Manufacture of a hollow corner cube retroreflector for next generation of lunar laser ranging

Yun He\textsuperscript{1,2,3}, Qi Liu\textsuperscript{1,2}, Hui-Zong Duan\textsuperscript{1}, Jing-Jing He\textsuperscript{2,3}, Yuan-Ze Jiang\textsuperscript{1,2} and Hsien-Chi Yeh\textsuperscript{1}

\textsuperscript{1} TIANQIN Research Center for Gravitational Physics, School of Physics and Astronomy, Sun Yat-sen University, Zhuhai 519000, China
\textsuperscript{2} MOE Key Laboratory of Fundamental Quantities Measurement, School of Physics, Huazhong University of Science and Technology, Wuhan 430074, China; liuq239@mail.sysu.edu.cn
\textsuperscript{3} Key Laboratory of Gravitation and Quantum Physics of Hubei Province, School of Physics, Huazhong University of Science and Technology, Wuhan 430074, China

Received 2018 April 11; accepted 2018 May 27

Abstract Lunar laser ranging has made significant contributions to the study of gravitational physics and the Earth-Moon system. The best results for fundamental gravitational experiments have been achieved using lunar laser ranging data accumulated so far. However, corner cube retroreflector arrays placed on the Moon currently set a limit on the laser-ranging precision, which is approximately several centimeters for a single photon received. To achieve millimeter precision, next generation of lunar laser ranging using a single hollow retroreflector with a large aperture has been proposed. We developed a prototype hollow retroreflector with a 100-mm aperture using silicate bonding together with a new fabrication method. Dihedral angle offsets of $0.5''$, $0.8''$ and $1.9''$ were realized, which partly come close to meeting the requirements (offset of $0.6''$ for each dihedral angle) for lunar laser ranging. Fluctuation of the wavefront is approximately $1.038\lambda$ at 633 nm. A thermal cycle test ranging from $-40\degree C$ to $+75\degree C$ was carried out for 18.5 periods (approximately 5 d). After this test, the dihedral angle offsets were measured to be $0.39''$, $1.00''$ and $2.06''$. The results indicate the potential application of our method for manufacturing a hollow retroreflector with a large aperture to realize lunar laser ranging.

Key words: gravitation: instrumentation — miscellaneous: Moon

1 INTRODUCTION

Lunar laser ranging (LLR) utilizes a corner cube retroreflector (CCR) array as a cooperative target to measure the round-trip travel time of a laser pulse and determine the station-target distance. Over the past 50 years, five CCR arrays placed on the Moon by Apollo astronauts and Soviet Lunokhod rovers are still in use. Ranging precision has been improved from a few decimeters to the order of a centimeter, contributing to the study of the Earth-Moon system and gravity physics (such as test of the equivalence principle, time-rate-of-change of the gravitational constant $G$, geodetic precession and test of Newton's inverse-square law) (Murphy et al. 2004; Murphy 2013). However, to measure the parameters of gravitational physics with higher precision, millimeter-level LLR precision is necessary.

As seen from the error budget of the Apache Point Observatory Lunar Laser Ranging Operation (APOLLO), CCR arrays currently on the lunar surface are the main source of ranging error for a single photon received (15–45 mm) (Murphy et al. 2008). Because of lunar libration, the CCR array plane tilts with respect to the Earth with varying orientations of up to $12\degree$ (Otsubo et al. 2010). As a result, it is impossible to determine exactly which small CCR reflects the received photon. In other words, the width of the returned pulses and the ranging uncertainty increase, giving rise to the largest
component in the error budget for laser ranging. In addition, reflection performance for the existing CCR arrays has attenuated to a factor of 1/10 after approximately four decades of operation (Murphy et al. 2010). Thus, the most feasible approach for realizing millimeter-precision LLR is based on improvement of the CCR array.

Recently, several research teams have proposed a new CCR for next generation of LLR (Ciocci et al. 2017; Currie et al. 2011, 2013; Turyshev et al. 2013; Araki et al. 2016), which comprises a single structure and wide aperture to overcome current ranging uncertainty. Currie et al. (2011, 2013) were developing a 100-mm solid CCR prism using fused silica. The relative signal strength of the prism material. This means that only the dihedral angle offset and flatness of the three reflecting planes determine the optical performance. In other words, non-uniformity of the refraction index inside the prism does not affect its optical properties. Moreover, with the same weight, the aperture of a hollow CCR with a thickness of 15 mm is approximately 60% larger than that of a solid CCR (with a 100-mm aperture), which means that more photons can be reflected.

