Optical characterizations of scaled model of low frequency telescope and a broadband achromatic half-wave plate

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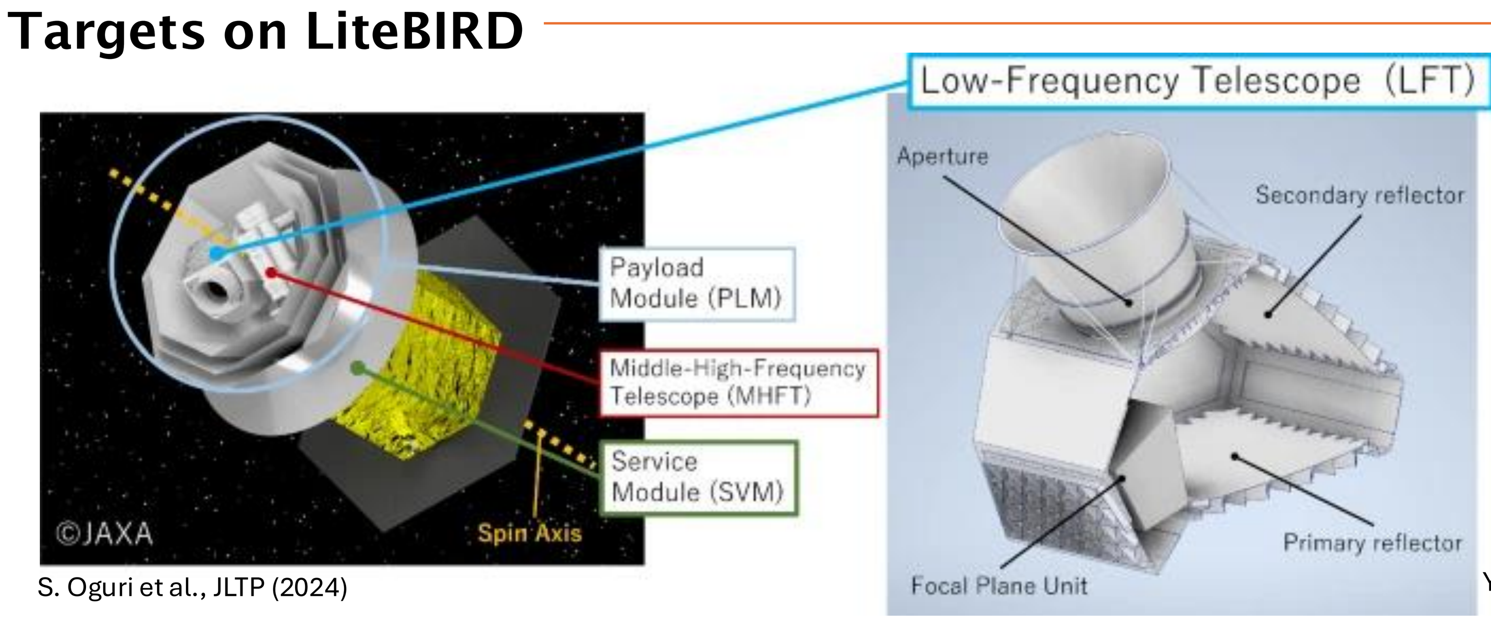
Introduction

We are aiming to detect the primordial CMB B-mode precisely to probe the cosmic inflation theory. To observe large angular scale of the power spectrum, a continuous rotating half-wave plate is an essential optical element. It can modulate the polarization of the CMB with respect to the rotation frequency and can mitigate the effect of the 1/f noise. However, HWP non-idealities are the source of the systematic effects on the estimation of tensor-to-scalar ratio. Here we will report on the characterization of HWP from two aspects;

- Characterize the modulated signal as transmission, modulation efficiency, phase of the modulated signal and other harmonics
- Characterize the beam pattern of scaled model of LiteBIRD low frequency telescope (LFT) with HWP

