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Development of the optical vacuum standard system in KRISS

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***Abstract* – Recently, 'a new realization of the Pascal' by using photon technology showed comparable results in terms of performance compared to the existing primary standard based on a mercury manometer. In this study, we describe KRISS optical vacuum standard system uses a 633 nm He-Ne laser, specially made by KRISS, as a light source, and a double channeled Fabry-Perot (FP) cavity made from ZERODUR. Hardware construction for KRISS optical pressure standard system has been completed. Currently, as the first step, it is aimed at calculating the pressure according to the frequency in the pressure range of 1 Pa to 10 kPa using nitrogen gas. Using the measured beating frequency, we determined the internal pressure in the cavity considering the refractive index virial coefficients (A_R, B_R and C_R) and density virial coefficients (A_p, B_p and C_p), the Boltzmann constant k_B, and the thermodynamic temperature. The uncertainty is currently in evaluation taking into account the uncertainty factor.**

I. INTRODUCTION

For the past 400 years, the representative vacuum standard in the low vacuum field has been a mercury manometer. However, since the use of mercury in general industry is scheduled to be banned due to recent international agreements such as the European Union, USA, and United Nations Environmental Program, a new primary standard that does not use mercury is required in the low vacuum field. Accordingly, there have been many researches to re-define the pressure [1]. One of these studies is a method of calculating the pressure by measuring the refractive index. The refractive index is related to the density of the medium, and if the density of the medium can be calculated, the pressure can be calculated using Boltzmann's constant and the gas equation of state [1]. Current research in this area shows some progress in terms of performance when compared to existing primary standards based on mercury manometers. The new low-vacuum standard based on the optical method has improved resolution, a faster detection response time and the wider covering pressure range compared to conventional mercury manometers. And more advanced technology has been achieved in terms of reproducibility and hysteresis [2].

In this study, we describe KRISS photonic pressure standard system uses a 633 nm He-Ne laser, specially made by KRISS, as a light source, and a 15-cm-long Fabry-Perot (FP) cavity made from ZERODUR with a 5 cm-by-5 cm cross-section for precise vacuum pressure measurements that was developed as a mercury-free standard.

II. EXPERIMENTAL SET-UP

The KRISS system used a 633 nm single-mode polarization He-Ne laser as a light source made by KRISS and modulated the light to a FP cavity using AOM and EOM. The difference between the frequency of the laser and the resonance frequency of the FP cavity was continuously measured using the Pound-Drever-Hall (PDH) method to measure the change in the frequency of the laser according to the pressure [3].

A cavity to be used was designed through optical analysis. Considering the wavelength of the He-Ne laser used as the light source, quantum number, FSR, pressure range to be realized, and the range of single mode implementation (RSMO), The length of the cavity was designed to be 150 mm considering the wavelength (633 nm) of the He-Ne laser used as a light source, the pressure range to be implemented, and the implementation range of a single mode. Considering the stability diagram (Fig. 1), the designed length of 150 mm appears to suitable for the cavity to work as a stable resonator [4].

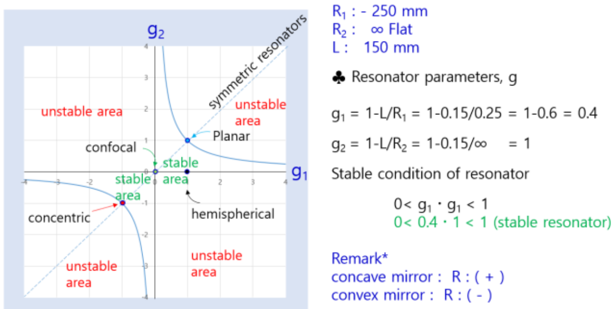

Fig. 1.Stability of resonator

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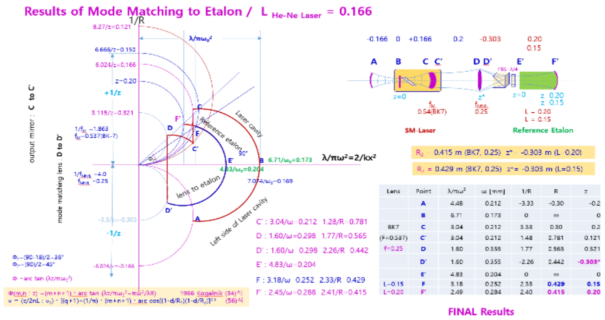

Fig. 2. Focal length and ridus of curvature of lens and mirror.