Turyshev et al. (2013) designed a hollow CCR with a 170-mm aperture that showed reflection performance equivalent to that of the largest Apollo 15 CCR array on the Moon. Araki et al. (2016) were developing a hollow CCR with a 200-mm aperture for LLR using single-crystal silicon. According to a simulation by Otsubo et al. (2010), the far-field diffraction pattern (FFDP) intensity for a 200-mm hollow CCR with an optimized dihedral angle of 0.35” was 50% larger than that for the Apollo 11 and 14 arrays. Oreb et al. (2006) developed a double hollow corner cube for NASA’s Space Interferometry Mission (SIM) with an aperture of approximately 73 mm (minor axis of an ellipse-shaped aperture). Optical contact was utilized to bond each glass panel together, and the dihedral angle offset for each reflector was within 0.4”. They also manufactured a same-sized double hollow corner cube using chemical bonding technology. The dihedral angle offsets were 1.68”, 0.03” and 1.68”, and 1.90”, 0.07” and 0.50” for each prototype (Burke et al. 2008).

To receive enough ranging photons, the divergence angle for the hollow CCR must be suppressed to achieve a relatively concentrated FFDP. According to simulations, the dihedral angle offset of a single hollow CCR used for LLR should have sub-arcsec deviation from a perfect right angle (Otsubo et al. 2010, 2011). Hydroxide-catalysis bonding (HCB) technology was proposed to assemble the hollow CCR, because its high strength (stretching yield strength >1MPa according to our experiment) and low coefficient of thermal expansion (CTE) are desirable for enduring vibration, impact and extreme temperature fluctuation during a space-based mission (Turyshev et al. 2013; Preston & Merkowitz 2013, 2014; Gwo 1998).

In this paper, we put forward a method for manufacturing a hollow CCR using HCB: we fabricated a prototype with a 100-mm aperture. A thermal cycle test was carried out to preliminarily ensure qualification. With some improvements, this method shows potential for application to the manufacture of a hollow CCR for the next generation of LLR.

2 SIMULATION OF A SINGLE CCR FOR LLR

According to the calculation of diffraction patterns by Otsubo et al., the velocity aberration is off-centered by 0.7” – 1.4” for LLR (Otsubo et al. 2011). The asymmetric dihedral angle offset of 0.65” – 0.8” for one angle and zero for the other two angles results in the best performance when the aperture is 100–200 mm, which increases the return energy by a factor of ~3.5 compared with the case of a symmetric dihedral angle. However, it is extremely difficult to realize such an asymmetric pattern model, because the accuracy requirement is nearly zero for the other two dihedral angles. A symmetric pattern model with accuracy at the arcsec level is achievable.

Here, we simulated the optical response of a 100-mm hollow CCR with different dihedral angle offsets and compared the intensity of the return signal with the 38-mm Apollo CCRs using MATLAB for programming. A symmetric pattern model was assumed, indicating the equality of each dihedral angle to form a circular FFDP. The index of refraction was set to 1.46 and 1.0 for a solid and hollow CCR, respectively. The incidence angle was set to 0°. The simulation was conducted at a wavelength
of 532 nm. Figure 1 shows the FFDP and the outgoing wavefront distribution for a 100-mm hollow CCR with all three dihedral angle offsets of 0.6′′.

Table 1 lists the return signal intensities for a 38-mm solid CCR and 100-mm aperture hollow CCR for different angle offsets. They were normalized to the signal intensity from an ideal 38-mm solid CCR. The 100-mm hollow CCR with dihedral angle offsets less than 0.6′′ shows 12.63%–15.49% of the signal intensity from the Apollo 11/14 retroreflector composed of one hundred 38-mm solid CCRs. It should be noted that the current performance of the Apollo retroreflector has degraded to a factor of 1/10; therefore, the intensity of the return signal from a new 100-mm hollow CCR with dihedral angle offsets of 0.6′′ may be 1.26 times that of the current Apollo 11/14 retroreflector array.