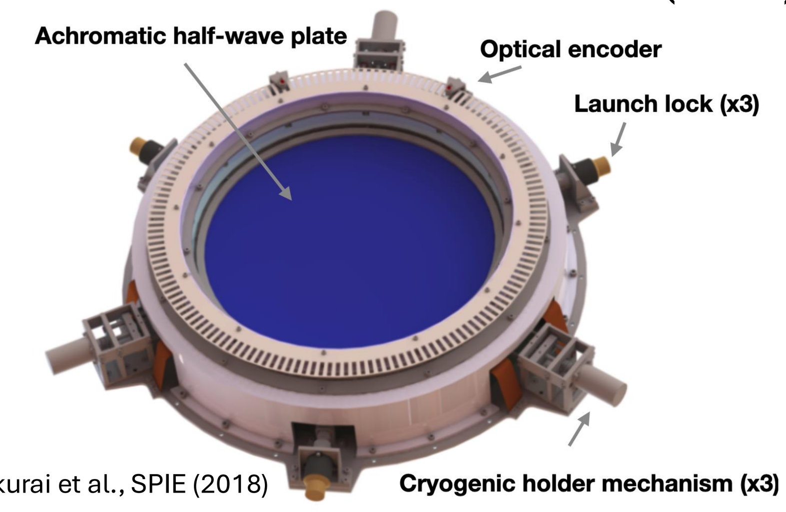
We have 200 mm diameter sapphire-based achromatic HWP with anti-reflection coating, which I made actually, and we are constructing our own transmission/reflection, beam pattern measurement system at Fuji Hall. Here we report on the abstract and prospect of the study of them.

Targets on LiteBIRD

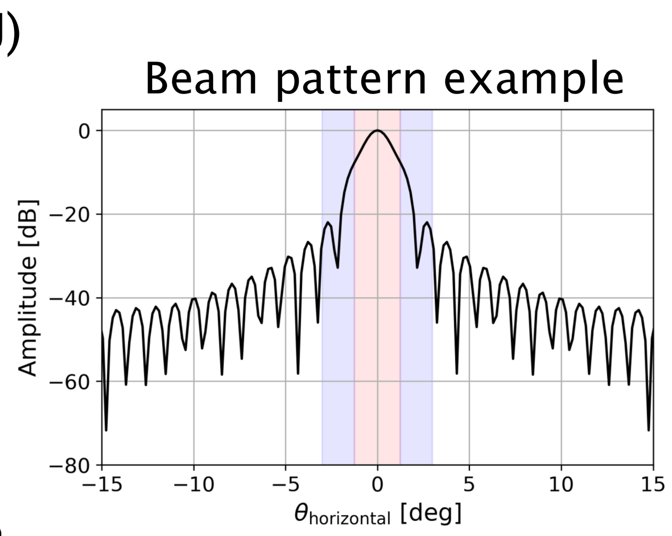


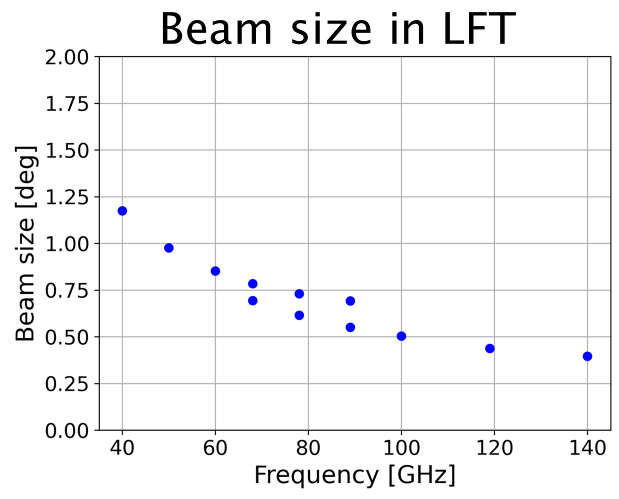
S. Oguri et al., JLTP (2024)

Polarization Modulator Unit (PMU)



Y. Sakurai et al., SPIE (2018)





Parameter	value
Far sidelobe	Accuracy of -56 dB
Near sidelobe	10% accuracy up to -20dB of main lobe
Main lobe	Beam widths match within 1%
Transmission	≥ 97%
Modulation efficiency	≥ 98%

According to LiteBIRD collaboration, PTEP 2023 and Y. Sakurai et al., SPIE (2018)

