Development of novel calibration methods and performance forecaster of cutting-edge superconducting detector MKIDs for CMB experiments

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論　文　内　容　要　旨

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学位論文の 題　　　目	Development of novel calibration methods and performance forecaster of cutting-edge superconducting detector MKIDs for CMB experiments (CMB 実験応用を目的とした最先端の超伝導検出器 MKIDs の新しい較正手法と性能推定ツールの開発)		

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The Big Bang theory has recognized widely as the standard model describing the evolution of the universe. However, the theory is inherent by the fundamental problems, e.g., the horizontal problem and the flatness problem. In 1980s, Alan Guth and Katsuhiko Sato proposed the inflationary cosmology. Assuming the universe had an exponentially expanding period at the very early universe, they showed that these problems are naturally solved. According to the standard inflation theory, the tensor fluctuation was generated due to the quantum fluctuation of the space-time during the inflation period and it drifts in our universes as the primordial gravitational wave. The cross mode and plus mode primordial gravitational waves imprint the *B*-mode and *E*-mode polarizations in the CMB, respectively. Since the scalar mode fluctuation generates only the *E*-mode polarization, the detection of the *B*-mode CMB polarization provides smoking　gun evidence of the inflation theory.

Many observation efforts have been done aiming for the first detection of the primordial *B*-mode CMB polarization. The power spectrum of the CMB *B*-mode polarization has two bumps. One is called recombination bump appeared at around small angular scale of 2 degree (l~100), and the other is called reionization bump appeared at around large angular scale of 20 degree (l<10). Many conventional ground-based CMB experiments target to detect the recombination bump. However, the expected amplitude of the primordial *B*-mode CMB polarization is less than the *B*-mode polarization caused by the disturbance on the *E*-mode CMB polarization due to the gravitational lensing effect of the large scale structure. On the other hand, the detection of the reionization bump from the ground-based observation is limited by 1/f atmospheric fluctuation. The atmospheric fluctuation becomes significant below 0.1 Hz. It is hard to detect reionization bump by conventional ground-based observations since it is impossible to cover a few tenth degree of sky within a few second. To access the reionization bump by the ground-based CMB polarization experiments, invention for observational strategy to mitigate the atmospheric fluctuation is required.

The sum of neutrino masses is one of the important parameters in describing the evolution of the early universe. It is experimentally proposed that the neutrinos have mass. Since the non-zero neutrino mass can not be explained by the standard model of the particle physics, the neutrinos are the only particles beyond the standard model currently known. We can evaluate the sum of the neutrino masses from the observation of the *B*-modes polarization due to the gravitational lensing effect of the large scale structure. However, to limit the sum of neutrino masses from the *B*-mode polarization due to the gravitational lensing effect of the large scale structure we need to know the precise optical depth at the reionization epoch τ, since the influence of the gravitational lensing effect of the large scale structure and Thomson scattering by the free electrons in the reionization are strongly degenerate. To evaluate the optical depth at the reionization epoch, the CMB *E*-mode polarization below l~ 10 is useful since the scalar perturbation below l~ 10 entered inside of the Hubble horizon after the reionization epoch. There is a systematic difference in the estimated τ between WMAP and Planck satellites results. The independent measurement of the optical depth at the reionization epoch by the CMB polarization experiment which is able to perform the secure measurement of the large angular scale signal is an important.

In order to observe the faint signal like the CMB polarization, various types of large format detector arrays toward astronomical observations, including CMB polarization observations are proposed. Recently, majority of CMB polarization experiments use a superconducting detector as a focal plane detector, because it is sensitive enough to reach the noise level of the photon noise of the atmosphere for the ground-based observations. At present, many millimeter and submillimter telescope including CMB observation use a large format Transition Edge Sensor (TES) array as a focal plane detector. The TES is a superconducting detector. In next decade, over mega pixel focal plane detector is going to be required in order to increase the precision of the observations. However, the development of the mega pixel TES camera is hard with the current readout multiplexer system. The Microwave Kinetic Inductance Detector (MKID) is the cutting-edge superconducting detector which enable to break the mega pixel wall. The advantage of the MKID is that it has
a potential to read over thousands pixels per single readout line. Moreover, the time response of the MKID (< 100 μs) is significantly faster than the TES.

