Proc. International Conference on Space Optical Systems and Applications (ICSOS) 2012, 6-1, Ajaccio, Corsica, France, October 9-12 (2012)

Design of Engineering Model of Corner Cube Retro-reflector by Evaluating Far Field Diffraction Pattern

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Abstract The measurement of the far field diffraction pattern (FFDP) for the characterization of a corner cube retro-reflector (CCR) was conducted as a part of the design of the laser reflector array (LRA) for satellite laser ranging (SLR) system. Before full installation a trial production of CCR and a test evaluation were performed in which polarization characteristics were considered. There is an agreement between the theoretical analysis and the experimental results. CCR prisms were manufactured by a prism maker, and the support structure and mechanical system were assembled at the National Institute of Information and Communications Technology (NICT).

Keywords: Satellite Laser Ranging, Laser Reflector Array

1. Introduction

A corner cube retro-reflector (CCR) is known as a kind of optical prism that reflects light only in the direction of incidence. On the ground, it is used as a target for range finders or as a part of a precise optical measuring instrument. In space, it is used as a functional device for target identification and satellite ranging as well as for free space optical communications[1][2][3].

In a satellite laser ranging (SLR) system, a satellite carries multiple CCRs (LRA: laser reflector array) and is critical to achieve 1 mm or sub-millimeter accuracy[4].

Regarding the CCR structure in the space environment, it is important to correctly design the size and the array format of multiple CCRs that obtain a desired link and are durable in the mechanical and thermal environment encountered during a launch and in space.

In Japan, there have been few advances in LRA development since the development of LRA in EGS "AJISAI" for the 1986 launch by the Japan Aerospace Exploration Agency (JAXA)[5].

All the earth observation satellites and positioning satellites (ETS-VIII, Quasi-Zenith Satellite) that require high-precision orbital determination carry foreign-made LRAs.

Since the 1990s, the authors have been engaged in the development of an SLR ground station, and have developed a LRA for the scientific satellite Astro-G as a means to obtain high-precision orbital determination for science and positioning missions[6][7][8][9][10].

This study describes the development of the optical design, especially the measurement of the far field diffraction pattern (FFDP) of a single CCR element.

2. LRA Design

The outlook structure design and parameters of LRA for a small Low Earth orbit (LEO) satellite is shown in Fig. 1. The CCR prism is protected in the holder. It sits on the bottom seat, and is kept a ring at the top. Both of them are made from a material that has heat insulation.

These structures (the CCR prism, maintenance ring, and holder) are developed from the shock, vibration test, and experience of the thermal simulation[11].

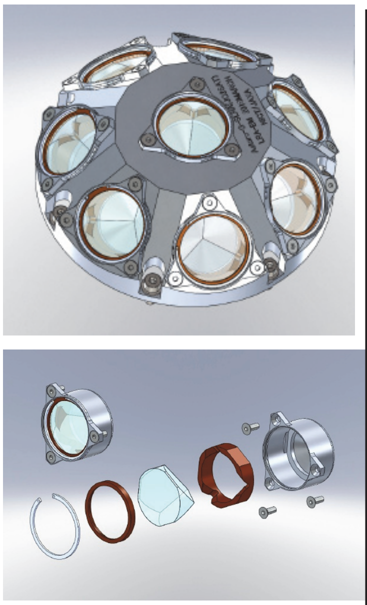

Fig.1 Structure of LRA (above), the holder for a single element (below), and specifications (right).

Diameter: 124 mm
Height: 43mm
Mass: 360 g
Number of Cubes: 8, made from synthetic fused silica (quarts)
Cube Diameter: ~28 mm
Angle of 7 surrounding CCRs: 45°
All cubes are coated to have reflectivity > 98% at 532 nm
Dihedral angle =1.4 arcsec +-0.4
Structure material:
Main material: A7075-T351
Surface Finish by Alodine
Retainers: BESPEL SP-1
Others: 28 mm Ring SUS304CSP/4H

3. Specification of Corner Cube Prism

The material of the corner cube, quarts, has various grades in terms of homogeneity and purity. We chose one of the three types of quarts domestic material suppliers. The grade is not always the highest but it passes radiation test and homogeneity check. The radiation test includes total dose up to a few 10^8 rad γ-ray. With respect to the refractive index homogeneity, high-precision measurement is performed on two types of synthetic quartz, and the value was 0.5 ppm, while the measurement rms value was 0.06 ppm.

