this position shift is thought to gradually progress throughout the stroke. On the other hand, the stroke needed for stabilizing the laser wavelength is around 0.05 mm since the purpose is to correct the expansion and contraction of the laser cavity length due to heat expansion. This is 1/100 or less of the maximum stroke of the cross roller guide[5], which is a representative limited distance rolling guide, as well as for the smaller versions. For the position shift for the entire stroke of the cross roller guide, the position shift against the movement of 1/100 stroke is expected to be sufficiently small, while it may not fulfill the performance required for the linear mechanism of the iodine stabilized He-Ne laser. Moreover, in the finite stroke rolling guide, since there is no entry or exit of the rolling body into the guide, it is not necessary to widen the ends of the guide as in the infinite stroke rolling guide. Therefore, it is expected to have high rigidity against tilt. After considering the conditions and required performances of the linear motion guide for cavity length control, as well as the performance of the linear motion guide used under that condition, cross roller guide emerged as an optimal linear motion guide.

The shape of the cross roller guide is suitable for a movement stage, and application to circular mechanism is difficult. With employment of the cross roller guide, the structure of the laser cavity was greatly changed from the conventional endplate and rod to a housing combining the plate members as shown in Fig. 10. Moreover, making use of the separation of the movement control of the laser mirror and the maintenance of linearity, I devised a structure where the linear piezoactuator was fixed with the Super Invar rod, and the other side of the Super Invar rod was fixed to the housing at the position of the other laser mirror, as shown in Fig. 11. With this structure, the resonator length is determined by the piezoactuator and the Super Invar rod. Since it is not necessary to consider the heat expansion of the housing material, aluminum could be used. Since aluminum has high heat expansion, it was not conventionally used as the housing of the laser resonator. However, it also has high heat conductivity, and it has excellent characteristic where the heat strain due to heat gradient is not likely to occur. Compared to Super Invar rod, the heat expansion coefficient of aluminum is 50 times more, but the heat conductivity coefficient is also close to 20 times, and the effect of the heat strain will remain within 3 times.

The new laser with the cross roller guide, aluminum housing, and control mechanism for resonator length by linear piezoactuator and Super Invar rod has extremely small tilt angle change of the laser mirror. Stable operation with small temporal change and environmental dependency has been achieved. Currently, among the five new lasers owned as the national standard of Japan, the difference in laser wavelength is held within ± 3 kHz converted to optical frequency by conducting appropriate adjustment. This is within 1/3 of the ± 10 kHz uncertainty recommended by CIPM. It is also stable against the changes in environmental temperature, and shows excellent performance where the change of the laser wavelength stays within the deviation of ± 5 kHz converted to optical frequency (relative 1×10^{-11}) even against large temperature shift of 25 ± 5 ºC.

5.2 Modulation mechanism of the laser resonator

In the iodine stabilized He-Ne laser, modulation of 6 ± 0.3 MHz converted to optical frequency is applied to laser wavelength to detect the saturated absorption signal of the iodine molecule. This modulation is accomplished by vibrating one of the laser mirrors by sine wave in the optical axis direction. In the case where the resonator length is 30 cm, the amplitude is (3.81 ± 0.19) nm. As mentioned

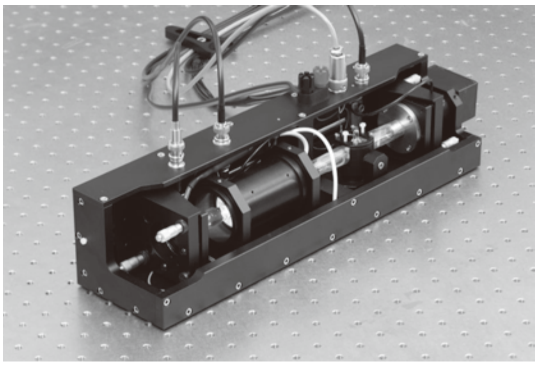

Fig. 10 Box-shaped laser cavity mechanism of the iodine stabilized He-Ne laser (new type).