### Table 1

<table>
<thead>
<tr>
<th>Dihedral angle offset (arcsec)</th>
<th>38-mm solid</th>
<th>100-mm hollow</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.0</td>
<td>1.00</td>
<td>12.80</td>
</tr>
<tr>
<td>0.2</td>
<td>0.94</td>
<td>14.19</td>
</tr>
<tr>
<td>0.4</td>
<td>0.80</td>
<td>15.49</td>
</tr>
<tr>
<td>0.6</td>
<td>0.59</td>
<td>12.63</td>
</tr>
<tr>
<td>0.8</td>
<td>0.39</td>
<td>6.57</td>
</tr>
<tr>
<td>1.0</td>
<td>0.22</td>
<td>1.83</td>
</tr>
<tr>
<td>1.5</td>
<td>0.03</td>
<td>0.63</td>
</tr>
<tr>
<td>2.0</td>
<td>0.03</td>
<td>0.12</td>
</tr>
<tr>
<td>2.5</td>
<td>0.01</td>
<td>0.06</td>
</tr>
</tbody>
</table>

We investigated a new manufacturing method for fabricating the hollow CCR using HCB technology based on Preston and Merkowitz’s method (Preston & Merkowitz 2013, 2014; Gwo 1998; Gwo et al. 2003). In our method, the optical contact was applied between the hollow CCR and mandrel, with the addition of a specific polishing procedure. A solid corner cube was used as a mandrel. The mandrel was made of BK9 glass with an aperture of 72 mm and dihedral angle offsets of 0.27′′, 0.39′′ and 0.31′′. The bonding solution was applied to bond the components together; the edges were beveled to ensure that the bonding solution does not seep onto the master corner cube. Three glass panels with a thickness of 15 mm were used to fabricate the hollow CCR. The front surfaces of these glass panels were well ground and polished to a flatness of ≤ λ/10 (at 633 nm). To overcome the distortion caused by thermal expansion, ceramic glass was chosen as the material for the glass panels; it has a CTE of less than 0.2 ppm K⁻¹.

The HCB procedure is divided into four steps, as shown in Figure 2.

First, the glass panels and master corner cube were both cleaned successively with acetone and alcohol to remove any dirt on the surface. The three glass panels were placed on top of a solid corner cube and compressed tightly, so that the contiguous surfaces connected together by optical contact, which is an effect of the Van der Waals force (Greco et al. 2001). In principle, following application of the optical contact, the angular precision of the master corner cube is copied to the dihedral angle of the hollow CCR.

Second, the lateral edges of the adjacent mirrors were incised and then polished to a plane (the symbol ‘i’ in Fig. 2) with flatness of better than λ/4 (at 633 nm). Because this plane was prepared as the bonding surface, a strict requirement for flatness was necessary to avoid the generation of internal stress after curing.

Third, a polished glass block of the same material as the glass panel was silicate bonded to the prepared surface in step 2 by placing a small amount of sodium silicate solution onto plane ‘ii’. The solution must be applied.
Fig. 1 (a) FFDP normalized to the ideal 38-mm aperture solid corner cube and (b) outgoing wavefront distribution for a 100-mm hollow CCR with all three dihedral angle offsets of $0.6''$. The black dashed lines indicate the off-centered location at $0.7''$ (3.5 $\mu$rad) and $1.4''$ (7 $\mu$rad), which are the intervals of velocity aberration for LLR.

Fig. 2 Four-step fabrication of a hollow retroreflector. Solid CCR is green. Glass panels of the hollow CCR are transparent. The glass block used to bond is blue. 'i' and 'ii' are the bonding surfaces.

Fig. 3 A prototype hollow CCR with 100-mm aperture.
in an amount such that it does not leak into the master corner cube, otherwise an etching effect is likely to occur. In addition, one must ensure that a sufficient quantity of solution is used, otherwise the strength of the bonding can be reduced, resulting in limited accuracy for the dihedral angle. A micropipette was used to ensure application of the solution with an equal amount every time. In this way, the bonding was precisely controlled.