The CCR specifications are as follows:

Optical effective diameter: 28 mm

Flatness of each surface P-V 1/10λ or better at 633 nm

Total output wave front flatness: P-V $\lambda/4$

Roughness: 10 Angstraum RMS (in each field)

Dihedral Angle (DAO; the angle means a small offset from 90°): 1.4 arcsec

Coating on the back surface -- incidence angle: 27–82° -- the reflectance Rp and Rs (per surface) ≥ 98% wavelength at 532 nm and at 847 nm, where P-V means peak to valley, suffix-p of R and -s expressed the polarization component for incidence angle from the inside of the CCR, respectively. In this study, we considered the evaluation by only λ = 532 nm on a test CCR which is uncoated and coated with dielectric multilayer or with a silver coat.

4. Optical Evaluation and FFDP

Each CCR was tested by a commercial interferometer to meet the specifications of the flatness, roughness, and DAO angle. In addition, FFDP corresponding to the intensity of the optical response from the CCR for light being received back on the Earth as a function of two-dimensional angles should be considered.

The observation method of FFDP is known as a technique for evaluating antenna in fields such as optical inter-satellite communication[14]. In order to maximize the link, the verification of the thermal influence on the CCR and the examination of the measured design have mainly been reported for the theoretical analysis using a concrete satellite [15][16][17][18]. There is an increasing need for the establishment of a method for the technical evaluation of the FFDP.

The condition used for the FFDP with a constant beam pattern form is that the observation point is located sufficiently far from a light source in what is called a Fran Hofer diffraction domain. This condition will serve as a standard for the FFDP in a laser with wavelength λ; the diameter of the opening of the antenna reflector is set to D and the distance is set to R [19], where

$$R > 2D^2/\lambda \quad (1)$$

If we set λ to 532 nm and D to 10 cm, it is sufficient for the distance to be set to R > 38 km. However, setting this value is practically difficult. Nonetheless, it is necessary to separate such a distance and to be able to directly measure intensity distribution.

Then, in the measurement of the equivalent FFDP, it was easy to remove the atmospheric influence of fluctuation, and composition was achieved in a laboratory. We investigated a method for expanding and observing the FFDP image using the focal point side of the quality lens, which is called the compact range method[14]. The focal plane of a lens is a system that uses the principle of projecting the image to infinity.

In the experiment system, we considered a system that adds the separation function of polarization, so that an evaluation can be performed considering the laser and

CCR to have the polarization characteristic.

5. Test Equipment

A block diagram of the equipment setup and an actual picture for FFDP measurement is shown in Figs. 2 and 3, respectively.

The laser used has a second harmonics output of continuous wave (CW) Nd:YAG laser. The laser has a beam diameter of about 0.6 mm, the TEM00 mode, and is expanded by 60 mm with a beam expander.

In this experiment, the diameter of the effective opening was only 15 mm owing to the limit of the apparatus.

Next, we used a polarization separation optical system vertical/horizontal separating optics (VHSO), such that the output of the system was toward the CCR according to the linear polarization of VHSO. When another optical pass was reversed, it was separated by the VHSO into horizontal and vertical polarized light components, and the catoptric light of CCR was divided into two optical paths.

Two polarization light is again sent along the optical axis within a VHSO optical system and it enters into the imaging lens L1.

The expansion projection of the FFDP imaged by the focus of L1 is carried out with the expansion by lens L2 at the screen.

The FFDP of each polarization component was observed by intercepting one side of the optical paths of the two polarization components.

The incidence light to the CCR used the collimation tester for the parallel adjustment of the beam expander output when considering it as the nearby beam, although it should be a plane wave in the ideal case.

