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Development of a 170-mm hollow corner cube retroreflector for the future lunar laser ranging*

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Over the past 50 years, lunar laser ranging has made great contributions to the understanding of the Earth–Moon system and the tests of general relativity. However, because of the lunar libration, the Apollo and Lunokhod corner-cube retroreflector (CCR) arrays placed on the Moon currently limit the ranging precision to a few centimeters for a single photon received. Therefore, it is necessary to deploy a new retroreflector with a single and large aperture to improve the ranging precision by at least one order of magnitude. Here we present a hollow retroreflector with a 170-mm aperture fabricated using hydroxide-catalysis bonding technology. The precisions of the two dihedral angles are achieved by the mirror processing with a sub-arc-second precision perpendicularity, and the remaining one is adjusted utilizing an auxiliary optical configuration including two autocollimators. The achieved precisions of the three dihedral angles are 0.10 arc-second, 0.30 arc-second, and 0.24 arc-second, indicating the 68.5% return signal intensity of ideal Apollo 11/14 based on the far field diffraction pattern simulation. We anticipate that this hollow CCR can be applied in the new generation of lunar laser ranging.

Keywords: lunar laser ranging, corner cube retroreflector, diffraction, alignment

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1. Introduction

Over the past five decades, lunar laser ranging (LLR) has been making great contributions to the study of the Earth–Moon system and the gravitational physics, such as the test of the equivalent principle, time-rate-of-change of the gravitational constant G, geodetic precession, and test of the Newton inverse-square law.[1,2] Ranging precision has been improved from a few decimeters to the centimeter level along with the progress of the ground-based laser ranging facilities.[3] Nevertheless, to test the parameters of gravitational physics with a higher precision, the millimeter-level ranging precision is necessary.

Nowadays, the corner cube retroreflector (CCR) arrays placed on the Moon by the United States of America and the former Soviet Union last century has become the dominating error source (15 mm–45 mm) according to the analysis of APOLLO (Apache Point Observatory Lunar Laser-ranging Operation).[4] As seen from the Moon's surface, the Earth's center appears to move around its mean position with $\pm 6.9^\circ$ in the north-south direction and $\pm 8.2^\circ$ in the east-west direction due to the combined effects of the perturbed orbit and the obliquity of the ecliptic for the Moon. This phenomenon is the so-called "lunar libration", which causes the tilt of the CCR array plane with respect to the orientation of the Earth, resulting in a spread of the arrival time as each CCR is at a slightly different distance from the Earth.[5,6] Moreover, the reflecting performance of these CCR arrays has attenuated to a factor of 1/10 after more than four decades' operation.[7]

Thus, upgrading the CCR array is a feasible approach for achieving millimeter precision LLR. Recently, several research teams have proposed replacing the CCR arrays with a single, wide aperture CCR to overcome the current ranging uncertainty.[5,6,8,9] Turyshev *et al.*[5] designed a hollow CCR with a 170-mm aperture that showed a similar reflection performance to Apollo 15. Currie *et al.*[6,8] developed a solid CCR prism with a 100-mm aperture for the new generation of LLR, which had 20% reflection performance of the initial Apollo 11/14. Araki *et al.*[9] proposed to develop a hollow CCR with a 200-mm aperture for the future LLR and had been focusing on the choice of the material and the thermal simulation for years.

Compared with a solid CCR, hollow CCR is probably a better choice to avoid the effect of the gradient and the variation of refraction index caused by the fluctuation of lunar temperature (100 K–400 K), as well as to get a smaller weight. Consequently, the flatness of the reflecting surface and the pre-

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cision of the dihedral angle are the main two decisive factors determining the optical performance of a hollow CCR.

In this paper, we present the manufacture of a hollow CCR with a 170-mm aperture and sub-arc-second angle precision using hydroxide-catalysis bonding (HCB) technology. In contrast to the previous reports, we put forward (i) special processing and measurement techniques of sub-arc-second precision perpendicularity, and (ii) adjusting method for the third angle using two autocollimators. The hollow CCR can be potentially applied for the next generation of LLR.

