Abstract

Cosmic microwave background (CMB) is a blackbody radiation with nearly perfectly isotropic temperature of 2.7 K all over the sky. It is a remnant of the hot Big Bang universe and is a powerful probe to investigate the history of the universe. Its temperature anisotropy has been measured at a micro-kelvin level by *COBE*, *WMAP* and *Planck* satellites, from which the cosmological parameters, such as the energy compositions and the age of the universe, have been precisely determined.

In addition to the temperature, polarization anisotropy of the CMB is expected to contain crucial information on the inflationary era of the universe. It is predicted that primordial gravitational waves generated by cosmic inflation would have imprinted a unique polarization pattern in the large-angular-scale polarization structure of the CMB. Detection of such signals, called B-mode polarization, is one of the key issues in cosmology today.

Towards the detection of primordial B-mode polarization, we need a telescope with a wide diffraction-limited field of view that accommodates a large number of detectors. To separate foreground radiations from CMB, a broad frequency coverage is also required. One of the challenges to develop a wide-field and broadband telescope is to reduce far sidelobes and cross polarization. Far sidelobes contaminate the CMB signals with stronger radiations at angles far from the observing direction, such as those from the Galactic plane. Cross polarization induces correlated polarization angle offsets among the detectors and mixes B-mode polarization with the other mode, namely E-mode.

Among several forthcoming CMB experiments, *LiteBIRD* is a space mission to be launched in the late 2020s. It performs all-sky observation of CMB polarization at a degree and larger angular scales for three years. It aims to determine the tensor-to-scalar ratio r, which parametrizes the amplitude of primordial gravitational waves, with a total uncertainty of $\delta r < 10^{-3}$. The Low-Frequency Telescope (LFT) aboard *LiteBIRD* is a reflective telescope with a crossed-Dragone design, whose aperture diameter is 400 mm. It observes the CMB and low-frequency foreground radiations over 34–161 GHz with a field of view of $18^\circ \times 9^\circ$. Its optical requirements include far-sidelobe knowledge of -56 dB and knowledge of correlated offsets among the detector polarization angles at an arcminute level.

In this study, we have characterized antenna patterns and polarization angles of the *LiteBIRD* Low-Frequency Telescope (LFT) by optical measurements in a laboratory environment. Because the LFT is in a design phase, we scaled down both the geometries of the antenna and the measurement wavelengths to 1/4 size, keeping the electromagnetic condition equivalent to the full-scale LFT. We chose the measurement frequency at 140–220 GHz, which corresponds to the lowest bands, 35–55 GHz, of the full-scale LFT, where diffraction becomes larger.

For antenna pattern measurements, we developed a planar near-field measurement setup. We measured the complex electric fields near the aperture and transformed them into the far-field antenna patterns. We measured antenna patterns for three focal positions, the center and the edges of the focal plane, with two orthogonal polarization directions. We evaluated far sidelobes up to 60° from the boresight with a dynamic range of more than 70 dB. The measured antenna patterns were consistent with simulated ones down to -50 dB level. Far sidelobes for two orthogonal polarization directions showed consistent patterns down to -40 dB level. We also measured the cross-polar patterns and confirmed that their peak levels are less than -20 dB, most of which originate from the feed.

To further investigate the far sidelobes, we analyzed stray light by picking up sidelobe components with different path length. We applied a time gating to the measured antenna patterns. From the frequency spectra measured in the aperture plane, we computed time profiles of the arriving waves with ~ 0.1 ns resolution (corresponding to a path-length difference of ~ 30 mm). We identified far-sidelobe components in the time-gated antenna patterns whose arrival time and angular direction are consistent with stray light predicted by a ray-tracing simulation. The identified far-sidelobe components include stray light reduced but reflected inside the front hood and stray light with multiple reflections without intercepted by the front hood. Their intensities are less than the -56 dB level, which is the far-sidelobe knowledge requirement for the LFT.

For polarization angle offsets, we measured the polarization angles for 20 detector positions. We developed a dedicated compact-antenna-test-range (CATR) system, whose size is feasible to use for future cryogenic measurements. We placed a collimated-wave source, which consists of small CATR reflectors, near the scaled-LFT aperture and rotated the scaled-LFT feed polarization. The measurements are explained well with a simple Jones matrix calculation. The measured polarization angles agree with those measured by rotating the collimated-wave polarization in the scaled-LFT aperture at the $15''$ level for the on-axis case. We confirmed that the polarization angles at the edges of the focal plane are rotated by 1.5° compared to those at the center, as predicted by simulations. The uncertainties in the obtained angles were up to $1.9'$, which comes from a frequency variation of the angles due to standing waves.