To correctly detect the FFDP, the focal position of the imaging lens L1 needs to be caught correctly. The position detection was performed by measuring the minimum position followed by a path using the knife edge method[20].

The specifications for the composition of the test apparatus equipment are shown in Table-1.

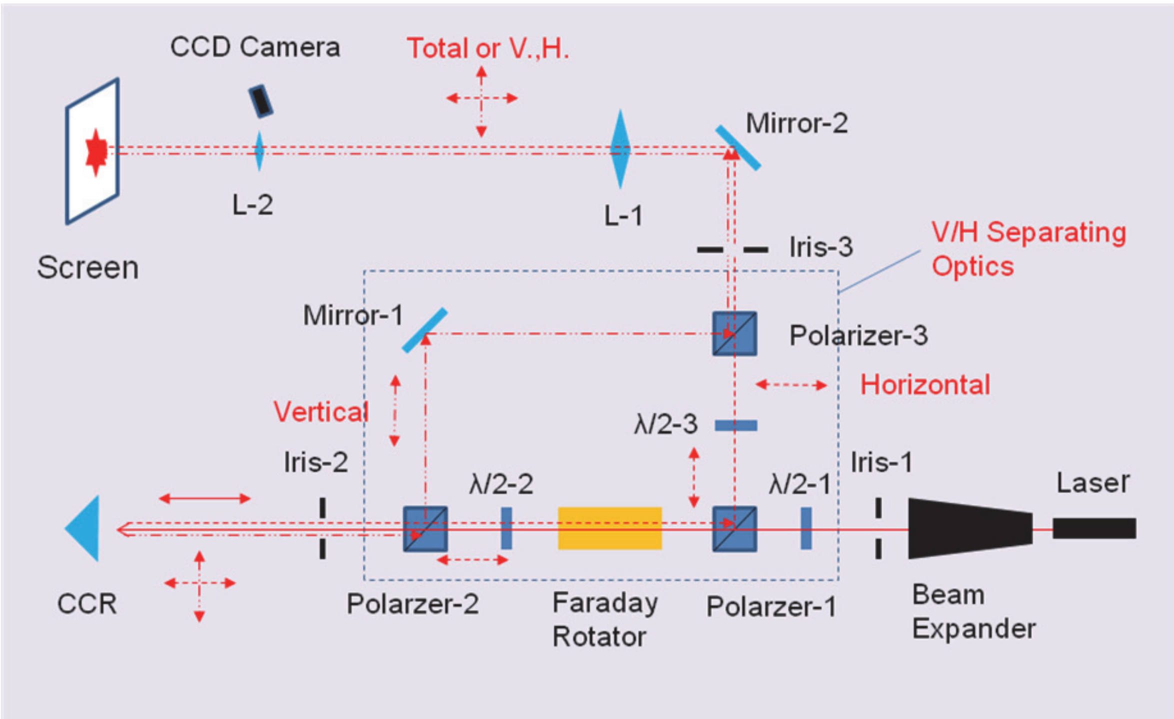

Fig. 2 Test optics for FFDP measurement of CCR

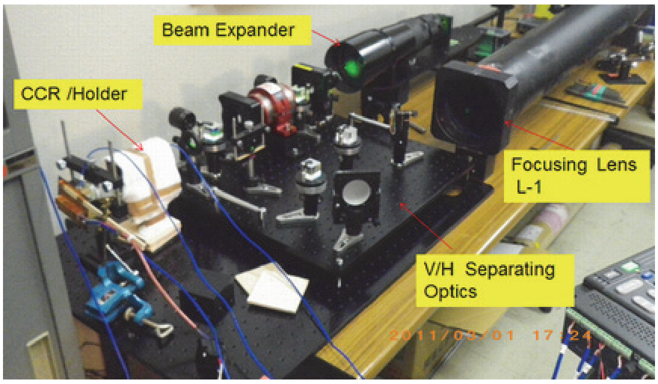

Fig. 3 Test Optics View

Table-1 Specifications of FFDP Test Optics

Laser	TEM00, CW Nd-YAG, λ 532 nm
Beam size 2w: 0.6 mm, Power 10 mW	
Beam Expander	ϕ100 mm, F 500 mm, ×100
Lens L1	ϕ120 mm, F 2250 mm
Lens L2	F 10 mm, Plano-Convex
λ/2 Plate 1-3	ϕ25.4, Distortion λ/10, AR coat.
Polarizer 1-3	VIS/NIR Polarizing Beam splitter Extinction Ratio Tp/Ts ≥ 1000:1
Faraday Rotator	ϕ15 mm, Rotating angle 45°, T > 98%
Mirror 1-2	ϕ50, Distortion λ/10, R > 98%
CCD Camera	Nikon D40x, 10.75 Mpixels

6. Calibration

In order to calibrate FFDP method, the comparison proofreading of the spread (angle) of FFDP on the enlargement projection out to the screen was performed using two methods: one is the diffraction pattern at a circular opening and another is based on the interference pattern of a double slit. Fig. 4 shows an interference/diffraction pattern obtained using the two respective methods[21].

The diffraction pattern (Franhofer diffraction pattern) is observed in the case where the plane wave with wavelength λ passes through the circular opening with radius r:

The radius alpha of the first dark ring (angle) is expressed as

$$\alpha = 0.61\lambda/r \qquad (2)$$

This becomes the radius, w, of the first dark ring on the screen, and is given as

$$w = 0.61\lambda Fm/r \qquad (3)$$

where F: focal length of an imaging lens