2. Simulation of single CCR for LLR

The velocity aberration, caused by the different motion velocity of the moon and the ranging station, introduces a location deviation between the ranging station and the center of the diffraction pattern when a laser ranging pulse arrives back to Earth.[10] The velocity aberration for lunar laser ranging mainly varies between 0.7 arc-second–1.4 arc-second, which is determined by the latitude of the ranging station.[11] Generally, slight angle errors of the CCR can compensate this location deviation so that the ranging station can be located in the area where most return photons can be received.

Table 1. Return signal intensity for a 170-mm aperture hollow CCR with varying dihedral angle offsets. The values are normalized to the ideal 38-mm aperture solid CCR used in Apollo arrays. The intensity is the average value for the lunar aberration region (0.7 arc-second–1.4 arc-second at far field). The Apollo 11/14 arrays on the Moon show the return signal intensity of 100.

Angle offset/arc-second	Relative return signal
0.1	28.7
0.2	62.2
0.3	87.0
0.4	85.8
0.5	62.0
0.6	33.1
0.7	13.1
0.8	4.9

According to the calculation by Otsubo *etal*.,[11] to acquire a similar optical response to Apollo CCR arrays for future LLR, the optimized aperture and the dihedral angle offset (deviation from a perfect right-angle) of a single CCR are 150 mm–250 mm and about 0.3 arc-second–0.4 arc-second, respectively. We plan to develop a hollow CCR with a 170-mm aperture. It is a choice that takes both the reflecting area and the technology difficulty into consideration. Based on our numerical simulation in Table 1, the optical performance of this size can still reach the same order of magnitude (6.6 times attenuation compared to the maximum) when the dihedral angle offsets are up to 0.7 arc-second. Hence, at least 13.1% optical intensity reflected from ideal Apollo 11 can be expected. The intensity of the return signal is rapidly attenuated when the angle offsets exceed 0.7 arc-second since the concentrative annular pattern deviates from the region of lunar aberration (0.7 arc-second–1.4 arc-second at far field).

3. Manufacture method

Many research groups experimentally studied the fabrication of a hollow CCR with high angle precision.[12–16] Preston and Merkowitz[12,13] developed several 40-mm aperture hollow CCRs using both hydroxide-catalysis bonding and epoxy bonding methods, and the best prototype realized the dihedral angle offsets of 0.93 arc-second, 0.52 arc-second, and 1.58 arc-second, respectively. Oreb *et al.*[14,15] developed a double hollow corner cube (three mirrors were bonded onto a base glass forming two hollow CCRs) using optical contact with an approximately 73-mm aperture (minor axis of an ellipse-shaped aperture) for NASA's Space Interferometer Mission (SIM). The dihedral angle offsets were within 0.4 arc-second and then went up to 1.68 arc-second, 0.03 arc-second, and 1.68 arc-second, and 1.90 arc-second, 0.07 arc-second, and 0.50 arc-second respectively for another prototype when the HCB technology was employed later.[16]

We developed a method for manufacturing hollow CCR with sub-arc-second precision using HCB technology, because its high strength and low coefficient of thermal expansion are desirable for enduring vibration, impact, and extreme temperature fluctuation during a space-based mission.[5,12,13,17,18] As shown in Fig. 1, two polished lateral mirrors (mirror 2 and mirror 3) were silicon bonded to another polished glass (base mirror) one by one to form a hollow CCR. The mirror 2 was first bonded onto the mirror 1, and then the mirror 3 was bonded onto the corresponding position one week later. Because of the great strength and rigidity of the HCB technology, the complete separation of the mirror 2 and the mirror 3 did not cause any instability of their exact locations as well as the precision of the angle between them. The mirror material is ultra-low expansion glass (ULE 7972 standard grade) produced by the Corning corporation. All of the reflecting surfaces and the bonding surfaces were polished to a flatness of $\leq \lambda/10$ (at 633 nm). The size of the lateral mirrors and the base mirror were 120 mm × 120 mm × 15 mm and 135 mm × 135 mm × 15 mm, respectively. In our method, the precision of the two dihedral angles (β_{12} and β_{13} in Fig. 1) were controlled by processing the lateral mirrors with a perpendicularity precision of sub-arc-second level. The precision of the third angle (β_{23} in Fig. 1) was obtained by adjusting on spot during the bonding process guided with an optical measure system containing two ELCOMAT 3000 autocollimators. The autocollimator has a resolution of 0.05 arc-second and a measurement accuracy of $\pm$0.1 arc-second over the 20 arc-second range, which ensures the feasibility to achieve the required angle precision.