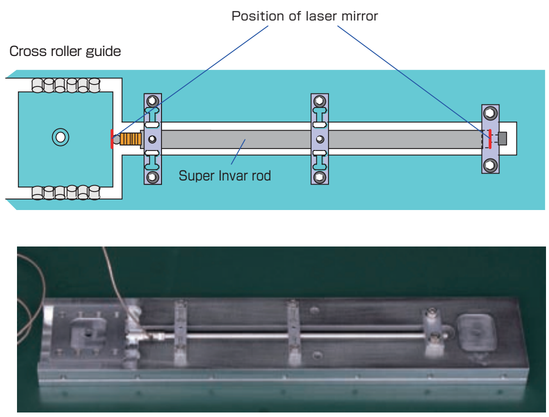

Fig. 11 Control mechanism for cavity length.

earlier, to obtain the control signal by third derivative, the third harmonic detection is done. When the third harmonic is included in the vibration of the laser mirror, the first derivative signal component enters into the third derivative signal, and the laser wavelength shifts as a result. Therefore, the vibration of the laser mirror is required to be pure fundamental with extremely low harmonic distortion. Moreover, to maintain the sensitivity of the phase sensitive detection constant, the phase relationship of the driving sine wave and the vibration must not change. Extremely high level of amplitude stability, ultra low distortion, and phase stability are required for the wavelength modulation actuator. In many iodine stabilized He-Ne lasers including the conventional laser, ring-form piezo stack actuator with the same structure as the ones to control the resonator length are used for modulation. In the conventional laser, one ring-form piezo stack actuator was used for both modulation and control.

The piezoactuator with stacked or multilayer structure is originally for control (DC operation), and the use with vibration (AC operation) is not assumed. The durability when it is vibrated is an issue. In conventional lasers, detachment of the adhesive surface of the piezoelement caused by modulating vibration occurred frequently. When detachment occurred, it cannot be repaired and the entire component must be replaced. The US made ring-form piezo stack actuator was expensive and the supply was unstable (because they were prioritized for military use), and this was a major barrier in using it in the iodine stabilized He-Ne laser.

5.2.1 Modulation mechanism using single-layer piezoelement

The detached ring-form piezo stack actuator must be discarded. One day, I attempted disassembling it to understand how it failed. By soaking the stacked piezoactuator in acetone, all the adhesives detached and it came apart easily. I found out that the stacked piezoactuator was constructed by stacking 10 piezoelement discs to which metal was deposited on both sides to function as electrode. Since the stroke of the actuator is 10 μm for applied voltage 1000 V, one element is 1/10 or 1 μm.

With the dissembled actuator in front of me, I thought of developing a single-layer modulation actuator using one element. There will be no detachment if it has only one layer. The amplitude necessary for modulation is about 4 nm as mentioned earlier, and the applied voltage equivalent to the displacement of the single-layer element is 4 V, a voltage that can be handled readily by circuit using ordinary op amp. Moreover, since the rigidity will increase greatly, the stability of operation can be expected to improve.

Figure 12 is the structure of the modulation actuator that was first fabricated. It has a simple structure where a ring-shaped piezoelement, an aluminum laser mirror holder, and an O-ring were held down in a case between two brass securing ring screws. The voltage is applied between the laser mirror holder and the securing ring. However, when this mechanism was set in the iodine stabilized He-Ne laser and I attempted stabilizing the wavelength, large wavelength shift over 10 times the recommended uncertainty was observed. The baseline of the third derivative signal was so tilted that it could be discerned visually, and there was an inclusion of the first derivative signal, or the substantial occurrence of third harmonic distortion in the modulation mechanism. In this structure, when static, the soft O-ring distorted and functions as expected. However, in vibration, the brass securing ring supporting the piezo vibrates due to action and reaction. The brass securing ring is in contact with the main body by the thread of the screw. The contact points of ordinary screws are partial, and it is thought that the rigidity is low against small displacement and nonlinearity is high. I suspected that the structure where the screws directly supported the object caused distortion.