A mirror was attached to both ends of the cavity for reflection and resonance of the He-Ne laser. One mirror was a flat type and the other was a concave type. For accurate resonance in the cavity, the radius of curvature of the mirror to be attached was calculated using theoretical calculations and Gaussian beam charts (Fig. 2) [5]. A lens with a focal length of 250 mm and a concave mirror with a radius of curvature of 370 mm were designed. In addition, the finesse suitable for the mirror was calculated by considering the reflectance of each mirror. The higher the finesse, the better the optical performance, but if it is too high, it becomes sensitive to the environment such as external contamination, so it is better to design it to have the minimum value considering the reflectance. In this study, it was designed to have a value of 1500. The mirror attached to both ends was coated to reflect more than 99.7% of the He-Ne laser used, and the cavity was attached using the optical contact method without using any other epoxy. One of the important factors determining the pressure in the optical vacuum standard is the internal temperature of the chamber. For this purpose, a constant temperature vacuum chamber was manufactured. A constant temperature chamber was fabricated using copper. The size of the chamber is designed to be 5 mm larger in height, width, and depth based on the size of the cavity that can be accommodated inside. Additionally, it is equipped with one port each for creating a vacuum at the center,

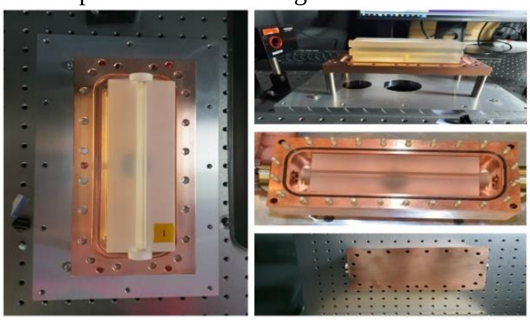

Fig. 3. A cavity and a vacuum chamber

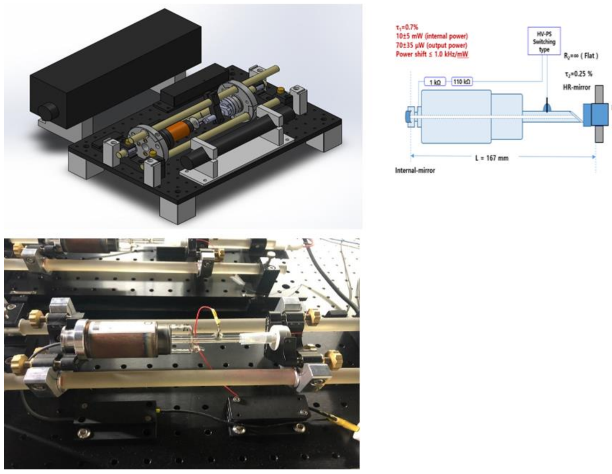

Fig. 4. A single-mode plorization laser

adjusting pressure, and measuring temperature., and a port for measuring temperature (Fig. 3). In addition, four windows were made on the outside so that the laser light source could pass through. In this case, the window was coated to pass the light source 100%, and it was tilted about 5' to prevent interference from a small amount of light reflected from the inner cavity lens. The temperature stability was improved by manufacturing a double chamber externally using aluminum, and the effect of temperature change according to the external environment was reduced by additionally manufacturing a triple chamber using an insulator.

A single mode laser was designed using the laser tube used for iodine stabilization (Fig. 4). In particular, Zerodur was used to minimize the displacement between both mirrors. In the case of a commercially used single-mode He-Ne laser, vertical polarization and horizontal polarization occur alternately, resulting in a slight change in frequency. In this study, the bluest angle was adjusted to have a single polarization regardless of the quantum number. Also, a PZT module (3 mm/V) was used for frequency modulation. In order to improve the long-term frequency stability, a method of changing the frequency by directly attaching the laser mirror to the PZT was used, and it was confirmed that the control stability was within ± 1 MHz during long-term use.

A measurement system using a dual channel FP cavity, was built. A precise lock-in amp was used to acquire the error signal, and a 19 MHz side band was confirmed from EOM phase modulation. In the case of the mode matching lens, resonance was performed using a focal length of 400 mm, and the resonance state was confirmed using a beam profiler, and a high-speed servo controller was used for PID control. The frequency change can be automatically measured using Lab-view. The measurement system is shown in Fig.5, and the beat frequency was measured using an iodine-stabilized He-Ne laser as a reference standard.

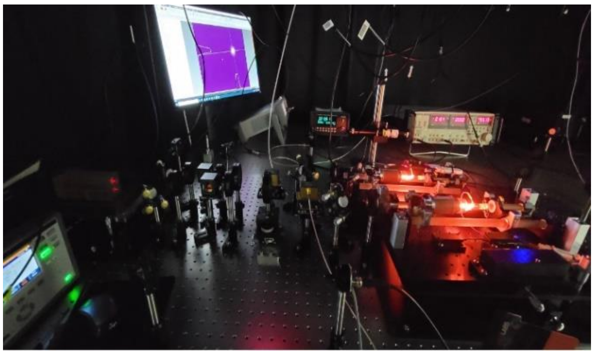

Fig. 5. A measurement system

III. RESULTS

It was found that the temperature inside the chamber had temperature stability within 5 mK during measurement when the triple chamber was used. As a result of measuring the beating frequency of the iodine stabilized laser and the manufactured laser, the distance moved in single mode was measured at approximately 890 MHz, which was similar to the design value.

