Development of a contact-less cryogenic rotation mechanism employed for a polarization modulator unit in cosmic microwave background polarization experiments

Yuki Sakurai\textsuperscript{1}, Tomotake Matsumura\textsuperscript{1}, Nobuhiko Katayama\textsuperscript{1}, Teruhito Iida\textsuperscript{2}, Kunimoto Komatsu\textsuperscript{3}, Hajime Sugai\textsuperscript{1}, Hiroyuki Ohsaki\textsuperscript{1}, Yutaka Terao\textsuperscript{4}, Yukimasa Hirota\textsuperscript{4}, Hisashi Enokida\textsuperscript{4}

\textsuperscript{1}Kavli Institute for the Physics and Mathematics of the Universe (WPI), The University of Tokyo Institutes for Advanced Study, The University of Tokyo, 5-1-5 Kashiwanoha, Kashiwa, Chiba, 277-8583, Japan \textsuperscript{2}ispace. inc., Sumitomo Shibakoen Building 10F, 2-7-17, Shiba, Minato-ku, Tokyo, 105-0014, Japan \textsuperscript{3}Graduate School of Natural Science and Technology, Okayama University, 3-1-1 Tsushima-naka, Kita-ku, Okayama, 700-8530, Japan \textsuperscript{4}Graduate School of Frontier Sciences, The University of Tokyo, 5-1-5 Kashiwanoha, Kashiwa, Chiba, 277-8561, Japan

E-mail: yuki.sakurai@ipmu.jp

Abstract. We present the design and the performance of a contact-less cryogenic rotation mechanism used in cosmic microwave background (CMB) experiments. A precise measurement of the CMB polarization is possible to verify the cosmic inflation theory that describes the very beginning ($10^{-38}$ seconds) of the early universe. The polarization modulator, that rotates a half wave plate continuously at the aperture of the telescope, is one of the key instruments in the experiments. In order to reduce noise and systematic uncertainties, the polarization modulator is required a stable rotation with minimal heat dissipation in a cryogenic environment less than 20 K. Thus, we adopted the rotation mechanism that combines completely contact-less bearing and motor, a superconducting magnetic bearing, and a hollow bore synchronous motor. The heat dissipation and the load torque due to the friction can be minimized by avoiding physical contacts. We constructed the prototype of the rotation mechanism and carried out mechanical and thermal performance tests. A continuous rotation test in cryogenic temperature is performed, and it is confirmed that the rotation stability is less than 1% with the rotation frequency between 0.5 Hz and 3.0 Hz. We also conducted a thermal performance test, and obtained the heat dissipation at the rotor of 9.0 mW. We discussed the reduction of heat dissipation using a developed magnetic circuit with improved magnetic field uniformity.

1. Introduction
The Big-Bang theory is established as a standard theory in current cosmology from both theoretical and observational point of view. However, it has several unsolved problems such as the flatness, the horizon and the mono-pole problems. Therefore, cosmic inflation theory \cite{1, 2} has been proposed, which describes rapid expansion of the universe after $10^{-38}$ seconds from the beginning of the universe. The mysteries of current cosmology can be solved by this theory, and it can be a clue to ultra high energy physics and furthermore ultimate unified...
theory. This inflation theory is predicted to leave a characteristic polarization pattern to cosmic microwave background (CMB) which was emitted at the Big Bang. The CMB is electromagnetic microwave radiation with a wavelength from $\mu$m to mm. It is still observable isotropically from the whole sky today. The CMB polarization observation experiments are actively planned and carried out worldwide toward the experimental verification of the inflation theory. In addition, the CMB polarization signal has sensitivity not only to the inflation but also to the large scale structure of the universe and the mass sum of neutrinos. Thus, the development of experimental instruments related to this experiment has been rapidly advanced.