Finally, approximately two weeks later, after the bonding layer was completely cured and reached its maximum strength, the hollow CCR was separated from the solid CCR by a freezing method. It should be mentioned that the CTE of the ceramic glass used for the hollow CCR is one order of magnitude smaller than that for the BK9 material used for the solid CCR; thus, the two materials separate as shrinking occurs simultaneously with different strains. This step must be carefully implemented, otherwise the dihedral angles might be altered, or even worse, the hollow CCR has a risk of cracking that results from pulling.

There are three advantages to our method. First, perpendicularity precision of sub-arcsec, which is extremely difficult to implement, is avoided. Second, there are definitely no over-constraints for the three bonding planes, because they are not directly bonded to each other in pairs. Therefore, less internal stress is formed, which can lead to deformation of the dihedral angle. Third, the bonding solution is placed onto surface ‘ii’ (Fig. 2(c)) using a micropipette, with the glass block (Fig. 2) carefully placed onto this surface, so that the bonding solution is uniformly distributed to obtain good bonding quality.

A protected silver film was then used to coat the front surface of the hollow CCR by the evaporation method. An alumina layer was first coated for the adhesion layer. A silver layer with a thickness of 80~100 nm was deposited to provide high reflectivity. Finally, a silicon oxide layer was applied to protect the silver layer from corrosion. Furthermore, the coated hollow CCR was stored in a drying cabinet with relative humidity below 30%. The reflectivity for each plane reaches > 98% at 532 nm so that the integrated reflectivity of the hollow CCR is > 94%.

4 Optical Performance and Test Results

Figure 3 shows the prototype 100-mm hollow CCR built using the method described in Section 3. The aperture is defined as the circle inscribed within the hexagonal cut perpendicular to the optical axis. We characterized the 100-mm aperture size based on a 72-mm size master CCR. One can expect to build a larger hollow CCR, with an aperture size such as 120 mm, when a larger master CCR with similar angular precision, made from the same material, is used in the future. As shown in Figure 4, the optical performance of the CCR was measured with a ZYGO laser interferometer. As a comparison, the calculated FFDP is also given here. The offsets for the three dihedral angles are 0.5”, 0.8” and 1.9”. The peak-to-valley fluctuation of the wavefront for the outward light is approximately 1.038λ at 633 nm, which indicates better performance in the middle part of the aperture. The ultra-embossment of the wavefront at the center is due to deposition of the coating material.

However, this 100-mm hollow CCR does not completely copy the angles of the master corner cube as we had expected. A part of the area of surface ‘i’ (Fig. 3) before the bonding process shows a degraded flatness, which indicates non-ideal bonding quality. The HCB technique requires an extreme flatness of better than λ/4 for each bonding surface. Because the surface ‘i’ (Fig. 3) is composed of two planes from two independent glass panels, it is not easy for them to be polished to a flatness of high quality. Therefore, in our future work, improvements need to be focused on the polishing process for surface ‘i’ (Fig. 3).

To ensure qualification for operation in a lunar/space environment, the hollow CCR must be tested by a series of experiments. We conducted a preliminary thermal test to verify the viability of the CCR manufactured by silicate bonding. For this test, the temperature interval ranged from −40°C to +75°C (limited by current equipment), and the heating and cooling rates were not less than 1°C min⁻¹. This temperature range covered the operating condition for most high-orbit satellites. The maximum and minimum temperatures were maintained for 90 and 60 min, respectively, during every period. Finally, we continuously tested the hollow CCR for 18.5 periods. The time for each period was 380 min, and the total time was approximately 5 d. The CCR survived with no damage; stricter thermal cycle testing, e.g., 100–400 K with simultaneous FFDP measurement, is necessary to further verify the performance of the hollow CCR and silicate bonding technology under lunar environment conditions.

The optical performance of the CCR was measured using an updated 6-inch ZYGO laser interferometer with new software after the thermal cycle test so that a pre-
cision of two digits after the decimal point could be obtained. The optical performance including outgoing wavefront distribution and interferometric fringe, as well as the calculated FFDP, is shown in Figure 5. As discussed by Burke et al. (2005), it is necessary to take some care in measuring such small angles using an interferometer. Thus, a double-pass measurement mode was used to eliminate the wavefront error caused by tilt of the reference flat. The “beam stop” was inserted between the reference flat and the interferometer body to block...
Table 2  Dihedral angle measured for the master CCR and hollow CCR before and after the thermal test. All values are reported in units of arcsec. The values in parentheses correspond to the angle across the beam stop (Burke et al. 2005).

