Beat frequency measurement of the stabilized He-Ne laser 633 nm calibration in SNSU-BSN

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Abstract. In the metrology area, typical stabilized lasers are used as length primary standard. KIM-1, i.e. the iodine stabilized He-Ne laser in National Measurement Standards Laboratory-National Standardization Agency of Indonesia (SNSU-BSN) has been traceable to SI through CCL-K11 inter-laboratory comparison. The result was suitable for KIM-1 to be used as the length primary standard in SNSU-BSN. Beat frequency measurement has been applied in the optical frequency and wavelength calibration system for stabilized He-Ne laser 633 nm using KIM-1 as a reference standard. In the calibration replica, a dual-frequency mode (Agilent 5519B) took a role as DUT laser, which emits a pair of beams with a central wavelength of 632.991 354 nm in the vacuum with frequency difference 3.4 to 4.0 MHz and ±0.02 ppm stability for a typical lifetime. As a measurement result, the beat frequencies of the 1st and 2nd polarized beam of Agilent 5519B against KIM-1 are (121.33±0.06) MHz and (118.59±0.06) MHz.

1. Introduction

As a device that emits light with typical property, i.e. directional, coherence, high intensity and monochromatic, lasers became widely used in various areas and applications, e.g. astronomy field, telecommunication, meteorology, medical, biology, renewal energy, information technology and metrology [1].

In the metrology area, typically stabilized lasers are used as length primary standard. Based on 17th Conférence Généralé des Poids et Mesures, CGPM in 1983, definition of meter as unit of length is the length of the path travelled by light in vacuum during a time interval of 1/299 792 458 of second. It can be realized by using frequency stabilized laser. Comité International des Poids et Mesures, CIPM composed recommendations for the practical realization of meter definition. The recommendations were drawn up based on the technique of measurement and improvement in the laser stabilization.

An iodine stabilized He Ne laser is one of the CIPM recommended stabilized lasers with relative uncertainty up to 2.1×10⁻¹¹[2]. Molecular cell of iodine is installed in the laser cavity to utilized the
hyperfine lines of the R(127) 11-5 transition in $^{127}$I$_2$ for stabilizing the laser frequency [3]. CIPM declare that the frequency and wavelength of the He-Ne laser stabilized by using iodine cell at $^f$ transition absorption line as frequency and wavelength reference. The iodine-stabilized He-Ne laser in Optical Frequency and Wavelength Laboratory, National Measurement Standards (SNSU-BSN, formerly RCM-LIPI) that called KIM-1 has previously involved in CCL-K11 inter-laboratory comparison (ILC) in 2014. The result was suitable for KIM-1 to be used as the length primary standard in SNSU-BSN [4].

In order to disseminate reference value of KIM-1, it is substantial to establish a stabilized He Ne laser calibration system that can be traced back to SI unit of length through KIM-1. The optical frequency and wavelength of the laser are two physical parameters which can be measured and calibrated [5]. The wavelength of laser can be measured directly using optical wavelength meter. Still, there is limitation of measurement capability due to resolution, accuracy and instability [6]. Beat frequency measurement is a method that can be applied in the calibration system of stabilized He-Ne laser by using KIM-1 as reference standard.

In this paper, we report the study and establishing the beat frequency measurement method used in an optical wavelength calibration system for stabilized He-Ne laser in SNSU-BSN.

2. Beat Frequency Measurement

In principle, beat frequency measurement in the optical wavelength calibration is frequency comparison between reference laser and unknown laser as device under test. Comparison system in the beat frequency measurement can be figure out as scheme in Figure 1.

![Figure 1](image)

**Figure 1.** The comparison of two laser frequencies as a basic principle of the beat frequency measurement in the laser wavelength calibration.

Based on the comparator, frequency of the unknown laser is obtained by formula:

$$f_{\text{UUT}} = f_{\text{STD}} - \Delta f \quad (1)$$

In practice, photodetector is used as one of the comparator components in beat frequency measurement of the optical wavelength calibration. It is equivalent with radio frequency mixer in optical domain. The oscillation of the electric field converted into an electrical signal that proportional to the square of the incident electric field. In case of two oscillating fields from the standard laser and DUT laser, RF signal intensity, generated by photodetector can be expressed as:

$$I = \left| E_{\text{std}} + E_{\text{UUT}} \right|^2 = \left( E_{\text{std}}^2 + E_{\text{UUT}}^2 \right)^2 + 2E_{\text{std}}E_{\text{UUT}}$$

where:

$$E_{\text{std}} = E_{01}\cos(\omega_1t)$$

$$E_{\text{UUT}} = E_{02}\cos(\omega_2t)$$

$$I = \left( E_{\text{std}}^2 + E_{\text{UUT}}^2 \right)^2 + 2E_{\text{std}}E_{\text{UUT}} \quad (2)$$
$E_{01}$ and $E_{02}$ are the amplitudes of the electric fields the standard laser beam and DUT laser beam with frequency $\omega_1$ and $\omega_2$, respectively. First term in Eq. (2) is continuous term and second term is oscillating term that can be obtained as:

$$I_{osc} = 2E_{01}E_{02} \cos(\omega_1 t) \cos(\omega_2 t)$$

$$I_{osc} = E_{01}E_{02} \left\{ \cos[(\omega_1 + \omega_2)t] + \cos[(\omega_1 - \omega_2)t] \right\}$$