m: magnification of the optical system.

In the case of a double slit, the interval of the interference fringes at two slits is used for comparison. When the interval of a slit is set to d, the interval of two fringes in the near axis (angle) δ is

$$\delta = \lambda/d \qquad (4)$$, and

the interval h on the screen is

$$h = \lambda Fm/d \qquad (5)$$

whereas the circular aperture radius r = 7.5 mm, F = 2250 mm, and d = 4.5 mm for an m = 187.8 time double slit in the experiment. The theoretical result is 2.37 μrad/mm. For comparison, the scale values on the screen obtained using the two methods are 2.30 μrad/mm and 2.36 μrad/mm, respectively, and the results obtained were mostly in agreement.

With regards to the intensity distribution, the image pick-up pattern obtained using a CCD camera was input into a CPU, and the three-dimensional analysis and drawing was performed with the image analysis software.

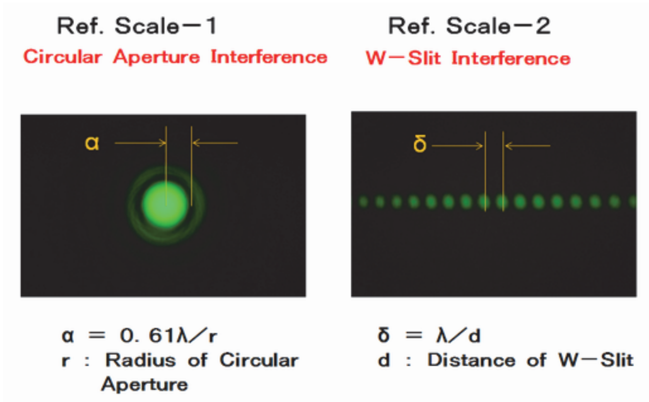

Fig.4 Calibration of FFDP by circular aperture (left) and double slit (right)

7. Measurement

The measurement of the FFDP was conducted from the following three perspectives:

1) The spread of the FFDP of the CCR, and the detection of the form and intensity distribution,

2) The detection of the difference in the FFDP by the coat existence of the CCR reflective surface,

3) The detection of changes in the FFDP by heating the CCR, considering the heat load of the CCR in the space environment.

The opening of the CCR used has a diameter of 28 mm, the material is made from quartz, and the offset angle between input and output beam element used was about −6.5 arcsec (dihedral angle = -1.4 arcsec). However, the diameter of the effective opening in a test was limited to 15 mm.