5.2.2 Improvement of dynamic property of the modulation mechanism

To improve the dynamic property and to reduce the harmonic distortion of the modulation mechanism, it is essential that the mechanical contacts are carefully finished planes to maintain highly rigid and stable contact. Moreover, it is important that the holders that support the vibrating laser mirror are immobile as much as possible. Considering these two points, Fig. 13 shows the modulation actuator that reduces the harmonic distortion and improves the operational stability. The point that differs greatly with the modulation actuator in Fig. 12 is the mass of the brass support base. The mass of the brass support base is about 200 g, and is about 50 times the mass of the 4 g vibrating part including the laser mirror and the holder. Due to this large mass ratio, only the laser mirror and the holder move even if the ring-shaped piezoelement expands and contracts at high speed, and the brass base remains immobile. Particular care is taken for

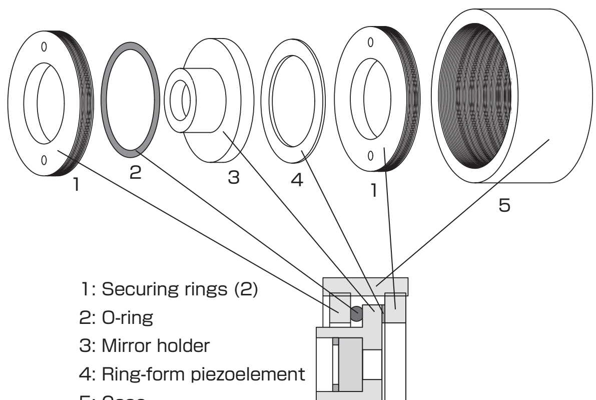

Fig. 12 Modulation actuator (before improvement, large harmonic distortion).

the finish of the contact planes of the brass support base, the ring-shaped piezoelement, the laser mirror holder, and the laser mirror. Lapping finish is done to increase the contact surface area to reduce the harmonic distortion. Also, the ring-shaped piezoelement and the laser mirror holder are placed on the brass support before assembly. Alcohol is poured on the contact plane, the brass support is flipped over, and firm planar contact is confirmed by seeing that the ring-shaped piezoelement and the mirror holder are fast and do not fall off.

The mirror holder is preloaded by a thin-walled phosphor-bronze cylindrical spring and a brass round nut, and is placed in contact with the ring-shaped piezoelement and the brass support base. The brass base, the bronze thin-walled cylindrical spring, and the brass round nut are electrically insulated using a nylon insulator. The driving voltage of the piezoactuator is applied between the brass round nut (+) and the brass base (G).

When designing, the purpose of the nylon insulator was electrical insulation, but it was found that it had another important function. When I used an aluminum insulator coated with insulating alumite to test the insulating materials to replace the nylon insulator, the modulation became unstable although there was no problem in the insulating property (substantial temporal change in amplitude occurred). The cause was the vibration of the mirror holder transferred to the phosphor-bronze thin-walled cylindrical spring and to the brass round nut through strong nonlinear screw contact. This resulted in complex resonation. The soft nylon insulator functioned as a damper that greatly reduces this resonance.

5.3 Anti-vibration mechanism

As mentioned earlier, to achieve a stable function of the iodine stabilized He-Ne laser, the laser resonator length change caused by vibration and acoustics of the external environment must be kept under the diameter of an atom (0.3 nm) or less. As an assumption for development of the vibration mechanism, it is necessary to establish a method for detecting and evaluation the slight changes of the resonator length. Following is a brief explanation of the slight change in resonator length and the anti-vibration mechanism.

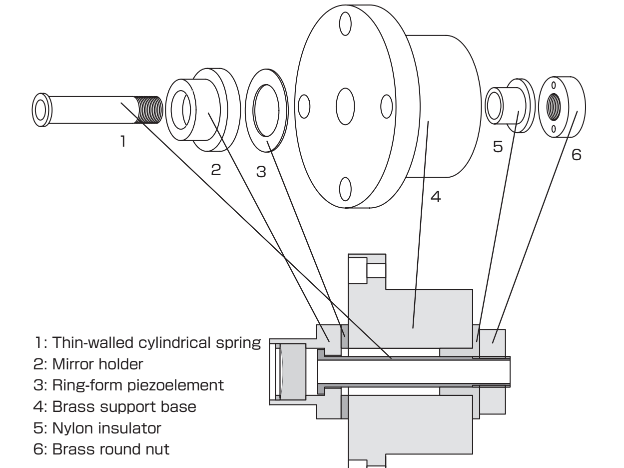

Fig. 13 Modulation actuator (after improvement, structure with low harmonic distortion).