As the simplest configuration, the instruments of the CMB polarization experiments consist of a telescope and a detector. The incident CMB signals are focused to a focal plane by the telescope, and then they are detected by an array of superconductor detectors. The CMB polarization signal is suffered from the thermal emission from instruments, and thus all instruments are cooled down to cryogenic temperature. In addition, the signal is very weak compared with the detector noise and fake signals from galaxy and atmosphere. Therefore, the critical point of this experiment is how to reduce the noise and systematic uncertainties. One of the key instruments to reduce them is a polarization modulator unit (PMU). It consists of an optical element, a half-wave plate (HWP), and a rotational mechanism. The incident linear polarized signal is rotated after passing through the PMU. As a result of this rotation, the signal is modulated to a high frequency region. This modulation significantly reduces the low frequency noise ($1/f$ noise) and mitigates the differential systematic uncertainties. The PMU has already been installed on ground and balloon experiments and its feasibility has been demonstrated [3, 4, 5]

Installing the PMU has great benefits, while there are systematic uncertainties and thermal noise due to the PMU itself. Thus, the rotation mechanism is required to perform a stable continuous rotation with minimal heat dissipation at cryogenic temperature less than 20 K. It can be realized by a completely contact-less rotation mechanism which can minimize the loss due to the physical friction and the load torque.

We fabricated the prototype system of the rotation mechanism and conducted the performance test at cryogenic temperature. In this paper, we describe the rotational performance and thermal characteristics of the prototype system.

2. Prototype system and experimental setup
We designed and fabricated the prototype system of the rotation mechanism of the PMU. The rotation mechanism has a hollow-bore for mounting the HWP to its inside. The typical diameter of telescope aperture is $\phi \sim 400$ mm in CMB polarization experiment. We designed a slightly smaller inner diameter of $\phi = 380$ mm for the demonstration purpose. The overall design and components follows a small prototype ($\phi = 100$ mm) which has already demonstrated stable rotation at cryogenic temperature [7]. The rotation mechanism consists of a superconducting magnetic bearing (SMB), a synchronous motor, an optical encoder, a cryogenic holding mechanism. Figure 1 shows a photograph and a 3D-CAD design of the prototype system.

The SMB is contact-less bearing, which employs an array of high temperature superconductor tiles as a stator and a permanent magnet as a rotor [6]. The rotor levitates above a stator and spins without physical contact, and thus this technology is suitable for this application. The rotor and the stator are formed into ring shaped using multiple segmented parts due to its large diameter. The stator is formed into a ring shape by combining 20 segmented three seeded superconductor bulks. We employs a YBCO($Y_{1.65}Ba_2Cu_3O_7$) as the material of the superconductor since its transition temperature of $\sim 95$ K is sufficiently higher than the required temperature of 20 K. We use a ring shaped NdFeB magnet as the rotor. It consists of 16 segmented NdFeB magnets magnetized axially with a magnetic remanece of 1.24 T.

The synchronous motor is used as drive mechanism in the rotation mechanism. It consists
Figure 1. The left and the right panel shows the photograph and the 3D-CAD image of the prototype system of the rotation mechanism.

of 12 poles and 18 phases A copper wire coils and a SmCo permanent magnet are adopted as a stator and a rotor, respectively. The stator coils are sandwiched between upper and lower pairs of rotor magnets. The magnets are surrounded by the C shaped magnetic yoke in order to close the magnetic flux. This design realizes the high efficient motor, and the loss can be minimized. The output of the optical encoder and a cryogenic hall sensor are used as feedback signals in order to control the motor. Three hall sensors are installed inside the stator. The optical encoder is used not only for the feedback signal but also for reconstructing the optical axis angle of the HWP during rotation. An infrared LED and a silicon photo-diode (SiPD) are used as a light source and a detector, respectively. The metal encoder disk with 128 slots is mounted on the top of the rotor. We adopted the incremental encoder to reconstruct both absolute and relative angles, and thus three sets of the LED and SiPD are installed near the stator of the motor.

The cryogenic holder mechanism has two purposes. One is to hold the rotor from room temperature to cryogenic temperature, and the other one is to cool the rotor after the rotation. It consists of a cryogenic stepping motor and a linear actuator. Three mechanisms are installed at 120 degree intervals. A convex arm is equipped in the actuator, and it is designed to match the V groove which is attached to the magnetic holder in the rotor. The stepping motor is possible to drive in vacuum and cryogenic temperature.

The prototype system is installed in a $\phi = 800$ mm 4 K cryostat using a Gifford-McMahon cooler with the cooling power of 1.5 W. The whole system is cooled down less than 10 K in about 10 days.