The lower channel of the FP cavity channels was maintained in a vacuum state while the pressure channel on the upper side was resonated (locked) with the laser while changing the pressure with N_2 gas, and the frequency change according to the pressure change in the chamber was measured. After measuring the beat frequency by comparing the resonant frequency of each channel with the frequency of iodine-stabilized He-Ne laser as a standard, the final beat frequency was calculated by calculating the difference between each beat frequency.

The internal pressure P_{FP} of the pressure channel of the FP cavity is calculated by the following equations [6]

$$P_{FP} = \frac{1}{c_1 - d_m - d_r}\left(\frac{\Delta f}{\upsilon}\right) - \frac{c_2 - c_1 d_m}{(c_1 - d_m - d_r)^3}\left(\frac{\Delta f}{\upsilon}\right)^2 + \frac{2(c_2 - c_1 d_m)^2 - c_3(c_1 - d_m - d_r)}{(c_1 - d_m - d_r)^5}\left(\frac{\Delta f}{\upsilon}\right)^3 \quad (1)$$

where $\frac{\Delta f}{\upsilon}$ is the fractional change of the resonance frequency of the cavity, Δf is the change in the beating frequency of the initial and final states, is the resonance frequency, and d_m and d_r are the distortions (due to compression) for the pressurized and reference cavities, respectively. means paragraph. Each proportional constant is defined by the refractive index virial coefficients (A_R, B_R and C_R) and density virial coefficients (A_p, B_p and C_p), the Boltzmann constant k_B and the thermodynamic temperature T as follows [5]

$$c_1 = \frac{3}{2k_B T} A_R$$

$$c_2 = \frac{3}{8(k_B T)^2}(A_R^2 - 4A_R B_P + 4B_R)$$

$$c_3 = \frac{3}{16(k_B T)^3}(5A_R^3 - 4A_R^2 B_P + 16A_R B_P^2 + 4A_R B_R - 8A_R C_P + 8C_R) \quad (2)$$

Each proportional constant has a different value depending on the type of gas used to generate the pressure in the cavity, $\frac{\Delta f}{\upsilon}$ and d_m and d_r are different values depending on each FP cavity. Among them, $\frac{\Delta f}{\upsilon}$ is the value actually measured according to the given pressure change. As mentioned above, the resonance frequency of each channel is compared with the frequency of the standard iodine-stabilized He-Ne laser to measure the beating frequency, and then the difference between these beating frequencies is calculated to calculate the final beating frequency.

Fig. 6 shows the result of a comparison with a capacitance diaphragm gauge (CDG, maximum capacity of 133 kPa) calibrated using the force balanced piston gauge (FPG) in the range of 1 Pa to 10 kPa. As can be seen in the figure 6, the system shows a difference of up to 3% in the pressure range of 100 Pa to 10 kPa indicating that it was well matched within the uncertainty of the CDG (5%).

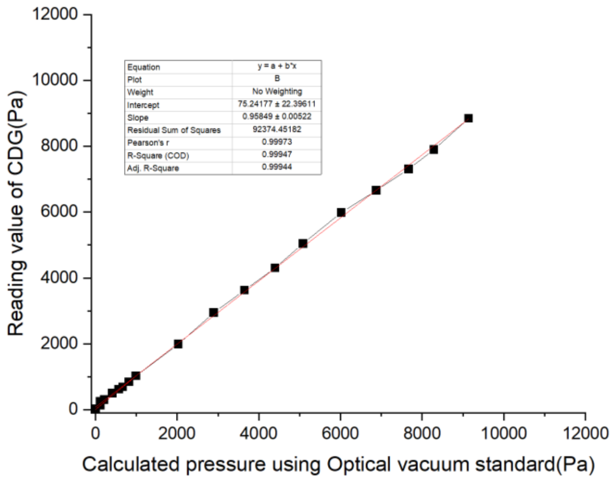

Fig. 6. A comparison with CDG

IV. CONCLUSIONS

Through this study, it was possible to establish the concept of a optical vacuum primary standard using refractive index. KRISS model was designed and a measurement system was established. In the future, it is planned to evaluate the standard pressure through frequency measurement and the uncerttainty of of the system will be also evaluated considering the factors used in eq. (1).

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