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PRECISION FREQUENCY MEASUREMENT FOR He-Ne/I_2 LASER EMISSION WITH kHz- ACCURACY

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Abstract. *An accurate and precise frequency measurement of S.I. unit traceability is essential not only in the field of frequency metrology but also in many fundamental scientific researches, because an accurate and precise frequency will be able to provide stable reference frequency related quantities like length and time – the two important elements of physics. In this paper we present our frequency measurement for laser emission of the He-Ne/I_2 laser system at the kHz accuracy and precision level. A frequency beat measurement of the laser under test with the standard frequency from a frequency optical comb is conducted. The second measurement method based on the heterodyne technique, where the beats between the hyperfine frequencies of $^{127}I_2$ isotope at frequency of 474 THz and the testing He-Ne laser frequency recorded. The measurement data from different measurement techniques show a good consistency and therefore the given data are reliable.*

I. INTRODUCTION

A measurement of S.I. unit traceability is important not only in the field of metrology, but also in many fundamental scientific researches. A precise optical frequency of laser emission will be able to provide stable reference frequency related quantities like length and time – the two important elements of physics which is necessary in almost of physical experiments. Among several types of frequency stabilized lasers recommended by the International Committee for Weights and Measures (CIPM) [1], He-Ne/I_2 laser emitted at wavelength of 632.8 nm (or at frequency of about 474 THz) is the one which is well known for its proven technology in producing a reliably stable frequency [2, 3, 4]. In our experiment, a commercial laser of the type He-Ne/I_2 with its technology [5] in producing accurate and precise frequency was selected.

The highly precise frequency measurement technique which often used is the heterodyne beating technique (or in other words the beat technique). The beat technique idea is straightforward in which the beat between the two different frequencies will be observed. If accuracy and precision of one of those two optical frequencies are known, then the beat signal will be the reflection and gives the physical features of the other. In case the accuracy and precision of the two optical frequencies are at the same level then the precision of the beat will be the average reflection of both. The nicety of this technique is also staying in the sense that it takes an advance in the field of radio frequency technology, since the beat signal frequency is often among the range of less than a couple of GHz [6,7].

In this paper, we present the results of an accurate and precise frequency measurement of S.I. unit traceability for a commercial He-Ne/I_2 system. There are two frequency measurement methods used in our experiments. The first method is the absolute frequency measurement which based on the detection of the beat of the testing laser and the frequency optical comb [8]. The second one is the matrix measurement that has beats of the optical frequencies radiated from two He-Ne/I_2 systems with known accuracy and precision of one [9]. The measurement uncertainties for those methods are estimated and all the results from different approaches are put together for comparison. The obtained results are in agreement so prove the reliability of the data. Furthermore, the measured values are within the CIPM's permissible frequency range.

II. EXPERIMENT RESULTS AND DISCUSSION

II.1. Absolute frequency measurement

A beat measurement setup between a frequency optical comb and the laser under test (LUT) is depicted in Figure 1. The beat signal was firstly filtered, amplified then frequency counted. The frequency counter is made by Agilent, model 53132A [10] and the RF signal filters of connector type are produced by Mini-Circuits® [11]. All the radio frequency synthesizers and frequency counter were referenced to the 10 MHz output of a hydrogen maser linked to the time scale of Coordinated Universal Time (UTC) of the Korea Research Institute of Standards and Science (KRISS) [12].

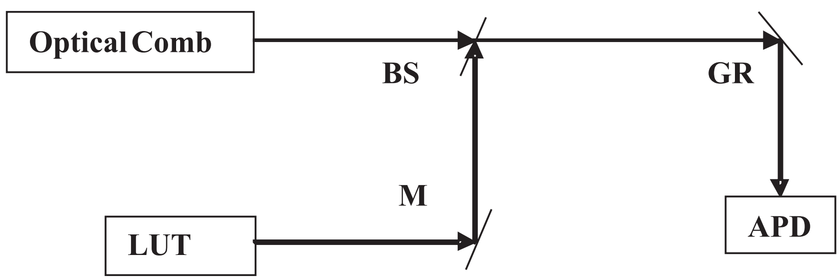

Fig. 1. Experimental setup for absolute frequency measurement (GR: grating, M: mirror, APD: avalanche photodiode, BS: beam splitter).