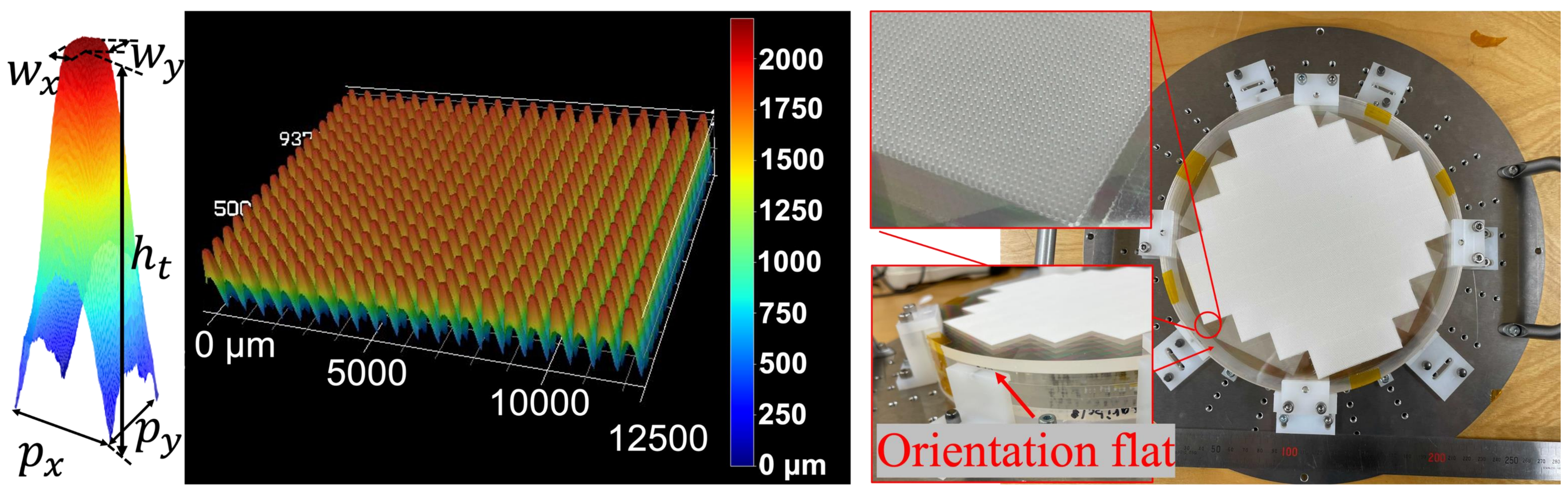
The low-frequency telescope is designed based on Cross-Dragon, which is compact, wider field of view and less cross polarization (while more prone to stray light). Definitions of the beam are

- Main lobe: depends on each frequency band
- Near sidelobe: 3 deg from center of the beam
- Far sidelobe: > Near field

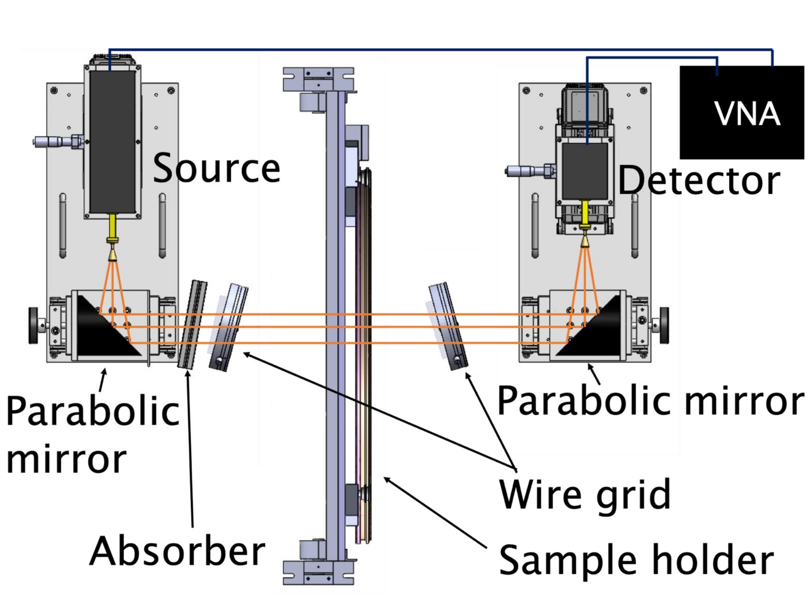
Our HWP consists of five a-cut sapphire plates stacked with specific relative optic axes. For anti-reflection, we make sub-wavelength structures (SWS) fabricated with laser ablation

