Evaluation of the blackbody radiation shift of an Yb optical lattice clock at KRISS

Myoung-Sun Heo, Huidong Kim, Dai-Hyuk Yu, Won-Kyu Lee and Chang Yong Park

Korea Research Institute of Standards and Science, Daejeon 34113, Republic of Korea

E-mail: cypark@kriss.re.kr

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Abstract
As optical clocks are improved to reach the frequency uncertainty below the $10^{-17}$ level, the frequency shift due to the blackbody radiation (BBR) has been one of the major systematic effects hindering further improvement. To evaluate the BBR shift of an Yb optical lattice clock at KRISS, we installed an in-vacuum BBR shield and made radiation thermometry using a black-coated-sphere thermal probe. After we quantitatively measured the conduction loss of the thermal probe and the effects of all the external radiation sources, we determined the temperature at the atom trap site with an uncertainty of 13 mK, which corresponds to an uncertainty of 0.22 mHz in the clock frequency (a fractional frequency of $4.2 \times 10^{-19}$). The total uncertainty of the BBR shift including the atomic response is $9.5 \times 10^{-19}$.

Keywords: optical clock, blackbody radiation shift, Yb optical lattice clock

1. Introduction

Stark shifts due to the blackbody radiation (BBR) in most optical clocks are at the 1 Hz level [1]. This shift is one of the significant effects contributing to the frequency uncertainty and also affects the long-term stability of optical clocks. The BBR shift of the clock transition ($\Delta \nu_{\text{BBR}}$) can be expressed as [2]:

$$
\Delta \nu_{\text{BBR}}(T_{\text{atom}}) = \Delta \nu_{\text{stat}} \left( \frac{T_{\text{atom}}}{T_0} \right)^4 + \Delta \nu_{\text{dyn}} \left( \frac{T_{\text{atom}}}{T_0} \right)^6 + O \left( \frac{T_{\text{atom}}}{T_0} \right)^8.
$$

(1)

where $T_{\text{atom}}$ is the temperature at the atom trap site, $\Delta \nu_{\text{stat}}$ is the coefficient related to the differential static polarizability between the clock states, $\Delta \nu_{\text{dyn}}$ is the coefficient associated with the small dynamic correction, and $T_0 = 300$ K. Since $\Delta \nu_{\text{stat}}$ is well known [2–4], the uncertainty in the BBR shift is mainly determined by the uncertainties of $T_{\text{atom}}$ and $\Delta \nu_{\text{dyn}}$. Much effort has been made for more accurate estimation of $T_{\text{atom}}$ during the last decade. The BBR shift uncertainty of $10^{-17}$ to mid $10^{-18}$ level was attained by measuring the temperature distribution around the vacuum system and by estimating the BBR from the heat sources [5–10]. To further reduce the BBR shift uncertainty to a low $10^{-18}$ or $10^{-19}$ level, well-controlled thermal environments were required. For example, the clock operation in cryogenic environments could reduce the BBR shift and its uncertainty [11–13]. Another method was to install an in-vacuum thermal shield at room temperature for an isothermal environment, and the additional inhomogeneous heat sources were dealt with a finite-element (FE) radiation analysis using effective solid angles [2, 14, 15]. Also, there has been a method of measuring $T_{\text{atom}}$ directly using a thermal probe [16] (and additional FE analysis in [17]) in a well-controlled thermal environment. In case of ion clocks [18, 19], the FE analysis with validation...
using a thermal imaging camera could reduce the uncertainty to $10^{-18}$ level.

This paper describes the BBR shift evaluation of KRISS-Yb2, a newly developed Yb optical lattice clock at KRISS (Korea Research Institute of Standards and Science). We installed an in-vacuum thermal shield for homogeneous temperature distribution around the atoms. This thermal shield was similar to that used in [2] but was modified to have one side exposed in the air for more convenient temperature control. The temperature at the position of atoms was measured using a black-sphere thermal probe (BSTP). Using this thermal probe, we also obtained the effective solid angles of dominant heat sources experimentally. This approach enabled us to determine directly $T_{\text{atom}}$ without knowing exact values of geometric view factors and emissivities. The estimated uncertainty of $T_{\text{atom}}$ was 13 mK.