The working parameters such as optical power (P), iodine cell temperature (T) and frequency modulation (M) and the measured absolute optical frequency of the LUT are given in Table 1 where the hyper-fine component f (thereafter will be called f - component for short) was measured in the ambient with the temperature of 24.5±0.5^{o}C and relative humidity of 45.5±0.5%RH. These conditions of environment are always kept during the experiments. The data show that the offset is of 1.63 kHz at the working conditions P = 80μW, T = 14.98 ^{o}C and M = 5.9 MHz. The measured frequency of LUT at laser power in the range of 70-135μW are still in the acceptable range of 473 612 353.604±0.012 MHz by the recommendation of CIPM's standard frequency. We obtained the average beat frequency of 63.6056 MHz and the maximum standard deviation is of 3.52 kHz in experiment. The typical signal-noise ratios (SNR) of beats were more than 25 dB in 300 kHz bandwidth.

Table 1. Absolute hyper fine f - component measurement

P(μW) T(^{o}C) M(MHz)	Absolute frequency (MHz)
80 14.98 5.9	473 612 353.605 63
70 14.98 5.9	473 612 353.604 57
135 15.00 6.0	473 612 353.599 80

The measured long term relative Allan deviation of the optical frequency is given in Figure 2 showing the stability of the laser frequency in the order of 10^{-11} or kHz – precision level. The black dots are the experimental data where the error bars are the deviations to the mean values. The solid line is fitted by the formula in [6] for the white noise of optical frequency.

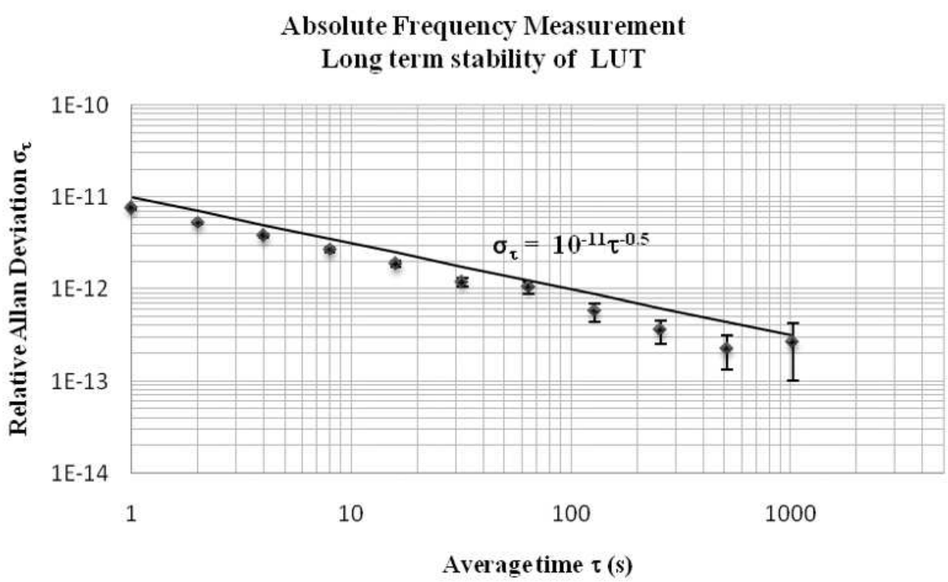

Fig. 2. Long term stability of LUT measured by absolute frequency method

The uncertainty budget for the absolute frequency measurement for the LUT is given in Table 2, where x_i is the influencing factors that affect the precision of the measurement, u (x_i) is the standard uncertainty of the factor x_i and c_i is the sensitivity coefficient. From this data table, the combined uncertainty u_c is estimated equal to 1.1 KHz at the expansion coefficient k=1 by Evaluation of Measurement Data - Guide to the Expression of Uncertainty in Measurement (GUM) [13]. This uncertainty is comparative to the ones have been reported in [14]. The calculated value of difference f – f components of LUT and reference laser is of 6 kHz.

Table 2. Uncertainty budget for absolute frequency measurement.