3. Rotational stability
We performed cryogenic rotation test using the prototype system in the 4 K cryostat. The typical rotation frequency of the PMU $f$ is required to be from 0.5 ~ 5.0 Hz. Also, the rotation stability $\Delta f$ is required to be less than 1.0% from the viewpoint of systematic uncertainties. The procedure of the experiment is as follows:

1. Install the prototype system in the cryostat and cool down to a thermal equilibrium.
2. Operate the cryogenic holder mechanism and release the rotor.
3. Set the rotation frequency and drive the synchronous motor.
4. Rotate at set frequency for a fixed time.
5. Turn off the synchronous motor and stop the rotation.
6. Close the holder mechanism and cool the rotor to the initial temperature.
We iterate above procedure by changing the setting rotation frequency to 0.5, 1.0, 2.0, 3.0 Hz. The rotation frequency is reconstructed by the encoder signal. The left plot of Fig. 2 shows the reconstructed rotation frequency for each setting frequency. We obtained the rotation stability as $\Delta f \leq 1\%$ for all rotation frequencies. We also tested the continuous rotation for long time of 23 hours, as shown in the right plot of Fig. 2. We did not observe deterioration of rotation even in the 23 hours operation. The 23 hours is not a limitation, and thus longer operation time will be tested according to the requirement of the experiment. From these result, we successfully demonstrated the feasibility of the cryogenic rotation below 10 K.

![Figure 2.](image)

**Figure 2.** The left plot shows the rotation frequency as a function of operating time for each rotational speed of 0.5, 1.0, 2.0 and 3.0 Hz. The right plot shows the long term operation performance. The continuous rotation is kept for 23 hours.

### 4. Thermal characteristics

It was confirmed that the requirement of the rotation stability is satisfied using the prototype system. Another important requirement of the PMU is related to the thermal characteristics during the rotation. The temperature of the HWP mounted on the rotor is required to be less than 20 K during the rotation to suppress the thermal loading from the HWP. The thermal simulation model of the prototype system has been built in order to estimate the heat dissipation at rotor with keeping the HWP temperature of less than 20 K. From the simulation, the heat dissipation at the rotor is required to be less than 1.0 mW. We performed the constant rotation test to estimate the heat dissipation at rotor of the prototype system. Since this rotation mechanism is completely contact-less, it is difficult to directly measure the rotor temperature during rotation. Thus, we estimated it using the temperature of the gripper arm of the holder mechanism. The left plot of Fig. 3 shows the thermal profile during the rotation test with setting rotation frequency of 1.0 Hz and the operation time of 5 hours. The procedure of the experiment is the same as that described in the previous section. The temperature of the gripper arm rises following the rotor temperature after the rotation. We measured this temperature rise for each operation time from 10 minutes to 23 hours. We carried out the same procedure in the thermal simulation assuming several constant heat input to the rotor. The temperature rises of the gripper arm from the measurement and the simulation are compared, and then it was confirmed that the heat input to the rotor was 9.0 mW. The experiment and the simulation are consistent within 5%. The right plot of Fig 3 shows the temperature rises of the gripper arm from the experiment and the simulation as a function of the operation time. The estimated rotor temperature is also shown in the plot. The thermal conductivity of the holder mechanism has
already been measured, and it is used for the thermal simulation. The validity of the thermal simulation has already been verified, as referred to [10].

![Figure 3](image)

**Figure 3.** The left plot shows the temperature profile during the rotation and the cooling. The rotation frequency is 1.0 Hz and the operation time is 5 hours. The right plot shows the comparison of the temperature rise of the holder mechanism between the experiment (blue) and the thermal simulation (red). The estimated rotor temperature (green) is also shown.