<table>
<thead>
<tr>
<th>Angle 1</th>
<th>Angle 2</th>
<th>Angle 3</th>
</tr>
</thead>
<tbody>
<tr>
<td>Master CCR</td>
<td>0.27</td>
<td>0.31</td>
</tr>
<tr>
<td>Hollow CCR (before)</td>
<td>0.5</td>
<td>0.8</td>
</tr>
<tr>
<td>Hollow CCR (after)</td>
<td>0.38 (1.17)</td>
<td>1.98</td>
</tr>
<tr>
<td></td>
<td>0.42 (1.30)</td>
<td>1.99</td>
</tr>
<tr>
<td>Hollow CCR (after)</td>
<td>(0.14)</td>
<td>0.92</td>
</tr>
<tr>
<td>Six Measurements</td>
<td>(0.26)</td>
<td>1.11</td>
</tr>
<tr>
<td>(after)</td>
<td>0.43</td>
<td>0.90 (2.59)</td>
</tr>
<tr>
<td></td>
<td>0.32</td>
<td>1.09 (2.16)</td>
</tr>
<tr>
<td>Average</td>
<td>0.39</td>
<td>1.00</td>
</tr>
</tbody>
</table>

As seen from the dihedral angle offsets, this 100-mm hollow CCR partly meets the requirements (offset of 0.6′′ for all three dihedral angles) for the next generation of LLR. However, according to our calculation, it is extremely difficult to receive return photons once the dihedral angle offsets exceed 0.8′′, because the far-field diffraction annulus, including most of the return energy, will extend to miss the region of lunar velocity aberration (0.7′′ − 1.4′′) where the ranging stations are located. The angular performance of our prototype is not sufficient for LLR, which indicates that more progress is necessary in future work. However, this result indicates the potential application of our method for manufacturing a hollow CCR with a large aperture to realize LLR.

The angle offsets for the preliminary prototype were not all the same as those for the master corner cube. Consequently, in our future work, efforts will be made to improve the optical performance of the CCR. The master solid corner cube needs to be replaced by a larger device with an aperture of 80–100 mm so that the polishing process in Figure 2 can be carried out in a more stable manner for improved flatness of surface ‘i’. This improvement can reduce the internal stress after bonding as well as deformation of the CCR after the separation step. Moreover, the glass block used for bonding in the third step may be cut into several smaller pieces. As a result, the local flatness of planes ‘i’ and ‘ii’ can be polished better for bonding to reduce the internal stress and deformation as much as possible.

In addition, a thermal cycle test with simultaneous FFDP measurement will be carried out over a wider temperature range from −170°C to +130°C (approximately 100–400 K), which is the actual environment on the Moon so that Moon-based application of the hollow CCR can be verified. More prototypes should be produced with the same method to confirm all the technical details for every procedure that may affect the experimental result. Consequently, in future applications, a more precise hollow CCR with the same or even larger aperture can be expected using silicate bonding technology.

Acknowledgements The authors thank Guoping Lin, Pengshun Luo and Jean-Michel Le Floch for their valuable advices, Cao Shenghong for his technical support in optical machining and Wuhan Union Optic Ltd for their optical measurement. This research is supported by the National Natural Science Foundation of China (Grant Nos. 11655001 and 11605065).
References

Ciocci, E., Martini, M., Contessa, S., et al. 2017, Advances in Space Research, 60, 1300
Murphy, T. W. 2013, Reports on Progress in Physics, 76, 076901
Oreb, B. F., Burke, J., Netterfield, R. P., et al. 2006, in Interferometry XIII: Techniques and Analysis, 6292, International Society for Optics and Photonics, 629202
Preston, A., & Merkowitz, S. 2013, Applied Optics, 52, 8676
Preston, A., & Merkowitz, S. 2014, Optical Engineering, 53, 065107