Although the MKID is the detector technology which is supposed to explore the mega pixel era, it has several fundamental problems which have to be overcome. The one is that there is significant systematic uncertainty involved in the calibration of the detector performance since there is no novel method for the responsivvity calibration. The MKID for millimeter and submillimter astronomical observations is operated at 250-300 mK. Every day or a few day, the MKID is once warmed up above the transition temperature and cooled down below the transition temperature again. Since the performance of the MKID changes every cooling cycle, we have to perform calibration of the performance of the MKID, especially its responsivity, every cooling cycle. Conventionally, the calibration of the responsivity of the MKID has been performed by measuring the change of the response when the temperature of the detector mount plate is heated up by controlling the heater attached to the mount plate. This method is inevitable from following systematic error. It always accompanies uncertainties whether the plate temperature measured by the thermometer coincides with the detector temperature. This method is also time consuming. It takes several hours for every calibration. Therefore, a few 10% of the observational time is consumed by the responsivity calibration. The other problem is that the 1/f type noise always appears and it limits the performance in low sampling frequency. This noise is supposed to be attributed to the two level system (TLS) formed in the interface of the supercoducting material and substrate. To realize the photon noise limit high sensitivity MKID down to low sampling frequency, we have to mitigate the TLS noise in someway. The third problem is that there is no method to measure the superconducting transition temperature, Tc, of the hybrid type MKID which is widely used for the recent astronomical observations. The superconducting transition temperature of the MKID is one of the crucially important parameters to fix the design of MKID and evaluate performance.

The GroundBIRD is a ground-based CMB polarization experiment to probe the inflationary cosmology. For enabling to attack the reionization bump of the primordial *B*-mode CMB polarization and to observe the precise optical depth to reionization from the ground by mitigating the 1/f atmospheric fluctuation, the GroundBIRD performs a rapid rotation scan around the zenith direction with inclining the telescope 30 degree from zenith at rotation speed of 20 rotations per minute, which corresponds to 3 seconds for one rotation. Because of the earth rotation 44% of the full sky area is covered in a day. Since the time response of MKID is significantly faster than TES and satisfies the requirements from the rapid rotation scan strategy, MKID is installed on the focal plane of the GroundBIRD. We show in this thesis that the performance of the prototype MKID is far from the GroundBIRD observation requirements based on the results of our performance verification experiments as shown in Chapter.3. The 1/f type TLS noise dominates over the generation and recombination noise below 100Hz. Further research and development is required to optimize performance of the MKID to the GroundBIRD observation. However, the one cycle from the design to evaluation is about three months. We have to iterate this cycle several times to feed back the results to new design. Dramatic reduction of the consumption for this research and development cycle is desired.

We propose new method for the responsibity calibration in Chapter 4. The method uses the change of the number of the excess quasiparticles while changing　the microwave readout power. By changing microwave readout power　from high power to low power abruptly, the number of the excess quasisiparticles transit to a new steady state　with time constant. This time constant is called quasiparticle lifetime and the time has an relation between the number of quasiparticles in the MKID. We evaluate the number of quasiparticles from the quasiparticles lifetime using theoretical formula. As a result,　the responsivity is extracted. We apply this method for the real measurement using the MKID maintained at 285 mK. We confirm the consistency between the results obtained using this method and conventional calibration methods. Since our method is free from the above mentioned systematic accompanying in the conventional method, the our method provides much more secure results compared with the conventional method. Furthermore, the time duration consumed for the calibration dramatically shortened, down to 10 minutes, by our proposed method.

