Development of Pancharatnam achromatic half-wave plate for polarization modulator of LiteBIRD

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研究拠点形成事業
Core-to-Core Program

Introduction

Inflation is one of the theories giving rise to the initial condition of the hot big bang of our universe. The rapid space expansion which occurred immediately after the universe was born expanded the quantum fluctuation of the space-time, generating the primordial gravitational waves. The primordial gravitational waves created the B mode polarization in large scales of Cosmic Microwave Background (CMB). The strength of the gravitation waves is represented as a tensor-to-scalar ratio r. Most of the inflation models with a single scalar field predict a value of r to be greater than 0.01. The value of r can be measured from B mode polarization.

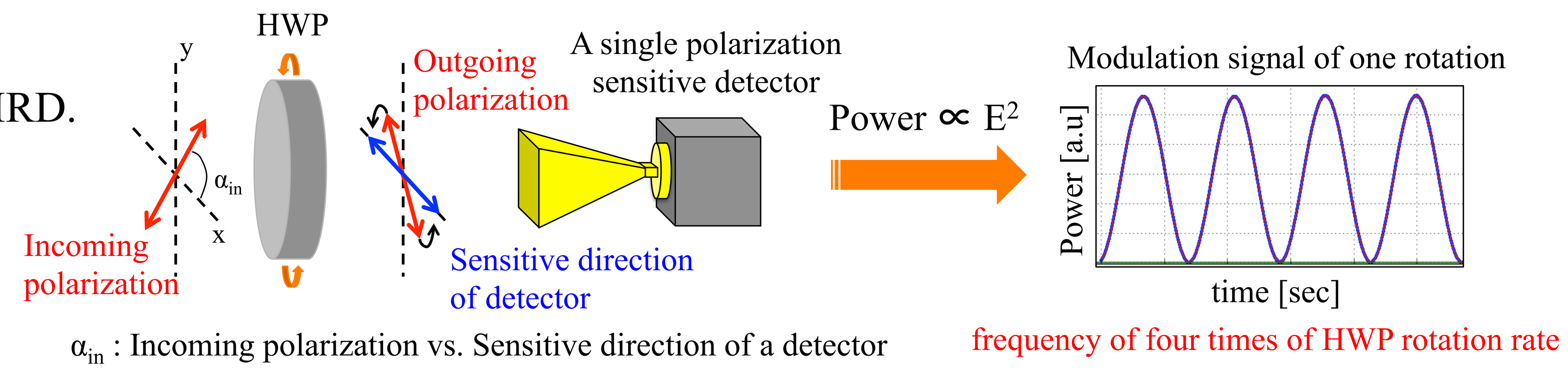
LiteBIRD is a satellite project to measure the polarization of CMB with an unprecedented accuracy by observing all the sky for three years at the sun-earth Lagrange point 2. The goal of LiteBIRD is to detect the B-mode polarization in a large angular scale and to measure the value r with an accuracy of $\delta r < 0.001$. In order to mitigate some of systematics, LiteBIRD plans to mount the continuous rotating half wave plates (HWPs) to modulate polarization of the incoming light. We report our development status of the HWP.

Polarization modulator

- The continuous rotating HWP can modulate the polarization angle of the incoming light electric field with a frequency twice of the rotation rate. When we use the detectors sensitive to the single polarization, the observed signal has a frequency of four times of the HWP rotation rate.
- The advantages of using the polarization modulators are followings:
  - The polarization can be measured using a single detector → Remove systematics arising from the difference in multi detector characteristics.
  - Mitigate 1/f noise by shifting the signal frequency above the knee frequency.
- The requirements to the HWP specification for the low frequency telescope of LiteBIRD.

Frequency range	Life time	Diameter	PME*	Transmittance	Temperature
34-270 GHz	> 3 year	40 cm	> 0.98	> 0.99	< 10 K

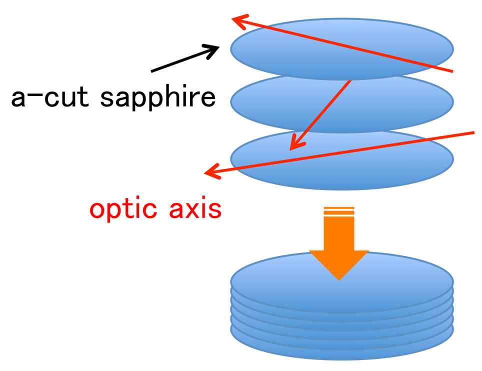
* Polarization Modulation Efficiency (PME), a ratio of the polarization intensity of the outgoing to incoming light. In ideal HWP case, PME is equal to one.