2. In-vacuum blackbody radiation shield

To evaluate the BBR shift accurately, we installed an in-vacuum BBR shield chamber made of copper inside a dodecagon titanium main chamber, as in figure 1. The outer rim of the BBR shield served as a gasket of the CF fitting on the main vacuum chamber, as in figure 1(a). The BBR shield chamber was composed of the body part and the cap part, and they were assembled together with titanium bolts. Active temperature control of the BBR shield was carried out using a pair of heater films on the side wall of the body part (red lines in figure 1(a), which was exposed in the air as depicted in figure 1(a). Its temperature was controlled to be slightly higher than the room temperature. Two identical heater films with the same amount of currents in the opposite direction were overlapped to minimize the magnetic field induced by the currents. There were six platinum resistance thermometers (PRTs) installed in three deep holes and three shallow holes on the air-side of the BBR shield chamber to monitor the temperature. These PRTs and the precision resistance meter (milliK, Isotech) were calibrated with an uncertainty of 12.5 mK by the temperature standard group at KRISS. The PRT at the center acted as a reference probe for active temperature stabilization. The inner surface of the BBR shield was black-coated with Ultrablack® of Acktar [20] (emissivity $> 0.98$ in the wavelength range 3 μm–10 μm) to reduce unwanted reflections. The QWP-mirror for retroreflection of cooling laser beams and the front window in figure 1(a) were indium-tin-oxide (ITO)-coated and will act as electrodes to generate an electric field for the evaluation of the DC Stark shift which may occur due to the unwanted patch charges. As seen in figure 1(b), four additional electrodes were installed on the cap.
Figure 2. (a) The in-vacuum black spherical thermal probe (BSTP). The BSTP was made of copper and has a hole for a PRT sensor head. The surface of the BSTP was black-coated with highly emissive material (Ultrablack®, Acktar), (b) picture of the installed PRT sensor (PT-111), (c) the BSTP was connected to the electrical feedthrough via four Manganin wires.

Figure 3. (a) Simplified geometry for the numerical simulation to investigate the effects of the geometry and the emissivity of the BSTP on the conductive heat loss. The axis origin is at the center of the spheres. The unit of length is mm. (b) The temperature variation along the wire $T_{\text{wire}}(z)$ was calculated with two different emissivity values of the wire ($\varepsilon_{\text{wire}} = 0.9$ for open squares and $\varepsilon_{\text{wire}} = 0$ for filled squares) to study the effect of the surface heat radiation on the wire. The BSTP was located at 0 on the $z$-axis.

part of the BBR shield for electric fields along the other two orthogonal axes.

The in-vacuum temperature-stabilized BBR shield can ensure a homogeneous thermal environment. For the clock operation, we needed several optical and open accesses. The body part of the BBR shield has twelve 16 mm-diameter apertures. As seen in figure 1(c), two of them along the horizontal axis were open for the atomic beam and the Zeeman slowing laser, and they were extended by the 35 mm-long copper tubes with 8 mm inner diameter to reduce the BBR through the open apertures. Two apertures along the vertical axis were closed with copper plates with 4 mm-diameter holes at the center for the access of the lattice laser (the red dashed line in figure 1(c)). The blue dashed lines in figure 1(c) represent the magneto-optical trap (MOT) lasers, each of which transmits through a 4.5 mm-thick BK7 window and retroreflected on the QWP-mirror. Copper plates covered the rear sides of these two QWP-mirrors to block the external radiation. One aperture covered by a 4.5 mm-thick BK7 window was used for the viewport of CCD camera and another one covered by 10 mm-thick lens with the focal length of 35 mm for a fluorescence detection. The remaining two apertures were blocked by copper plates, one of which had an electrical feedthrough connected to the electrode on the QWP-mirror. The cap part of the BBR shield has one 16 mm-diameter aperture covered by a BK7 window. All the windows and a lens were made of BK7 glass to suppress the transmission of the external radiation above 3 μm, and their surfaces were coated with ITO material to drain out electrical charges from their surfaces and generate the electric field.
Figure 4. (a) The effect of the emissivity $\varepsilon_{\text{BSTP}}$ of the BSTP and the wire emissivity $\varepsilon_{\text{wire}}$ on $T_{\text{BSTP}}$ with the radius $r_{\text{BSTP}}$ of the BSTP fixed at 5 mm. (b) The effect of $r_{\text{BSTP}}$ and $\varepsilon_{\text{wire}}$ on $T_{\text{BSTP}}$ with $\varepsilon_{\text{BSTP}} = 0.9$. Insets are detailed plots near 0 mK. All the curves on data points in the plots are drawn as a guide to the eye.

In summary, the BBR shield chamber has four apertures open for the entrance of atoms and the lattice laser beam, and five apertures (four on the side and one on the top) closed with BK7 optics. These apertures on the BBR shield can introduce additional thermal radiation different from the temperature of the BBR shield. Also the low thermal conductivity of BK7 windows induces the temperature inhomogeneity of the BBR shield chamber. Those effects were investigated using the BSTP described in the following.