(3)

Frequency of red He-Ne laser is in the range 473 THz. However, bandwidth of photodetector is in some GHz. The standard laser and DUT laser should be separated by only some GHz. Due to the limitation of photodetector bandwidth, the first term in Eq. (3), i.e. the higher frequency term could not be detected. Only the lower frequency term, i.e. second term can be detected and observed. In this term, $|\omega_1 - \omega_2|$ is corresponds to the beat frequency of the standard laser and DUT laser that expressed as $\Delta \omega$.

3. KIM-1 as length primary standard in SNSU-BSN

The optical frequency of KIM-1, Neoark 92SI iodine stabilized He-Ne laser of SNSU-BSN has been verified through CCL-KI11 key comparison. Beat frequency measurement was used as a method in comparison of KIM-1 and NIMT-1 (iodine stabilized He-Ne laser of National Institute of Metrology Thailand) where held in NIMT Thailand, July 28th–August 11th, 2014. It was obtained $2.0 \times 10^{-11}$ as degree of equivalence (Δf) of KIM-1 with expanded uncertainty (u) $6.3 \times 10^{-11}$. Based on the result, KIM-1 is opportune as length primary standard [4].

4. Experiment of the Beat Frequency Measurement in SNSU-BSN

The experiment on beat frequency measurement for stabilized He-Ne laser calibration was conducted in the Optical Frequency Laboratory of SNSU-BSN. In the calibration replica, laser head Agilent 5519B took a role as device under test of stabilized He-Ne laser.

After preheated and locked on f absorption line by manual frequency locking to suppress frequency noises, the reference stabilized He-Ne laser could emit laser with a more precise wavelength [7]. KIM-1 applies the radiation of He-Ne laser with internal iodine cell using third harmonic detection technique, emitting laser beam at a wavelength of 632.991 212 57 nm with a frequency of 473.612 353 613 THz and relative expanded uncertainty of $6.3 \times 10^{-11}$[4][2].

By Wollaston Prism, unpolarized laser beam of DUT was split into two linear polarized laser beams. Each polarized laser beam of DUT was delivered and optically interfered with reference beam of KIM-1 at beam splitter, alternately. Then, focusing to sensor on photodetector by objective lens. The beat signal of polarized beam of DUT and KIM-1 was detected by photodetector (Thorlabs PDA10A) which sent signal to frequency counter (Agilent 53132A) to measure the frequency difference. The frequency counter is traceable to 10 MHz of National Frequency Standard (NaFS) Cesium Atomic Clock HP5071A.

The spectral accuracy and signal-to-noise ratio of the beat signal were monitored by digital oscilloscope (Agilent-DSO6052A) in FFT mode. Figure 2 show the diagrammatical setup of the beat frequency measurement system. In order to reach the maximum beat signal, $\frac{\lambda}{2}$ plate used to match polarization of two beams. The beat frequency gathered once every second by automation program based on C++ while the counter was continuously performing processing of $10^5$ measurement data.
5. Result and Discussion

In the experiment, the DUT laser was a dual-mode laser (Agilent 5519B), which emit a pair of beams with central wavelength of $\lambda = 632.991354$ nm in vacuum, frequency difference 3.4 to 4.0 MHz and $\pm 0.02$ ppm stability for typical lifetime [8]. In order to reach a single-mode laser (polarized), beam of Agilent 5519B was aligned pass-through Wollaston prism. The result of the beat frequency signals observation of each polarized beam and KIM-1 shown in Figure 3. For the 1st polarized beam against KIM-1 ($\Delta f_1$), beat signal is larger than center frequency 121 MHz that set in FFT mode of the oscilloscope, show in Figure 3 (a). However, in case of 2nd polarized beam against KIM-1, beat frequency less than 121 MHz ($\Delta f_2$), show in Figure 3 (b). In order to reach maximum beat signals ($\geq 40$ dB), single mode beam of KIM-1 was aligned and adjusted by $\frac{1}{2}$ wave plate to be match with polarized beam of Agilent 5519B. As the measurement result, a frequency difference for each polarized beam of Agilent 5519B against single-mode beam of KIM-1 are show in Figure 4.