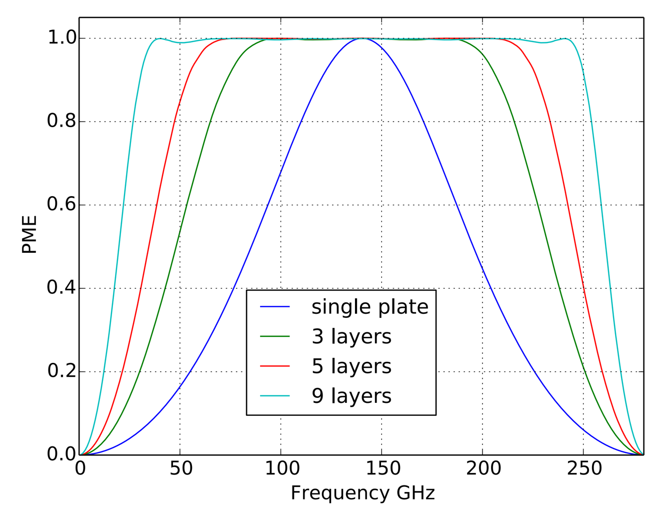


α_{in} : Incoming polarization vs. Sensitive direction of a detector

Achromatic half wave plate (AHWP)

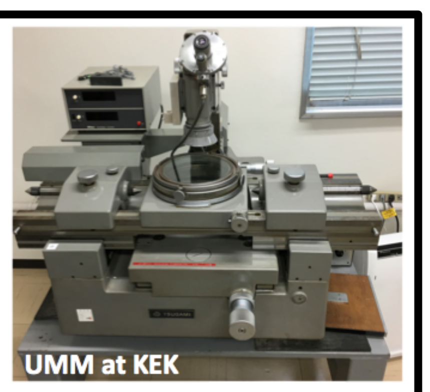
- A single layer HWP cannot cover all the frequency range from 34 to 270 GHz.
- To cover the targeted frequency range, we make use of Pancharatnam-type achromatic half-wave plate (AHWP).
- AHWP consists of a stack of nine layers.
- The relative optic axes are rotated by the angles optimized by the PME.
- The material we are going to use is A-cut sapphire plates.
- The right-hand plot shows the calculated PME as a function of frequency for AHWP stacking single, three, five and nine layer HWPs, assuming the perfect anti-reflection structure of the surface.