Fig. 5 shows the total light pattern (left), horizontally polarized light component (middle) vertically polarized light component (right) at the image pattern retrieved by the FFDP's CCD camera.

Patterns in upper row shows a reflective surface with no coat and lower low shows a reflective surface with a silver-coated element. The incidence light was set as horizontally polarized light.

In the case of the non-coated CCR, the polarization of reflected light is changed between before and after reflection. On the other hand, for the silver-coated CCR, the polarization is the same as that of the incidence light, and it does not change. Those polarization change characteristic is used to confirm apparatus function and theory of reflection of CCR.

The spread of the pattern was verified using the comparison scale described by the calibration, and was about 100 μrad.

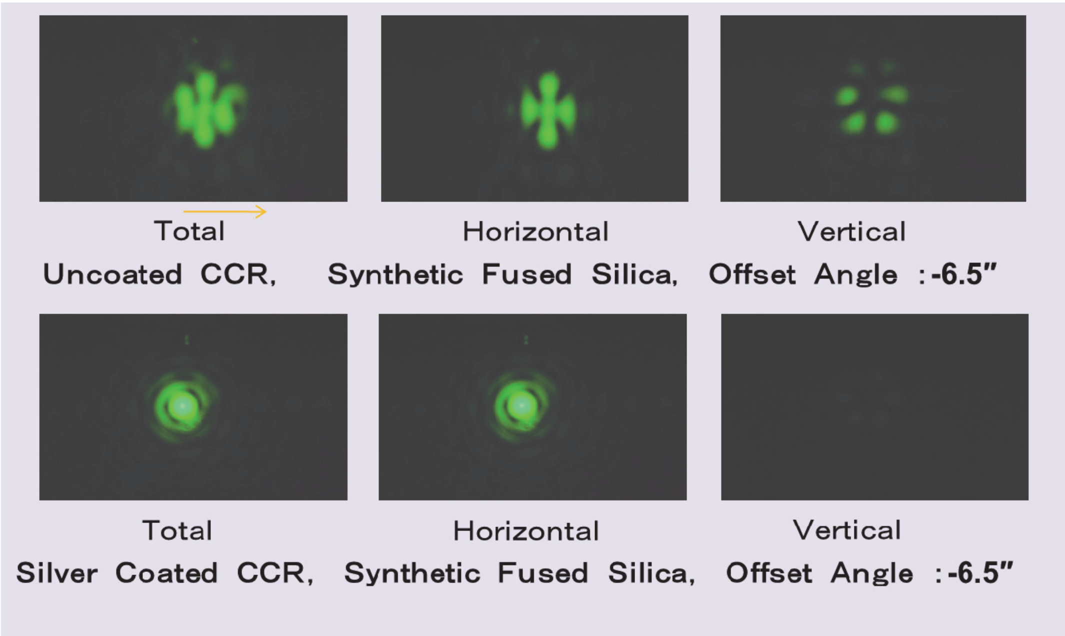

Fig.5 FFDP of Uncoated (above set), and Silver coated (below) CCR for linear polarization input

CCR is usually manufactured at normal temperatures, and a performance test is performed.

However, in a CCR carried on a satellite into an orbit, temperature distribution arises owing to the difference in the heat generated by the heat source inside and outside the satellite apparatus; this difference is caused by factors such as sunlight, the earth infrared radiation.

Fig. 6 shows the conceptual map of the temperature distribution inside the CCR, which represents the heat environment of the CCR in the assumed satellite.

Fig. 7 shows the heat distribution on the upper part and the inside of the CCR under the influence of sunlight, where the finite element method (FEM) model of the CCR is simplified in the analysis.

In the hot orbit (corresponding to case3 in Fig.6), the mean temperature is −20°C; however, the temperature in an orbit has a peak to peak variation of 15°C, and the difference in the temperatures between the upper and lower surfaces of CCR is a maximum of 2°C.