There are two key technical issues for this method. First, it is really difficult to process two lateral mirrors (mirror 2 and mirror 3 in Fig. 1) to a perpendicularity precision of the sub-arc-second level (α_2 and α_3 in Fig. 1). The second issue is how to adjust the dihedral angle β_{23} to a right angle with sub-arc-second level offset when bonding them to the mirror 1. Especially, the time allowed for the adjustment is only within 30 seconds before the curing process would start.

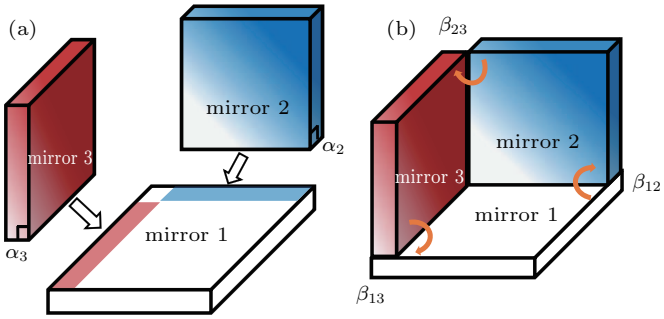


Fig. 1. (color online) The schematic drawing of the manufacture method of the hollow corner cube retroreflector: (a) before bonding and (b) after bonding. Mirror 1 is the base mirror; mirrors 2 and 3 are the lateral mirrors. Mirrors 2 and 3 are completely separated by a tiny gap. α_2 and α_3 are the perpendicularities of mirror 2 and mirror 3, respectively. β_{12}, β_{13}, and β_{23} are the dihedral angles formed by mirrors 1 and 2, mirrors 1 and 3, and mirrors 2 and 3, respectively.

To resolve the first issue, we designed an auxiliary fixture as shown in Fig. 2 to process the required perpendicularity for mirror 2 and mirror 3. The fused silicon blocks were first ground and polished to a flatness of $\lambda/10$ (at 633 nm) and were optically contacted to the ULE mirror whereafter. Surface A and surface D were polished together to form a single plane, and meanwhile angle 2 was regularly checked by a ZYGO interferometer with an internal right-angle measurement. Here the requirement of the offset to a right angle is less than 0.5 arc-second so that the perpendicularity precision of the mirror (angle 1) is better than 0.5 arc-second as well. It should be mentioned that to achieve the greatest performance in lunar laser ranging, 0.3 arc-second is best, according to the analysis in Section 2. However, because of the technical limit, we thought 0.5 arc-second is a moderate requirement here that can also be accepted. The bonding layer is extraordinarily thin (< 100 nm) and the homogeneity of its thickness is very good as observed by atomic force microscopy. We anticipate that the perpendicularity of the mirror 2 and mirror 3 will be copied to the dihedral angle β_{12} and β_{13}, respectively, after bonding with a deviation of less than 0.2 arc-second. Thus, the final angle performance of the CCR can fully meet the requirement of 0.7 arc-second for LLR application.

To resolve the second issue, Burke *et al.*[16] adjusted the third dihedral angle of a hollow CCR using a laser interferometer based on estimating the shape of interferometric fringes. Here, we employed two autocollimators marked as "a" and "b" as shown in Fig. 3, to set up an optical configuration for adjusting the third dihedral angle. In addition, we designed a special jig that is adjustable on three dimensions. First, we utilized a solid corner cube with one dihedral angle precision of 0.2 arc-second (measured by ZYGO) to align the optical axes of the two autocollimators perpendicular to each other. Secondly, the solid CCR was replaced with the combination of mirror 1 and mirror 2 that had already been silicon bonded together. The combination was fixed on the adjustable jig and then was adjusted to make the readings of both axes of the autocollimator "a" close to zero. Thirdly, we dropped the bonding solution on mirror 1, put mirror 3 on it, and quickly adjusted mirror 3 in pitching and yaw, making the readings of both axes of the autocollimator "b" get close to zero within 30 seconds. The difference of the actual readings of the "X" axis between two autocollimators was the dihedral angle offset between mirror 2 and mirror 3. It should also be noticed that this difference takes the instrument errors and the angle errors of the solid CCR into account. The final value of the dihedral angle needs to be verified by the ZYGO interferometer.