5. **Improvement of the heat dissipation**

The obtained heat dissipation at the rotor from the performance test is 9.0 mW, which does not satisfy the requirement of 1.0 mW. Thus, it is necessary to reduce the losses of the rotation mechanism. The major source of the heat dissipation at the rotor is hysteresis and eddy current losses due to the SMB. These losses strongly depend on the magnetic field homogeneity of the rotor magnet. It is defined as

\[
\frac{\Delta B}{B} = \frac{B_{\text{max}} - B_{\text{min}}}{B},
\]

(1)

where \(B_{\text{max/min}}\) and \(B\) are maximum, minimum and mean values in the magnetic field distribution, respectively. The current rotor magnet is formed by 16 segmented NdFeB magnets with an axial magnetization with respect to the stator. We measured the magnetic field of axial direction at the center position of the magnet in the cross section. The magnetic field distribution of this magnet has spikes due to gaps between the segmented magnets. The magnetic field homogeneity of the NdFeB magnet is 9.4%, and this is the cause of the losses. Therefore, we developed a ring shaped magnetic circuit. It consists of 64 segmented SmCo magnets with a magnetic remanence of 1.17~1.21T. It is magnetized in the radial direction with respect to the stator. The segmented magnets are sandwiched with ring magnetic yokes in the radial direction. The effect due to the gap between the segmented magnets is alleviated by the magnetic yokes. We measured the magnetic field at the center position and its homogeneity is 2.1%. The NdFeB ring magnet and the developed SmCo magnetic circuit are shown in Fig. 4, and the magnetic field distributions are shown in Fig. 5.

According to the Beans model of the SMB theory, the energy loss due to the hysteresis is modelled as

\[
\Delta E \propto \frac{(\Delta B)^3}{J_c},
\]

(2)

where \(\Delta E\) is the energy loss, \(\Delta B\) is the magnetic field homogeneity and \(J_c\) is a critical current density of the YBCO. The hysteresis loss is proportional to the cube of \(\Delta B\) since \(J_c\) is constant.
Figure 4. The photograph of the fabricated magnets. The left photo shows the NdFeB ring magnet formed by 16 segmented axial magnetized magnets. The right photo shows the SmCo magnetic circuit formed by 64 segmented radial magnetized magnets and ring shaped magnetic yokes. The conceptual diagrams of the cross section and the magnetic flux lines are also shown below each photo.

value. The energy loss due to the eddy current is proportional to the square of the $\Delta B$. Thus, the hysteresis loss and the eddy current loss are expected to reduce fractions of $(2.1/9.4)^3 = 0.01$ and $(2.1/9.4)^2 = 0.05$, respectively. There are also hysteresis and eddy current losses due to the synchronous motor. However, these losses can be significantly reduced by the optimization of the material selection and the mechanical design. In the prototype system, it is composed of almost metallic material, and the energy loss is not fully taken into account in the mechanical design of each mechanism. In addition, we conducted electromagnetic simulations and confirmed that they have not significant impact compared with the SMB losses. From the above discussion, it is promising to reduce the rotor heat dissipation to less than 1.0 mW.

Figure 5. The magnetic field from the NdFeB ring magnet (left) and the SmCo magnetic circuit (right) with respected to the angle of the ring magnet. The magnetic field homogeneities of the NdFeB magnet and the SmCo magnetic circuit are 9.4% and 2.1%, respectively.
6. Conclusion

We are developing a contact-less cryogenic rotation mechanism of the polarization modulator used for the CMB polarization experiment in order to verify the inflation theory. We constructed the prototype system and carried out the performance test.

The stable continuous rotation in cryogenic temperature was successfully demonstrated with rotation frequencies from 0.5 Hz to 3.0 Hz. The rotation frequency was reconstructed with the optical encoder and the rotation stability was less than 1.0%. We also succeed to operate a long term operation of 23 hours.

The requirement of the heat dissipation at the rotor is less than 1.0 mW to keep the HWP temperature less than 20 K. Thus, we carried out the thermal performance test in order to evaluate the rotor heat dissipation. The temperature difference of the holder mechanism before and after the rotation was measured for each operation time. We established the thermal model of the prototype system, and simulated the temperature of the holder mechanism with a constant heat input to the rotor. The measured and the simulated temperatures of the holder mechanism are consistent within 5% with the rotor heat dissipation of 9.0 mW. The estimated heat dissipation does not satisfy the requirement. However, there is much room for improvement. One of the major improvements is to use the developed SmCo magnetic circuit as the SMB rotor, which has better magnetic field homogeneity than the current magnet. Other hysteresis and eddy current losses can be significantly reduced by an optimization of a material selection and of a mechanical design. We will continue to this development to minimize the heat dissipation.

Acknowledgments

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