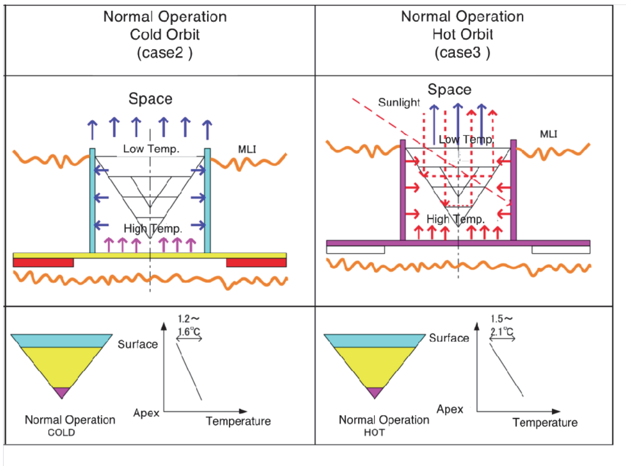

Fig. 6 Thermal Environment on CCR in Orbit

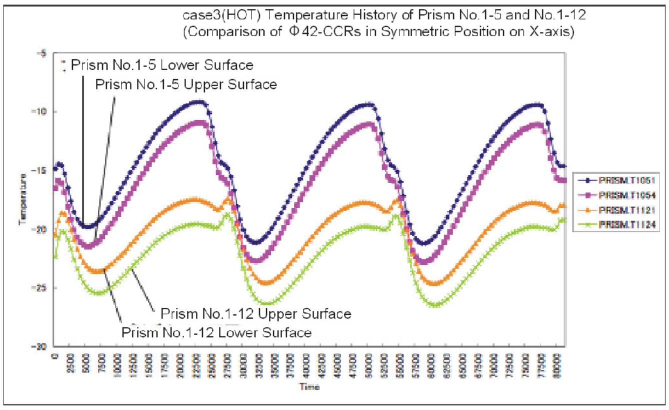

Fig. 7 Temperature History of Prism in a Satellite Orbit

The temperature change in the CCR due to the heat load in a room is shown in Fig. 8.

In the test, considering its influence on the FFDP, the CCR shows an example where pattern changes are detected while heating the entire surface of a reflective surface, where there is a significant change in the FFDP caused by heating.

By analyzing the atmosphere, this equipment heated a part of the CCR without making contact.

In future, techniques regarding low-temperature analysis and measurement in a vacuum will be studied.

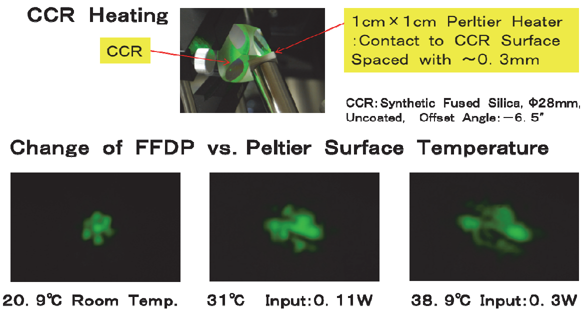

Fig. 8 Changes of FFDP by heating a CCR surface

CCR: −6.5 arcsec offset angle, Uncoated, 28, Synthetic fused silica

Heating by Peltier device (size: 1 × 1 cm^2) closed setting (about 0.3 mm) at the CCR back face.

8. Comparison with Theoretical Analysis

The theoretical analysis of FFDP is considered by carrying out simulations. Here, parameters, such as the caliber, form, wavelength, polarization, and incidence angle, were setup using a type of ray-tracing method mentioned in the reference.

The comparative example of the FFDP measurement result and the theoretical analysis result are shown in Fig. 9.

The effective 15 mm CCR corresponds to the experiment case. The laser is a horizontally polarized light, CCR has a setup of edge-up, and the incidence angle of the laser to CCR is perpendicular to the entrance plane.

Comparative examples are shown using two cases.

(1) Fig. 9-1 shows the case involving material BK-7 with the reflective surface in which the offset angle of the CCR is 0 arcsec (DAO=0 arcsec) and the back surface has no coat, noting the theoretical DAO can be set 0, however manufacturing of CCR DAO has a few 0.1 arcsec error.