Figure 2. Scheme of the configuration setup for beat frequency measurement in SNSU–BSN.

Figure 3. Beat frequency signals of: a) 1st polarized beam of Agilent 5519B and KIM-1 ($\Delta f_1$); b) 2nd polarized beam of Agilent 5519B and KIM-1 ($\Delta f_2$).
Based on the result measurement result, the beat frequency of both comparisons are shown relatively stable with an average value of 121.332 014 MHz and 118.588 376 MHz, respectively for $\Delta f_1$ and $\Delta f_2$. The type A and type B evaluations were calculated to determine the uncertainty of the measurement [9].

The formula of type A uncertainty for standard uncertainty that called $u_{rep}$ is determined by formula

$$u_A = \frac{s}{\sqrt{n}}$$

with $s$ is standard deviation and $n$ is number of measurement. So, the type A uncertainties are 0.000 988 MHz and 0.000 712 MHz.

The type B uncertainty sources mainly from the meaning devices used during the measurement. The relative uncertainty of KIM-1 equal to $6.3 \times 10^{-11}$ is obtained from CCL-K11 key comparison of optical frequency/wavelength standards [4]. The relative uncertainty of NaFS as reference frequency of the frequency counter Agilent 53132A is calculated from UTC uncertainty, UTC-UTC(IDN) Link uncertainty, UTC(IDN) uncertainty and stability of NaFS from Circular T, equal to $8.2 \times 10^{-12}$. NaFS was distributed by means of distribution amplifier. Therefore, it is necessary to give considerations to incremental uncertainty derived from insertion of distribution amplifier. SNSU-BSN used a distribution amplifier with maximum of variation temperature 6°C and temperature coefficient 10 ps/degree, thus:

$$u_{(DA)} = \left( \frac{(\text{Temp Coeff})(\text{Temp Variation})}{\text{Variation Time}} \right)^{2}$$

with half day of variation time. So, the relative uncertainty of distribution amplifier equal to $1.4 \times 10^{-15}$. NaFS realized in atomic clock ensemble is provided to the measurement setup via 25 m coaxial cable with temperature coefficient 0.3 ps/m/degree. The relative uncertainty of the coaxial cable is determined by formula:

$$u_{(Cx)} = \left( \frac{(\text{Temp Coeff})(\text{Temp Variation})}{(\text{Cable Length})}\right)^{2}$$

and the result equal to $1.0 \times 10^{-15}$. The relative uncertainty 0.01 – 225 MHz frequency measurement by Agilent 53132A is equal to $1.3 \times 10^{-1}[10]$.

The identified uncertainties are tabulated in Table 1.

**Figure 4.** Beat frequency of the 1st and 2nd polarized beam of Agilent 5519B against single mode laser of KIM-1.
### Table 1. Uncertainties Tabulation of Beat Measurement Result

| Uncertainty Source                   | $\Delta f_1$ (MHz) | $\Delta f_2$ (MHz) |
|--------------------------------------|--------------------|--------------------|
| Type $A$, $u_{rep}$                  | 0.000 988          | 0.000 712          |
| Type $B$                             |                    |                    |
| Accuracy of KIM-1                    | 0.030 027          | 0.030 027          |
| Stability of NaFS                    | $9.70 \times 10^{-10}$ | $9.95 \times 10^{-10}$ |
| Distribution Amplifier               | $1.66 \times 10^{-13}$ | $1.70 \times 10^{-13}$ |
| Coaxial Cable                        | $1.19 \times 10^{-13}$ | $1.21 \times 10^{-13}$ |
| Error counter                        | $1.54 \times 10^{-9}$ | $1.58 \times 10^{-9}$ |
| Combine uncertainty                  | 0.030 043          | 0.030 035          |
| Expanded uncertainty ($k=2$)         | 0.060 086          | 0.060 070          |

As well as the level of beat signal higher than 40 dB with resolution bandwidth 300 MHz, the uncertainties from the optical component can be neglected. Table 1 shows that the expanded uncertainty of the six uncertainty sources for each beat frequency measurement are 0.060 086 MHz and 0.060 070 MHz by 95% confidence level with the value of coverage factor of $k=2$.

### 6. Conclusion

Beat frequency measurement has been established for the optical wavelength calibration system in SNSU-BSN. It is used to calibrate the optical frequency and wavelength of the stabilized He-Ne laser 633 nm. KIM-1, i.e. iodine stabilized He-Ne laser of SNSU-BSN that traceable to SI through CCL-K11 key comparison took a role as a reference standard. The measurement results show that the measurement set up is capable of measuring a frequency difference of the stabilized He-Ne laser and KIM-1 with sufficient stability and uncertainty ($\pm 0.05\%$). Analysis in the calculating of the DUT wavelength compare with KIM-1 is necessary as the upcoming research project.

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