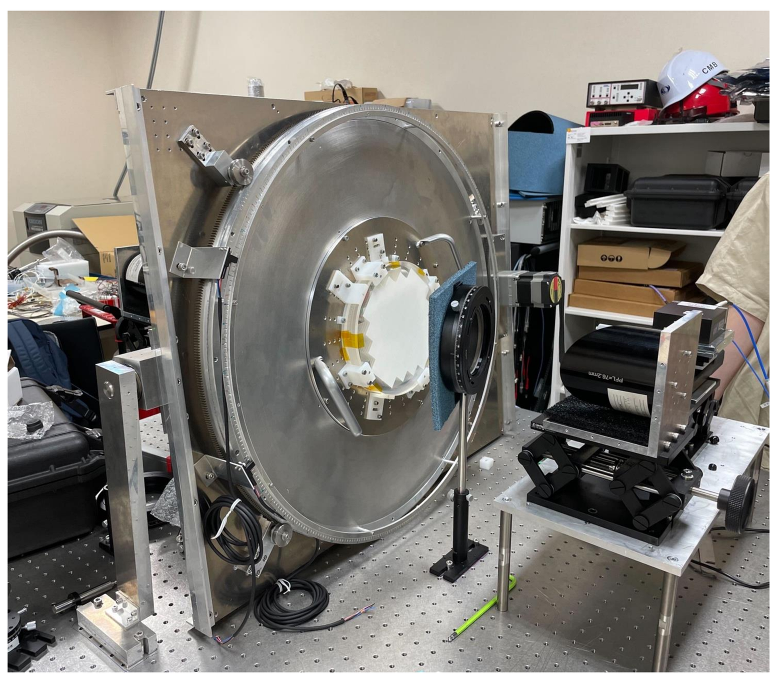
HWP characterization

I made D200 mm achromatic HWP with SWS (pitch of 0.6 mm and the height of 2 mm), within 1 week including both sides.