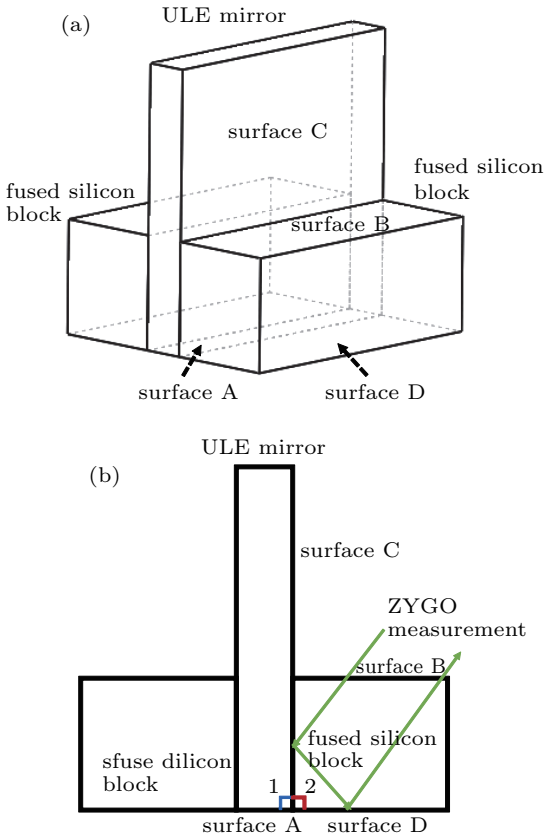


Fig. 2. (color online) The schematic diagram for processing perpendicularity of mirror 2 or 3 as seen in Fig. 1 with (a) the three-dimensional view and (b) the front view. The ULE mirror is mirror 2 or 3 in Fig. 1. Two fused silicon blocks are auxiliaries used for optical machining. Angle 1 shows the perpendicularity of mirror 2 or 3. Surface A is the plane to be polished and bonded to mirror 1. Surface C will be the reflecting plane of the hollow CCR. The green light is the laser beam from the ZYGO interferometer to measure angle 2.

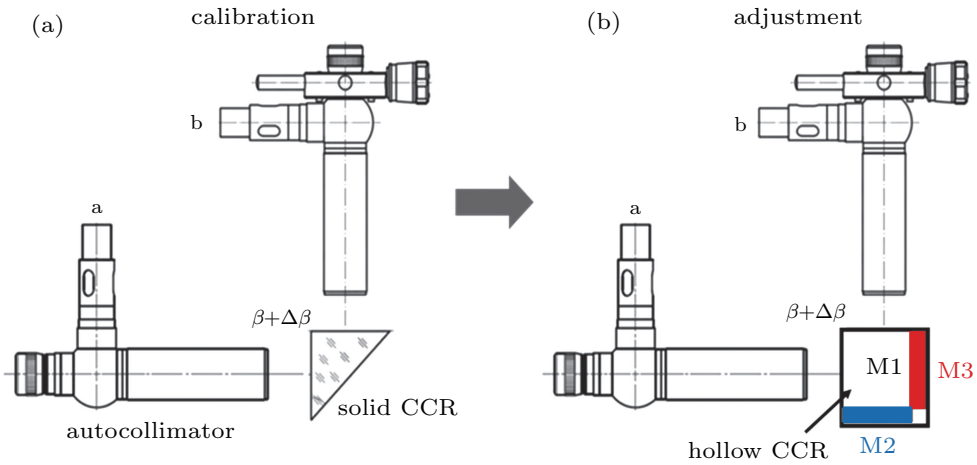


Fig. 3. The optical system for the adjustment of the third dihedral angle. Two autocollimators are marked as "a" and "b". The M1 represents the base glass of the hollow CCR; M2 and M3 represent mirror 2 and mirror 3 in Fig. 1, respectively.