(2) Fig. 7-2 shows the case involving the synthetic quartz material with the reflective surface in which the offset angle of the CCR is −6.5 arcsec (DAO=-1.4 arcsec) and the back surface has a silver coat.

The viewing angle of the display (the range of the square frame) is 120 × 120 μrad for both the measurement and analysis.

From the spread observed, the form of the pattern can be determined, and the qualitative intensity distribution is generally in good agreement. However, some lobes of image in measurement results differ in size and intensity distribution due to imperfectness of optics.

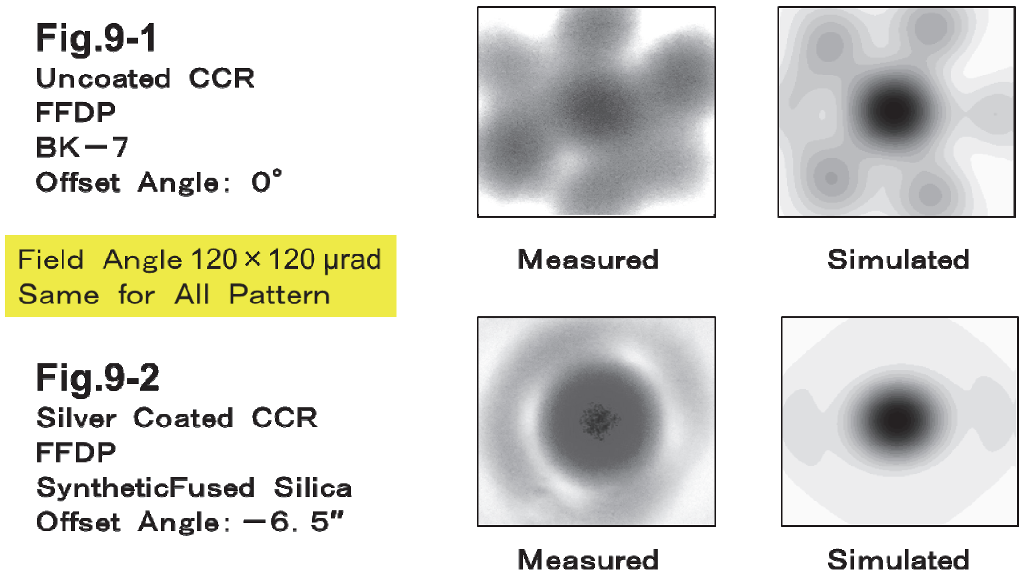

Fig. 9 Comparison of the Measured and Simulated FFDP

Laser input direction: normal to front face of CCR

Field of View: 120 × 120 μ/ rad

9. Conclusion

An experimental method used to view the FFDP with the polarization characteristic of CCR has been established for the purpose of evaluating the CCR onboard a satellite. The test set was preliminary, however, we obtained the following results:

1) The observation of the actual CCR FFDP and comparison with theoretical distribution.
2) Detection of the polarization characteristic of CCR using FDDP.
3) Detection of the change in FFDP by heating the CCR considering the heat load in the space environment.

It is the main problem that the temperature gradient of the FFDP in the CCR, which is because of heating in the space environment mainly due to sunlight. We intend to perform additional studies on an equivalent testing technique for sunlight irradiation in a vacuum condition.

The test is effective for limited apparatus for a CA diameter of 15 mm. The actual satellite loading CCR ranges from 10 mm to several hundreds of millimeter. Construction of a system that is applicable to CCRs with actual dimensions is a goal of future studies.

We hope to continue study and have an opportunity to apply the results to a domestic SLR satellite.

Acknowledgement

This experiment was carried out on the JAXA Sagamihara campus and was the basis of a joint research project named Astro-G, which was aimed at highly precise orbital determination, and was conducted between National Institute of Information and Communications Technology (NICT) and JAXA. The FFDP equipment that was utilized was developed by NICT. We appreciate the assistance provided by Dr. Hiroshi Takeuchi, who allowed the use of the facilities at the JAXA Institute of Space and Astronomical Science.

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