The optical intensity change of laser output is measured for the stabilization of the laser wavelength, and this is amplified and connected to loudspeakers. The intensity change caused by wavelength modulation (6 MHz converted to optical frequency) of frequency f (3 kHz) can be heard as sound. The change of wavelength by wavelength modulation is converted to intensity change at laser wavelength – output curve $I(\lambda)$ and is heard as sound. At the same time, the resonator length change caused by external vibration also causes wavelength change, and that also can be heard. The amplitude of sound is proportional to the wavelength change or change in the resonator length. Therefore, if the sound of the external vibration can be kept to 1/10 of the amplitude of sound caused by wavelength modulation (1/100 in intensity, -20 dB), stable operation of the iodine stabilized He-Ne laser can be achieved. The metal housing of the iodine stabilized He-Ne laser was placed directly on the optical table with a honeycomb structure (the surface is 5 mm thick stainless plate). The sound from the loudspeaker when the table surface is scratched with a coin or tapped lightly was similar to the sound heard when a person pressed an ear against the table surface.

To assess the performance of anti-vibration rubber, aluminum plate with thickness of 1 cm (same as the bottom plate of the laser body) was placed on the table, and the sound heard when the table surface was scratched or tapped while pressing the ear against the plate was checked. Next, the anti-vibration rubber to be assessed was placed beneath the metal plate, and the degree of reduction of sound was checked.

Three hemisphere rubber feet with radius of 7 mm made of polyurethane, which showed excellent sound insulation in the above simple experiment, were placed at the bottom of the housing of the new iodine stabilized He-Ne laser (Fig. 14). When it was placed directly on the table and operations such as optical axis adjustment were done, the wavelength stabilization became unlocked due to vibration, but with the anti-vibration effect of the rubber feet, there was hardly any effect on wavelength stabilization due to ordinary operations on the table.

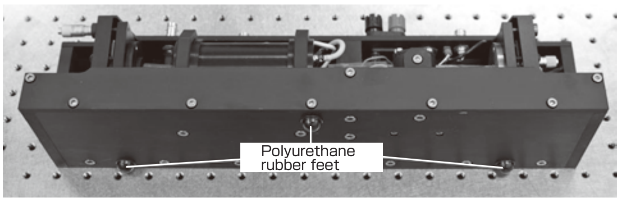

Fig. 14 Sub-nanometer vibration-proof mechanism (rubber feet).

6 Performance of the developed national standard and its utilization

The new iodine stabilized He-Ne laser is used as the national standard of Japan at AIST and as the standard of the calibration service providers that provide the wavelength standard. This laser has new, original mechanisms as explained above. Its greatest characteristic is that it is supplied as a do-it-yourself assembly kit rather than a whole product. As mentioned earlier, what is important for a standard using the quantum mechanical property of iodine molecule absorption line is the technology of extracting the standard (wavelength) from that property. To put this thinking to practice, the author published *Monograph of Metrology*[6] that explains the details and plans of the new iodine stabilized He-Ne laser. Based on this monograph, one can create lasers that will satisfy the recommendations of CIPM. However, although the parts are generally available, it is hard work to procure all of the necessary parts to fabricate the laser. Therefore, we gathered all the necessary parts and distributed them for a charge to companies as a do-it-yourself kit. Since it is a kit, it is guaranteed that each member satisfies the specification, but the final performance as a standard (absolute wavelength and uncertainty) depends on the owner's technology. Technological instruction for assembly is provided by request. By distributing this kit, we realized a "bargain" price as a national standard at 2,000,000 yen a set including the laserhead and the controller (control part is provided in almost completed form).

The attempt to transfer the technology of wavelength standard is also done internationally. AIST has been working on the project to assist the establishment of the National Institute of Metrology Thailand (NIMT). The first kit of the iodine stabilized He-Ne laser was delivered to NIMT through this project. Current, similar technological transfer is planned for the national standard labs in the ASEAN countries.