4. Result

Figure 4 shows the 170-mm hollow CCR built by using the method described above and the whole instrument with mounting. Some parts outside the effective reflecting area of the CCR were cut to reduce the weight and the volume. The dihedral angle precisions were measured by using a 6-inch (the unit 1 in = 2.54 cm) ZYGO laser interferometer. The offsets for the three dihedral angles are 0.10 arc-second, 0.30 arc-second, and 0.24 arc-second. Particularly, the value of 0.24 arc-second is corresponding to the dihedral angle β_{23} adjusted by the jig.

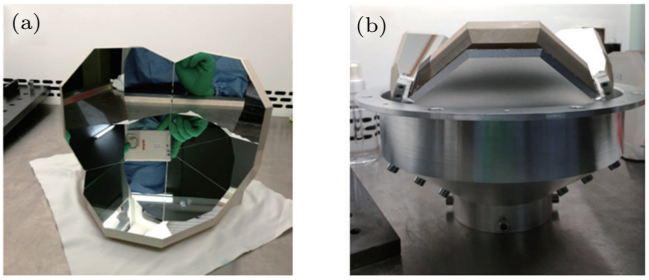


Fig. 4. (color online) (a) Hollow corner cube retroreflector with 170-mm aperture and (b) the whole mounting.

The far field diffraction pattern of this hollow CCR is calculated as shown in Fig. 5. Based on our simulation, the relative optical response is 68.5% of the ideal Apollo 11/14 within the off-central area of lunar aberration (3.5 μrad–7 μrad). Furthermore, Murphy *et al.*[7] estimated that the efficiency of the Apollo arrays was diminished by at least a factor of 10 based on the laser ranging data of the Apache point. This attenuation was attributed to the lunar dust or the abrasion on the front faces of the corner-cube prisms. Therefore, this 170-mm hollow CCR may probably realize a relative optical response of much more than 68.5% in practice for the initial years after its placement.

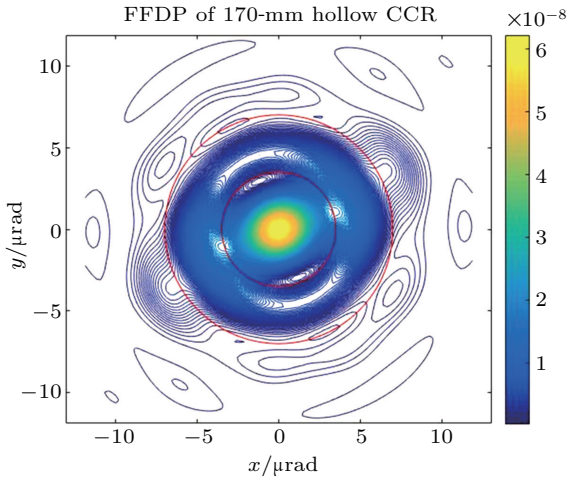


Fig. 5. (color online) The far field diffraction pattern of the 170-mm hollow CCR with the dihedral angle offsets of 0.10 arc-second, 0.30 arc-second, and 0.24 arc-second. The red lines show the off-centered location of 0.7 arc-second (3.5 μrad) and 1.4 arc-second (7 μrad), which are the intervals of the velocity aberration for LLR.

5. Conclusion

A hollow corner cube retroreflector with a 170-mm aperture was developed using the HCB technology. The dihedral angle offsets of 0.10 arc-second, 0.30 arc-second, and 0.24 arc-second were realized, which completely met the requirement (required by the lunar libration) of ≤ 0.7 arc-second for LLR. The 68.5% relative intensity of Apollo 11/14 arrays can be expected at least, indicating the potential application in the next generation of LLR.

The thermal cycle test with temperature ranging from −40 °C to +75 °C was carried out. The changes of dihedral angle did not exceed 0.2 arc-second. In our future work, thermal cycle testing with simultaneous FFDP measurement will be operated to verify its optical performance in the actual lunar environment (−170 °C to +130 °C).[19] The robotic way of deploying the CCR on the Moon and the pointing to the Earth also need to be considered. Additionally, to meet

the launch requirement, this hollow corner cube retroreflector also needs to be tested with a series of experiments including acceleration, vibration, impact, and solar radiation.[20–22]

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