### 3. In-vacuum black-sphere thermal probe

Although the BBR shield drastically reduces the thermal environment’s inhomogeneity, we cannot neglect the effects of external heat radiation sources and the residual inhomogeneity of the temperature and emissivity. To determine $T_{\text{atom}}$ exactly, one usually needs to know exact values given for geometric view factors and emissivity of all the external heat sources, which is sometimes not feasible. Therefore, we decided to directly measure the temperature at the atom trap site using an in-vacuum black-coated spherical thermal probe (BSTP) and estimated the effective solid angles of dominant heat sources.

We will discuss the design considerations of the BSTP, such as geometry and emissivity. Then we will describe its systematic errors.

The BSTP is a black-coated (Ultrablack®, Actkar) 10 mm-diameter copper sphere with a PRT sensor (PT-111, Lakeshore) as in figure 2. The PRT sensor head (1.8 mm diameter and 5.0 mm length) was glued in the hole of the copper sphere using a thermally conductive epoxy. The resistance of the PRT was measured using four 200 mm-long 0.1 mm-diameter enameled Manganin® leads connected to the electrical feedthroughs on the top of the main chamber using the four-point probe method. The BSTP was hung by gravity and was located at the center of the BBR shield. Those Manganin wires are electrically conductive and thermally insulating with low thermal conductivity of 22 W m$^{-1}$ K$^{-1}$ at 300 K, which is about half the value of a widely used phosphor bronze wire.

We found that the resistance value of the PRT sensor changed after gluing it inside the copper sphere. Thus, the PRT sensor installed in the copper sphere was altogether calibrated by the temperature standard group at KRISS with an uncertainty of 12.5 mK. Repeatability and self-heating of the PRT in vacuum were measured to be 2 mK and 5.5 mK, respectively.

Due to the conduction loss through the Manganin wires, the temperature, $T_{\text{BSTP}}$, measured by the BSTP can be different from $T_{\text{atom}}$. Thus, we investigated the dependence of the temperature, especially the conduction loss, on the size and the emissivity of the BSTP by the numerical simulation under simplified thermal environments, as seen in figure 3(a). The outer and inner concentric shells corresponded to the main vacuum chamber and the BBR shield, respectively, and their radii were 100 mm and 50 mm, respectively. The temperature $T_{\text{VC}}$ on the outer spherical shell was fixed at 20 °C, and the temperature $T_{\text{BBRC}}$ on the inner shell is at 30 °C. A Manganin wire connected the copper sphere with the outer shell without touching the inner shell through the 4 mm-diameter hole.
Figure 6. Schematic diagram of the whole vacuum system of the Yb optical lattice clock at KRISS. Calibrated PRTs were installed in the positions depicted by red stars and K-type thermocouple sensors by blue stars. Another PRT, not displayed here, was installed on the front of the main chamber. The heat conductions from the Zeeman slower (ZS) and the Zeeman slower laser input window (ZSLW) were reduced using bellows. The thermal radiations from the atom oven and ZSLW were blocked using shutters. AH coil: anti-Helmholtz coil.

Table 1. Experimental conditions and determined normalized solid angles. Numbers not parenthesized in the ‘Temperature range’ column were ranges for data set to obtain solid angles, and those parenthesized were for verification data set.

| Heat sources | Temperature range/°C | Normalized effective solid angle $\Omega_{\text{eff}}$ |
|--------------|----------------------|-----------------------------------------------|
| BBR shield ($T_{\text{BBR}}$) | 22.0–24.0 (22.0–24.0) | 0.97814(15) |
| Right nipple ($T_{\text{nipple}}$) | 20.9–21.8 (21.3–21.9) | 0.00229(85) |
| Main chamber ($T_{\text{main}}$) | 21.3–21.9 (21.2–22.7) | 0.01911(78) |
| Zeeman slower ($T_{\text{ZS}}$) | 21.2–33.9 (21.5–34.2) | 0.000116(26) |
| Zeeman slower laser input window ($T_{\text{ZSLW}}$) | 20–200 (20–200) | 0.000041(1) |
| Atom oven | 20–400 (room temperature) | Suppressed |
| Total | 21.9–23.9 (22.0–24.0) | 0.9997(12) |

*Varied by the control of the stabilized temperature of the BBR shield.

*Varied by anti-Helmholtz coil current, cooling water temperature, and room temperature.