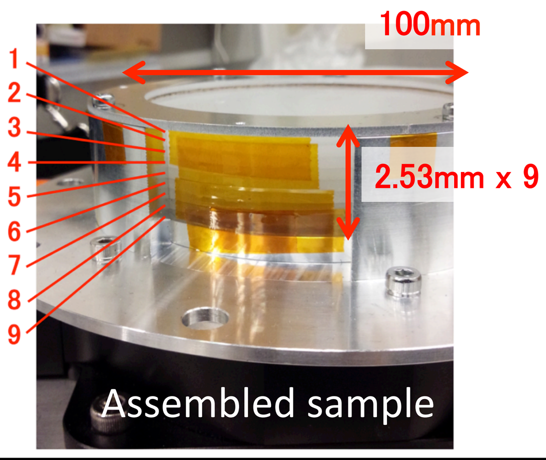


Sample assembly

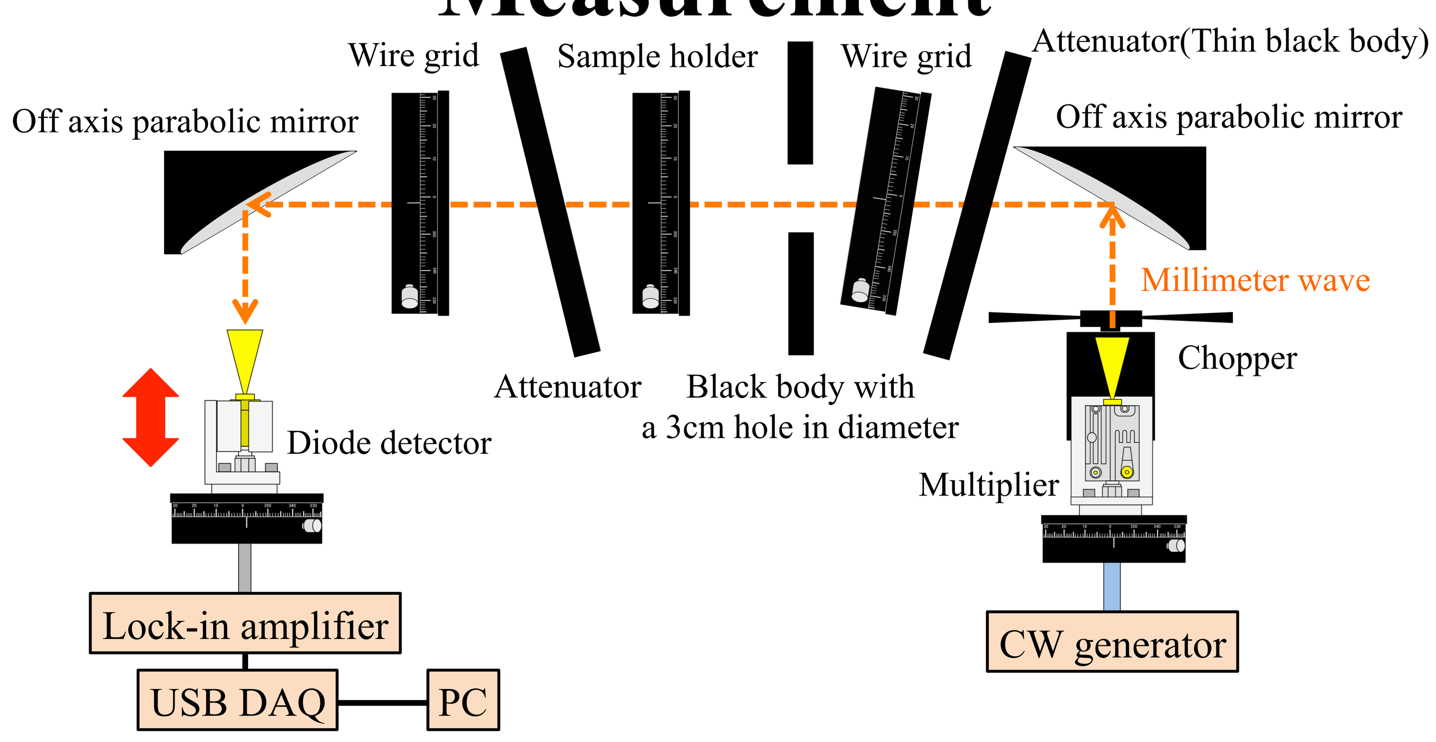
- We fabricated the AHWP using a universal measurement machine.
- The accuracy of relative angle between those plate is 10 arcmin with reference to orientation flat surface.



- The sapphire plates thickness is 2.53 mm, diameter is 100 mm.
- The thickness of sapphire plates is a little thin to center frequency of LiteBIRD.
- The anti-reflection is not applied in this sample.