We propose a new method to measure the Tc of MKID by abrupt　change of the applied readout microwave power. The number of quasiparticles in the MKID decrease with the quasiparticle lifetime during abrupt　change of the applied readout microwave power. Therefore, we can measure the relation between the quasiparticle lifetime and the detector phase response by abrupt change of the readout microwave power. As a results, we can estimate the intrinsic quasiparticle lifetime. The intrinsic quasiparticle lifetime is theoretically modeled by Tc, the physical temperature of the device and other known parameters. We can extract Tc by comparing the measured lifetime with theoretical model. Using an MKID made of aluminium, we demonstrate this method at a 0.3 K operation. The results are consistent with those obtained by Tc measured by monitoring the transmittance of the readout microwave power for various device temperature. The proposed method opens a possibility to measure Tc of the hybrid type MKID directly. Since there was no method to measure Tc, the speculated value of Tc has been adopted. The speculated values vary largely from author to author in the range from 1.1K to 1.5K. This introduces tenfold difference in the estimated noise level of the MKID under dark condition. Our method fixes this large uncertainty and dramatically improves precision of designing the MKID. Since the photon noise of the atmosphere dominates over the intrinsic noise of the MKID for the GroundBIRD application, the uncertainty of the noise level introduced by the uncertainty of Tc in the range of 1.1 K to 1.5 K is about 20%.

We develop the forecaster which evaluate the performance of MKID quantitatively by setting environmental variables and design parameters as sown in Chapter 6. By inputting the design parameters of the prototype MKID into the forecaster, we confirmed that the TLS noise dominates over the BLIP noise below 100 Hz and that the main problem of the prototype MKID is its design. We show that this bad performance is attributed to the design. Since the total width of the coplanar waveguide (CPW) line made from Nb of the prototype MKID is too narrow, the contribution of the TLS noise became prominent. A new design of MKID with widening the total width of CPW line made from Nb is proposed. We evaluate the expected performance of the new design MKID using the forecaster in Chapter 7. We showed that the TLS noise is significantly reduced from that of the prototype MKID and is suppressed below the BLIP noise down to the GroundBIRD rotation frequency (0.3 Hz).

別　紙

論文審査の結果の要旨

沓間君は、日西韓国際共同プロジェクトである宇宙マイクロ波背景放射偏光観測実験 GroundBIRD 望遠鏡の開発に主要メンバーとして携わり、その過程で得た超伝導検出器 MKID の開発に関わる成果を博士論文としてまとめた。沓間君は、MKID の基礎開発に質的改善をもたらす独創的な性能評価手法を２つ考案した。これらの成果は、それぞれ査読論文 Applied Physics Letters、AIP Advance に沓間君を筆頭著者とした論文として出版された。一つ目の成果は、入力パワーを瞬時の切り替えに伴う出力の変化から、MKID の応答時定数を測定する方法の考案と実験による実証である。この方法により今まで数時間掛かっていた MKID の性能評価測定が数分でできるようになった。この方法の出現により、天候の急激な変化や装置の状態の変化に応じて頻繁に検出器の性能評価ができる可能性が開かれ、測定のさらなる精密化が可能となった。二つ目の成果は、入力パワーゼロの時の時定数である固有時定数を外挿し MKID の超伝導転移温度を測定する手法の考案と実験による実証である。この手法の出現によりこれまで超伝導転移温度の測定が困難であった複数の材質からなるハイブリッド型 MKID の超伝導転移温度の測定が初めて可能となった。MKID の設計確度の向上に大きく貢献する成果である。さらにハイブリッド型 MKID のこれまでの知見を整理し、設計パラメータ・使用環境パラメータを入力すれば性能をシミュレートしてくれる GUI インターフェースを開発した。これにより作成と評価を繰り返すことで完成まで長い年月が掛かっていた開発過程を一気に加速することに道をつけた。手始めにこれを GroundBIRD 望遠鏡搭載用ミリ波カメラの設計に応用し、その設計に基づいた検出器をオランダ・デルフト工科大学と共同で製作中であり、GroundBIRD 実験が一気に進展することが期待される。以上のことは沓間君が、自立して研究活動を行うに必要な高度の研究能力と学識を有することを示している。したがって，沓間弘樹提出の博士論文は，博士（理学）の学位論文として合格と認める。