*Varied by anti-Helmholtz coil current, cooling water temperature, and room temperature.

*Varied by ZS coil current and room temperature.

There are two 10 mm-diameter apertures along the $y$-axis of the inner shell as in the BBR shield.

Figure 3(b) shows the calculated temperature $T_{\text{wire}}(z)$ along the wire. When we neglected the radiation from the wire surface by setting the emissivity zero, the temperature dropped linearly from the BSTP to the end of the wire at the outer sphere. But with the finite emissivity, the part inside the inner shield absorbed the heat radiation, and the temperature changed more slowly. This radiative absorption significantly reduced the conduction loss from the BSTP, which can be clearly seen in figures 4(a) and (b). Figures 4(a) and (b) shows the dependence of $T_{\text{BSTP}}$ against $T_{\text{BBRC}}$ on the emissivity and the radius of the BSTP, respectively, with different values of $\varepsilon_{\text{wire}}$. $T_{\text{BBRC}}$ without the wire corresponds to $T_{\text{atom}}$ (represented by black-filled squares in figures 4(a) and (b)). As shown in the insets, $T_{\text{atom}}$ differed from $T_{\text{BBRC}}$ due to the external radiation coming from the outer shell even without the conduction loss.

For a given value of $\varepsilon_{\text{wire}}$, $T_{\text{BSTP}}$ deviated more from $T_{\text{atom}}$ for smaller values of the emissivity $\varepsilon_{\text{BSTP}}$ or radius $r_{\text{BSTP}}$ of BSTP. As shown in figure 4(a), with $r_{\text{BSTP}} = 5$ mm and $\varepsilon_{\text{wire}} = 0.9$, the difference of $T_{\text{BSTP}}$ from $T_{\text{atom}}$ was smaller than 5 mK for $\varepsilon_{\text{BSTP}} > 0.8$. Also, for given $\varepsilon_{\text{BSTP}} = 0.9$ and $\varepsilon_{\text{wire}} = 0.9$, the difference of $T_{\text{BSTP}}$ from $T_{\text{atom}}$ is smaller than 5 mK for $r_{\text{BSTP}} > 4$ mm, as shown in inset of figure 4(b).

Although the larger values of $r_{\text{BSTP}}$, $\varepsilon_{\text{BSTP}}$ and $\varepsilon_{\text{wire}}$ are of help to make $T_{\text{BSTP}}$ be closer to $T_{\text{atom}}$, it should be noted that too big $r_{\text{BSTP}}$ will not well represent atoms at the trap site. Considering these aspects, we chose the BSTP with $\varepsilon_{\text{BSTP}} > 0.9$ and $r_{\text{BSTP}} = 5$ mm in our experiment. In this condition, the offset of $T_{\text{BSTP}}$ from $T_{\text{atom}}$ which can be thought as the black line, due to the conduction loss by wire was expected to be much smaller than the calibration accuracy of the BSTP, 12.5 mK.

Next, we experimentally verified the effect of the conduction loss of the BSTP. We changed the temperature $T_{\text{end}}$ at the
The difference between the estimated $T_{\text{atom}}$ from the equation (5) and $T_{\text{atom}}$ estimated from $T_{\text{BSTP}}$ for various experimental conditions. Twenty-nine data points depicted as open circles were used for the calculation of effective solid angles in table 1. Black circles were obtained from other sets of experimental conditions. We took 2 mK conservatively as an uncertainty in the prediction of $T_{\text{atom}}$.

4. Measurements of thermal radiations and uncertainty evaluation

The whole experimental setup is shown in figure 6 with the BSTP installed. The BSTP will be removed in the actual clock operation. Atoms can see external BBRs from various parts. In general, the temperature at atoms, $T_{\text{atom}}$, can be derived with