Influence factor	Value	Uncertainty	Sensitivity coefficient	Estimated. uncertainty (KHz)	%
	x_i	u(x_i)	c_i		
Laser power	80.000 (μW)	2.4(μW)	-0.106 (KHz/μW)	0.25	5
Modulation width	5.900 (MHz)	0.05 (MHz)	-8.39 (KHz/MHz)	0.42	14
Temperature	14.98 (ºC)	0.05 (ºC)	-11.747 (KHz/ºC)	0.59	28
Electronic offset	0.00 (mV)	0.50 (mV)	1.59 (KHz/mV)	0.80	51
Repeated measurement	63.606 (KHz)	0.11 (KHz)	1.0 (KHz/KHz)	0.11	1
Hydrogen maser	0.00 (KHz)	0.10 (KHz)	1.0 (KHz/KHz)	0.10	1

II.2. Matrix measurement

In our matrix measurement, an AOM double-pass setup was used. Since the frequency offset of the AOM just is of 40MHz, then there are still a lot of noises which influence the signal quality. However, the double pass scheme can separate all peaks a gap of 80MHz, therefore the signal quality is better improved. The matrix measurement setup is given in Figure 3 where the same frequency counter like the one mentioned above is used.

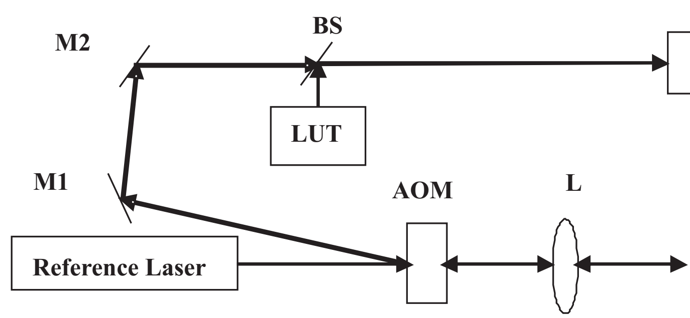

Fig. 3. AOM double pass setup for matrix measurement (AOM: acousto-optic modulator, L: lens, M/M1/M2: mirror, BS: beam splitter, APD: avalanche photodiode).

Table 3 shows the beat values obtained from a matrix measurement. From this table, the average frequency difference between f – f component could be obtained and equal to 5.6 kHz. So compare to this result and the one obtained in the absolute frequency method, it is seen that the difference is of 0.4 kHz.

The uncertainty budget for matrix measurement is given in Table 4. The combined uncertainty is u_c=1.2 kHz. The difference of the measured frequency from both methods is smaller than the uncertainty. The results and the discussion mentioned above are

Table 3. Beats (in MHz) from matrix measurement between LUT and reference laser.

	j	i	h	g	f	e	d
J		21.5717	43.511	147.264	160.4621	173.8258	186.6909
I	-21.562767		21.9426	125.6963	138.8947	152.2587	165.1234
H	-43.4993	-21.9336		103.7586	116.957	130.321	143.1855
G	-147.2492	-125.645	-103.743		13.2091	26.5727	39.4359
F	-160.449	-138.885	-116.945	-13.191		13.3703	26.2353
E	-173.8137	-152.248	-130.31	-26.5554	-13.3573		12.871
D	-186.6831	-165.119	-143.18	-39.4262	-26.2279	-12.8632	

Table 4. Uncertainty budget for matrix measurement.

Influence factor	Value	Uncertainty	Sensitivity coefficient	Estimated uncertainty (KHz)	%
	x_i	u(x_i)	c_i		
Laser power	80.000 (μW)	2.4 (μW)	-0.106 (KHz/μW)	0.25	5
Modulation width	5.900 (MHz)	0.05 (MHz)	-8.39 (KHz/MHz)	0.42	12
Temperature	14.980 (ºC)	0.05 (ºC)	-11.747 (KHz/ºC)	0.59	24
Electronic offset	0.00 (mV)	0.50 (mV)	1.59 (KHz/mV)	0.80	44
Repeated measurement	5.6 (KHz)	0.46 (KHz)	1.0 (KHz/KHz)	0.46	15

all comparative to the measurements reported and updated continuously in [14] by the International Bureau of Measurement and Weight (BIPM).

III. CONCLUSION

The measured optical frequency values by the matrix and the absolute frequency methods in the same working conditions resulted in a frequency difference of 0.4 kHz. He-Ne/I_2 lasing frequency measured by the absolute frequency method using the optical frequency comb was of 473 612 353.604±0.012MHz as recommended by the CIPM. The measurement uncertainties of the optical frequency values were estimated to be of 1.1 kHz and of 1.2 kHz for the absolute frequency and matrix measurement methods, respectively. The measured relative Allan deviation shows a relative value less than of 10^{-11} (or a couple of kHz). The consistency between the results obtained from both methods and the Allan deviation confirm the accuracy and the precision of the data at level of few kHz. Our results are comparative to the similar experimental ones in the continuously updated database of BIPM.

IV. ACKNOWLEDGEMENT

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