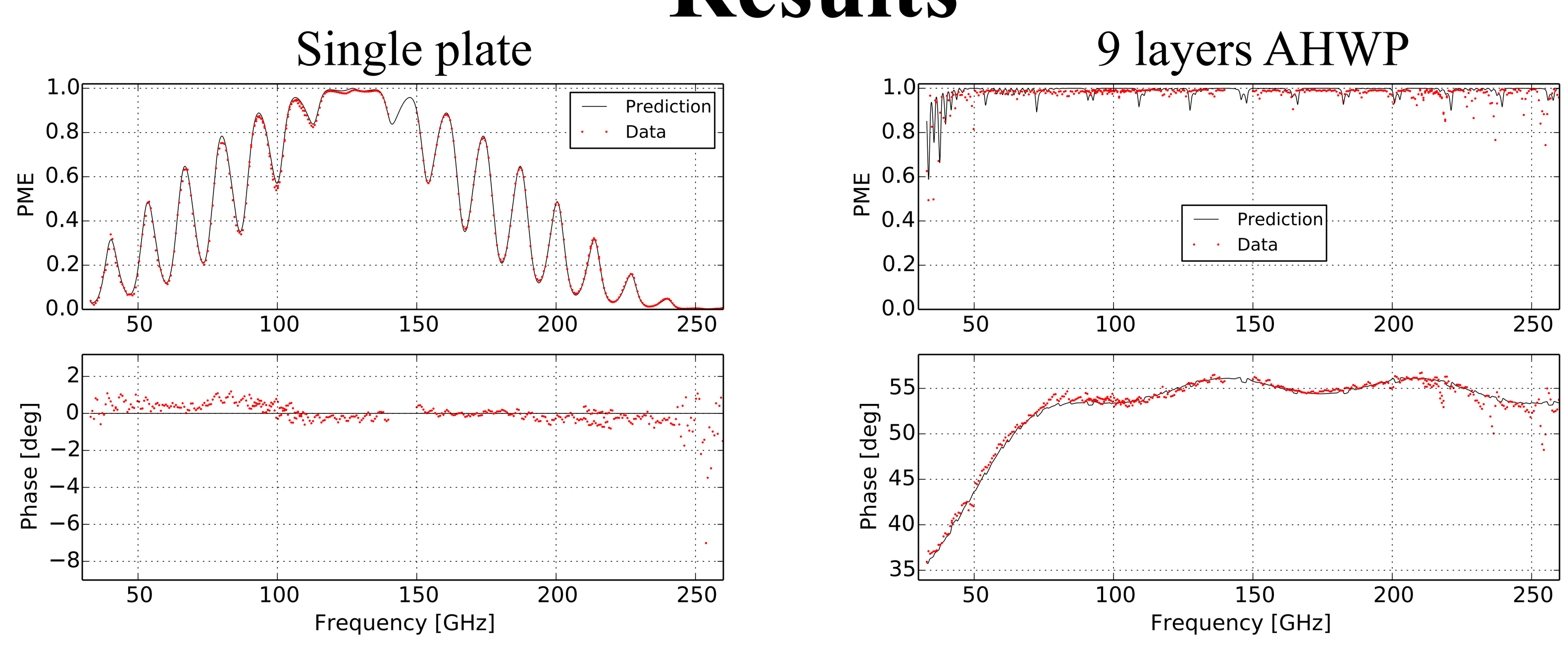
Measurement



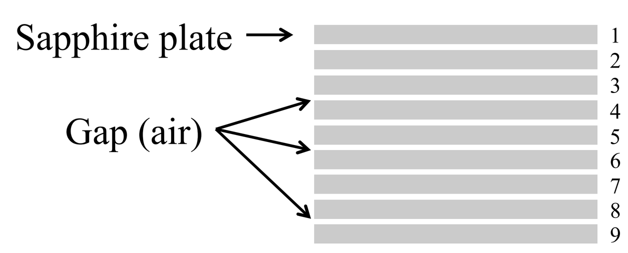
- This system can measure the transmitted power of the specimen with the frequency range of 33 to 260 GHz.
- The injected waves are polarized larger than 99%.
- The plane wave is formed with the first parabolic mirror.
- We set the nine layer AHWP in the system and rotate it continuously.
- We measure the single polarization power of the light passing through the plate as a function of the rotation angle.
- We fit the angle dependence using the function D(t) to obtain PME which is defined as the ratio of a_4 / a_0, and a phase of the modulation with a frequency four times of the rotation rate.

$$D(t) = a_0 + \sum_{n=1}^{8} a_n \cos\{n(\omega t + \phi_n)\}.$$

Results



- The black line is the prediction calculated taking into account the reflection.
- The dips of the PME are caused by the reflection.
- We measured the PME and phase for a single plate to test the measurement system, and confirm that the measurement results are consistent with the predictions.
- We confirm that the PME of the nine layer AHWP covers the wide frequency range.
- We find some dips found in the nine layer AHWP are deeper than the expectations. This is supposed to be caused by the air gap between the HWP layers.

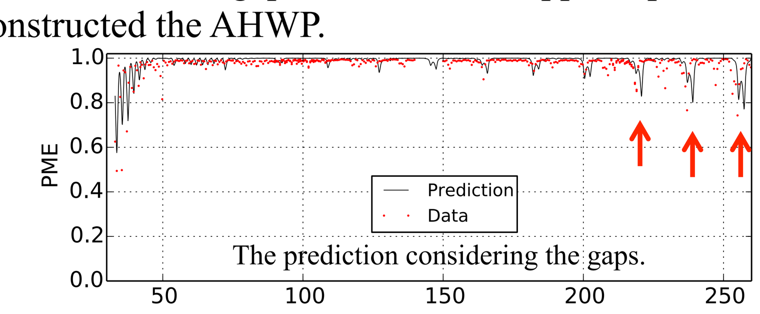


- In the table, we compare the mean PME values of individual frequency bands between the measurements and the expectations with and without the gaps.

band GHz	Simulation*		Data
	w/o gaps	w/ gaps**	
40 (34.0-46.0)	0.919	0.921	0.897
50 (42.5-57.5)	0.989	0.992	0.966
60 (53.1-66.9)	0.984	0.988	0.982
69 (60.2-75.8)	0.984	0.988	0.982
78 (69.0-87.0)	0.991	0.995	0.982
89 (78.8-99.2)	0.994	0.998	0.983
100 (88.5-111.5)	0.989	0.995	0.986
119 (101.2-136.9)	0.990	0.994	0.986
140 (119.0-161.0)	0.994	0.996	0.985
166 (141.1-190.9)	0.993	0.993	0.984
195 (165.8-224.3)	0.991	0.988	0.980
235 (199.8-270.3)	0.990	0.976	0.963

Because the thickness of sapphire plates is a little thin to center frequency of LiteBIRD, The PME shifted higher frequency.

The effect of the gap between each sapphire plates that constructed the AHWP.



The prediction considering the gaps.

* The value of the simulation assumes the case where the incident light is completely polarized.
** The thickness of each gap are assumed 8 μm. This value is the thickness variation in the plane of a sapphire plate.

Summary

- We have measured the PME and phase for the AHWP and found that those are consistent with the expectations with the wide frequency range.
- We have a plan to measure the transmittance, to implement the Moth-eye anti-reflection structure and to evaluate the performance with the designed modulator size of 40cm diameter.