$$T_{\text{atom}} = \sum_i \Omega_i^{\text{eff}} T_i^a.$$  

$\Omega_i^{\text{eff}}$ is a normalized effective solid angle of a heat source $i$, satisfying $\sum_i \Omega_i^{\text{eff}} = 1$ and $T_i$ is its temperature. $\Omega_i^{\text{eff}}$ includes the effects of the geometric view factor and the emissivities of all the relevant parts. Dominant heat radiation (and therefore the largest $\Omega_i^{\text{eff}}$) were from the temperature-controlled BBR shield chamber whose temperature was set slightly higher than the main chamber by 1 K–3 K. In our experimental condition, temperature of each part of the main chamber was similar within 0.5 K and could be represented by the temperature of the main chamber, $T_{\text{main}}$, which is the average value of temperatures on the top, at the side, and at the front of the main chamber. The radiation from the main chamber has effects on BSTP in several ways. One is the direct radiations through open apertures of the BBR shield and transmitted radiation through BK7 optics on the BBR shield, which is significantly suppressed by BK7 glass. The other indirect effect is absorption and emission by BK7 optics on the BBR shield, which causes temperatures of BK7 optics lower than that of the BBR shield due to poor thermal conductivity of BK7 material and imperfect thermal contact with the BBR shield. All of these contribute to the effective solid angle of $T_{\text{main}}$. In addition, we considered the temperature $T_{\text{nipple}}$ of the nipple at the right of the main chamber separately because its radiation can be transferred directly through the open aperture of the BBR shield. It is noted that the conduction and radiation from the heated atom oven ($T = 673$ K) were suppressed with the bellow and the shutter [21] which is closed during the clock spectroscopy.

Because $T_{\text{atom}}$ can be estimated from the temperature of the BSTP using equation (3), we have

$$T_{\text{atom}}^a = (T_{\text{BSTP}} - \Delta T_{\text{self}} - \Delta T_{\text{conduction}})^a = \sum_i \Omega_i^{\text{eff}} T_i^a.$$  

$\Delta T_{\text{self}}$ is the self-heating offset, 5.5(2.0) mK, as described previously. To obtain $\Omega_i^{\text{eff}}$ we varied experimental conditions (stabilized temperature of the BBR shield chamber, anti-Helmholtz coil current, ZS duty cycle, cooling water temperature, etc) as described in table 1, and measured $T_i$ and $T_{\text{BSTP}}$ simultaneously and obtained 29 samples of distributed temperature (open circles in figure 7). From the multi-variable non-linear fit of these samples using equation (4), we obtained $\Omega_i^{\text{eff}}$ as in table 1. Normalized solid angles are given in table 1 and summed up close to 1, confirming that we did not omit significant heat sources.

Within the range given in table 1, the temperature at atoms can be estimated using the following equation,

$$T_{\text{atom}} = \sqrt{\Omega_{\text{BBR}}^{\text{eff}} T_{\text{BBR}}^{\text{eff}} + \Omega_{\text{nipple}}^{\text{eff}} T_{\text{nipple}}^{\text{eff}} + \Omega_{\text{main}}^{\text{eff}} T_{\text{main}}^{\text{eff}} + \Omega_{\text{ZS}}^{\text{eff}} T_{\text{ZS}}^{\text{eff}} + \Omega_{\text{BK7}}^{\text{eff}} T_{\text{BK7}}^{\text{eff}}}.$$  

The difference between $T_{\text{atom}}$ measured from $T_{\text{BSTP}}$ and the predicted values using equation (5) was 0.0 ± 2.0 mK as shown in figure 7 within the experimental condition in table 1.

The total uncertainty of the atomic temperature under normal operating conditions for the Yb optical lattice clock is given in table 2.
5. Conclusion

To evaluate the BBR shift of the Yb optical lattice clock (KRISS-Yb2), we adopted an in-vacuum BBR shield and radiation thermometry using a BSTP. We could obtain the BBR shift uncertainty is 9.5 × 10^{-19}, which implied that high-emissivity surface of the lead wires mitigated the conduction effect significantly, and this was in good agreement with the experimental observation. At the normal operating condition for the Yb optical lattice clock, we obtained the uncertainty of 13 mK, which corresponds to an uncertainty of 0.22 mHz in clock frequency, or 4.2 × 10^{-12} in terms of a fractional frequency. When we combine this with the contribution by the dynamic correction from the atomic response $\Delta v_{dyn}$ in equation (1) [2], the total BBR shift uncertainty is 9.5 × 10^{-19}. This will pave the way for Yb optical clock to reach the uncertainty of low 10^{-18} level.

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ORCID iDs

Huidong Kim https://orcid.org/0000-0002-1623-5520
Won-Kyu Lee https://orcid.org/0000-0002-2142-8343

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Table 2. Uncertainty of the atomic temperature ($T_{BBR} = 296.15$ K, $T_{amb} = 295.15$ K).

| Effects                  | Correction/mK | Uncertainty/mK |
|--------------------------|---------------|----------------|
| $T_{BSTP}$ calibration   | 0.0           | 12.5           |
| $T_{BSTP}$ wire loss     | 0.0           | 0.36           |
| $T_{BSTP}$ self-heating  | 0.0           | 2.0            |
| Model prediction from equation (5) | 0.0 | 2.0 |
| Total                    | 0.0           | 13             |