This laser was used for international comparison, and was found to have excellent feature unseen in other lasers, as a standard that follows the recommendation of CIPM. One of the recommended parameter of CIPM states that the temperature of the wall of the tube of the iodine cell must be maintained at 25 ± 5 ºC. This temperature is almost the same as the environmental temperature, and the iodine stabilized He-Ne laser should function in the temperature range of 25 ± 5 ºC. The new laser fulfills this condition. It is capable of maintaining wavelength stability in the range of 25 ± 5 ºC, and the wavelength change showed good results where uncertainty stayed at half or less of the recommended by CIPM (5 kHz or less converted to optical frequency). On the other hand, many lasers including the conventional laser require strict stabilization of environmental temperature to fulfill the uncertainty recommended by CIPM. The change in tilt angle of the laser mirror due to the expansion and contraction of the ring-form piezo stack actuator used in many lasers may become a factor of change in laser wavelength. To prevent the change in the tilt angle, it is necessary to conduct strict environmental temperature stabilization to minimize the expansion and contraction of the actuator, in addition to the use of ultra low expansion material for the laser main body. Once, we conducted the international comparison by gathering the iodine stabilized He-Ne lasers of various nations that were used as national standards in one place. During that session, the temperature of the room where the lasers were set up changed about 2 ºC due to the malfunction of the air conditioner. Many lasers became unlocked and stopped functioning while the new laser continued to perform without unlocking, and demonstrated its high performance.

7 Conclusion

The author became involved with iodine stabilized He-Ne laser as a user. In "developing the precision interferometer," my initial topic of research, my latent desire was to improve the usability and reliability of the iodine stabilized He-Ne laser that was the standard light source for wavelength. When I saw the portable laser from New Zealand, the desire became manifest and I started the research as explained earlier. However, if I was not a user but a developer of the conventional laser, I am likely to have said, "This is the national standard and I don't care about the usability. Rather, it is more important to develop the next-generation standard with higher precision."

I think the greatest factor that made me set the direction of the research − to achieve special function by using the universal parts in unconventional, special ways − was the fact that the improvement of the iodine stabilized He-Ne laser was not my official topic. In the early phase of the research, I had extremely low budget and I had no time schedule or obligation to come up with a result. This allowed me to try bold experiments and that set the direction of research. If a research plan was written as an official project with formal budget request, I am certain I would have made safe choices of using special parts and special materials in a conventional manner.

I mentioned in the previous chapter that a "bargain" price was achieved by providing the iodine stabilized He-Ne laser as a do-it-yourself kit. However, the true significance of DIY is the increased motivation of the users. The assembly of the laser is done as a training session, where many participants work on it with enthusiasm and become totally absorbed in it. The author tells the participants who finish the session and are taking the assembled and adjusted iodine stabilized He-Ne laser home, "This laser is not a standard but just a thing. Standard is the technology you have learned and your will to maintain this standard."

Notes

Note 1) Currently, the SI Base Units of length is the meter (metre). The metre is the length of the path travelled by light in vacuum during a time interval of 1/299 792 458 of a second.

Note 2) Currently, the helium-neon laser in which the emission frequency (wavelength) is stabilized to the specific absorption line of the iodine molecule is commonly used as the primary standard of length. The frequency recommended is ν = 473,612,353,604 kHz. Wavelength λ is calculated by dividing the speed of light c (299,792,458 m/s) by ν. $\lambda = c/\nu$

References

[1] R. B. Hurst, N. Brown, V. D. Dandawate, G. R. Hanes, J. Helmcke, H. P. Layer, L. Zhongyou, W. R. C. Rowley, T. Sakurai and M. S. Chung: International intercomparison of iodine-stabilized helium-neon lasers at 633 nm involving ten standards laboratories, *Metrologia*, 24 (1), 39-44 (1987).

[2] T. J. Quinn: Practical realization of the definition of the metre, including recommended radiations of other optical frequency standards (2001), *Metrologia*, 40 (2), 103-133 (2003).

[3] J. Ishikawa: Wavelength calibration and its uncertainty at 633 nm, *Sansoken Keiryo Hyojun Hokoku (AIST Bulletin of Metrology)*, 4 (1), 71-77 (2005) (in Japanese).

[4] *Ball Spline Series (Catalog)*, THK Co., Ltd., Tokyo (2008) (in Japanese). https://tech.thk.com/upload/catalog_claim/pdf/381_ballspline.pdf

[5] *THK General Catalog,* A8, B8, THK Co., Ltd., Tokyo (2008) (in Japanese).

[6] J. Ishikawa: Design and Construction of a 633nm Iodine Stabilized Helium-Neon Laser Based on the CIPM Recomendation, *Sansoken Keiryo Hyojun Monogurafu (AIST Monograph of Metrology)*, 2(2003) (in Japanese).

Author

Jun Ishikawa

Completed the master's course at the Interdisciplinary Graduate School of Science and Technology, Tokyo Institute of Technology in 1982. Joined the National Research Laboratory of Metrology, Agency of Industrial Science and Technology, Ministry of International Trade and Industry in 1983. Worked on the development of precision interferometer, and was exposed to the iodine stabilized He-Ne laser as a light source for wavelength standard. Joined the National Metrology Institute of Japan, AIST in 2001. Transferred to the Digital Manufacturing Research Center in 2006, where he worked on visualization of skill at the site of manufacturing. Currently, leader of research team for measurement and analysis technology. Received Ichimura Academic Award (The New Technology Development Foundation) in 2006. Received the Commendation for Science and Technology by the Minister of Education, Culture, Sports, Science and Technology in 2006.

Discussion with Reviewers

1 Addition to research objective and scenario

Comment (Akira Ono, AIST)

For *Synthesiology*, please add the "objective of research" and "scenario for achieving the objective."

Answer (Jun Ishikawa)

As you indicated, I added a new section for "objective of research" and "scenario for achieving the objective." However, this research was started without a scenario (plan), and I frankly explained the course of events at the time.

2 Use of *AIST Monograph of Metrology* in the reference

Question and comment (Akira Ono)

I think Reference 6 is extremely important in terms of diffusion of this technology. While there is a tendency to write up only the highlights of the original technology in research papers and be done with it, I don't think I've seen a complete disclosure of necessary information to enable reproductive fabrication of the device. What was your motivation for writing Reference 6, and how is it being utilized?

Answer (Jun Ishikawa)

Unlike the International Prototype Metre Standard Bar, which is an artificial object, the essence of the laser wavelength standard that utilizes the quantum mechanical property of the iodine molecule is in the technology of extracting the optical wavelength from the quantum mechanical property. Therefore, the maintenance and transfer of the standard is the maintenance and transfer of the technology. The *AIST Monograph of Metrology* was written for the purpose of maintenance and transfer of the technology for the iodine stabilized He-Ne laser. The paper was revised to reflect this thinking.

3 Mass and size of the standard

Question (Akira Ono)

You mention that the national standard can be taken aboard an airplane for transfer. That must be extremely convenient for conducting international comparisons smoothly. What is the mass and size of the newly developed laser? Can it be taken aboard the airplane cabin?

Answer (Jun Ishikawa)

The body of the laser is 420 mm in length, 105 mm in width, 95 mm in height, and 5.3 kg in weight. The control device is 400 mm in depth, 420 mm in width, 100 mm in height, and 7.5 kg in weight.

When boarding the airplane, the laser body is taken aboard the cabin as a hand-carry item, and the control device is checked in. If we concentrate on downsizing and weight reduction, a smaller and lighter laser can be made, but I opted for this size due to the ease of fabrication, assembly, and adjustment.

At this point, the greatest barrier to hand-carrying the device on the airplane is the regulation after 9.11. Since the wavelength-stabilized laser is a special device which people are not familiar with, I have a very hard time explaining what it is.

4 Uncertainty of laser wavelength

Question (Akira Ono)

What is your assessment of the uncertainty of the laser wavelength of the new laser? I imagine that it is smaller than the value of uncertainty recommended by CIPM. If possible, can you show the budget table along with the factors of uncertainty?

Answer (Jun Ishikawa)

Table "a" shows the budget table of the uncertainty of iodine stabilized He-Ne laser recommended by CIPM. Of the uncertainties shown in the table, I think the estimate of the uncertainty caused by one-directional optical intensity within the resonator is too large. However, I think this includes the gas lens effect and gas prism effect that were difficult to assess separately in the conventional iodine stabilized He-Ne laser that had problems with linearity in its control mechanism. The researcher who has been working on iodine stabilized He-Ne laser for a long time at the Bureau International des Poids et Mesures acknowledged this point.

Since the linearity of the control mechanism of the new laser is excellent, the gas lens and gas prism effects can be separated, and the uncertainty budget will be as shown in Table “b”. To reduce the uncertainty due to gas lens and gas prism effects, it is necessary to precisely fabricate the geometric shape of the laser discharge tube, and such laser tube is not available in reality. The effect of purity of iodine was reduced by improving the filling process of the iodine cell, and the uncertainty of beat frequency measurement was reduced by improving the measurement technology.

5 Precision of the standard owned by the calibration service provider

Question (Akira Ono)

You say that several calibration service providers in Japan own the iodine stabilized He-Ne laser as their own standards, and I believe they are brought to AIST for regular calibration. When the calibration was conducted, what was the difference compared to the wavelength (frequency) of the national standard at AIST. Did it fall within the range of uncertainty assessed for the new laser, or did some of them surpass the range?

Answer (Jun Ishikawa)

The new lasers were all assembled and adjusted under the author’s technological instruction at AIST. Therefore, the frequency difference of 5 kHz or less against the national standard was checked at the time of shipment. Except for the case where the emission ceased due to clouding of the optical window, I confirmed that the initial performance was almost completely maintained at the time of recalibration.

Table a Uncertainty of the iodine stabilized He-Ne laser recommended by the CIPM.

Parameter	Recommended value	Tolerance	Coefficient	Uncertainty(kHz)
Iodine cell				
Wall temperature	25 ℃	5 ℃	0.5 kHz/℃	2.5
Cold-finger temperature	15 ℃	0.2℃	−15 kHz/℃	3.0
Effect of iodine purity				5.0
Frequency modulation width peak-to-peak	6 MHz	0.3 MHz	−10 kHz/MHz	3.0
One-way intracavity beam power	10 mW	5 mW	<1.0 kHz/mW	5.0
Uncertainty of beat frequency measurement				5.0
Combined standard uncertainty				10.0

Table b Uncertainty of the new iodine stabilized He-Ne laser.

Parameter	Recommended value	Tolerance	Coefficient	Uncertainty(kHz)
Iodine cell				
Wall temperature	23 ℃	2 ℃	0.5 kHz/℃	1.0
Cold-finger temperature	15 ℃	0.1 ℃	−15 kHz/℃	1.5
Effect of iodine purity				2.0
Frequency modulation width peak-to-peak	6 MHz	0.2 MHz	−10 kHz/MHz	2.0
One-way intracavity beam power	10 mW	2 mW	<1.0 kHz/mW	2.0
Uncertainty of beat frequency measurement				0.0
Gas lens effect, gas prism effect				5.0
Combined standard uncertainty				6.3

6 What happened to the overseas researcher

Question (Akira Ono)

The researcher from New Zealand inspired you to carry out your idea. What kind of research did this researcher do afterwards? Can you answer to the extent you know?

Answer (Jun Ishikawa)

After that, due to the administrative reform in New Zealand, many research institutes were reduced, abolished, or merged, and I’ve heard from his successor that the researcher transferred to a private company. New Zealand’s iodine stabilized He-Ne laser is currently an American product, and it’s a little sad to hear that the laser that he used for the international comparison is no longer used and sits in the corner of the lab.

7 Examples of *Product Realization Research* conducted by overseas national standards laboratory

Question and comment (Akira Ono)

The universalization research for the national standard that you conducted can be considered a *Product Realization Research*. I don’t think there are so many examples in the AIST Metrology Standard Groups engaging in research with a clear goal of product realization. However, some researches such as “remote calibration” are being done in the mid-tier of the traceability system involving the calibration service providers, and it seems that you are strongly aware of the importance of *Product Realization Research*.

Around the world, to the best of the author’s knowledge, is there any example, other than New Zealand, of such *Product Realization Research* done by a national standard laboratory?

Answer (Jun Ishikawa)

Attempts at product realization of iodine stabilized He-Ne laser was done from its early stages (around 1980), but it mostly involved the manufacturers almost entirely copying the R&D product from the laboratory to create the product. As a result, there were problems in price, size, and operability, and it was not of high quality as a product. The laser from New Zealand was developed from the user’s standpoint for the purpose of using it for international comparison. It had outstanding portability and operability at that time. Although the laser never became a product in New Zealand, I think it is essential to carry out the universalization research from the user’s standpoint to achieve successful product realization. I don’t know so many examples where universalization research was carried out from the user’s standpoint for a device with highly specialized purpose such as the iodine stabilized He-Ne laser. However, product realizations for more general devices (such as the mirror holder) have been done at national standards laboratories, and these have superior performances compared to the conventional products from manufacturers.