Measurement setup at IPMU

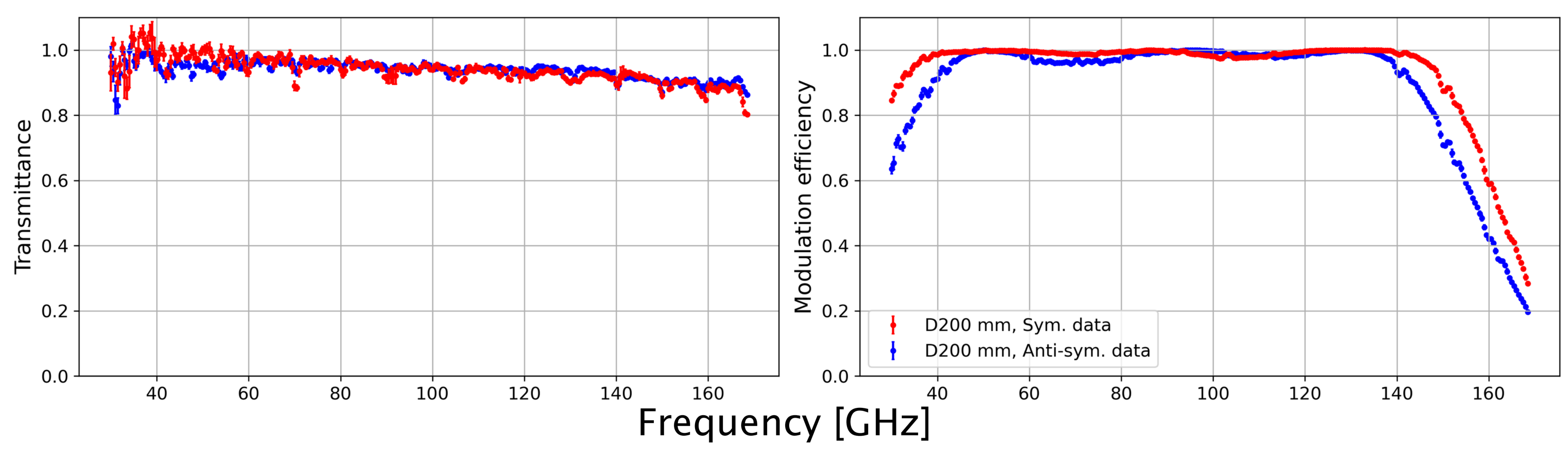




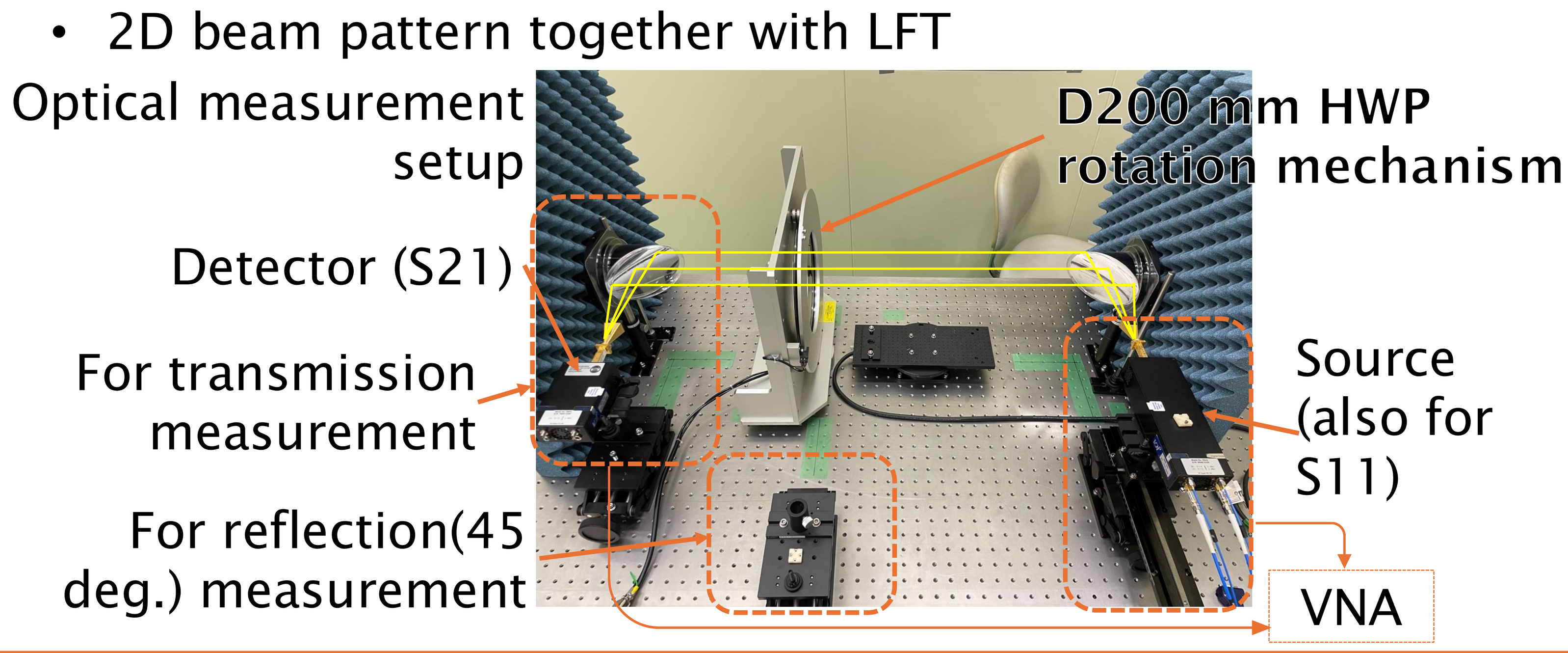
Rotate sample, measure the modulation signal, and fit the data with

$$T(\nu, \rho) = a_0 + \sum_{i=1}^{8} a_i \cos(i\rho + i\phi_i)$$

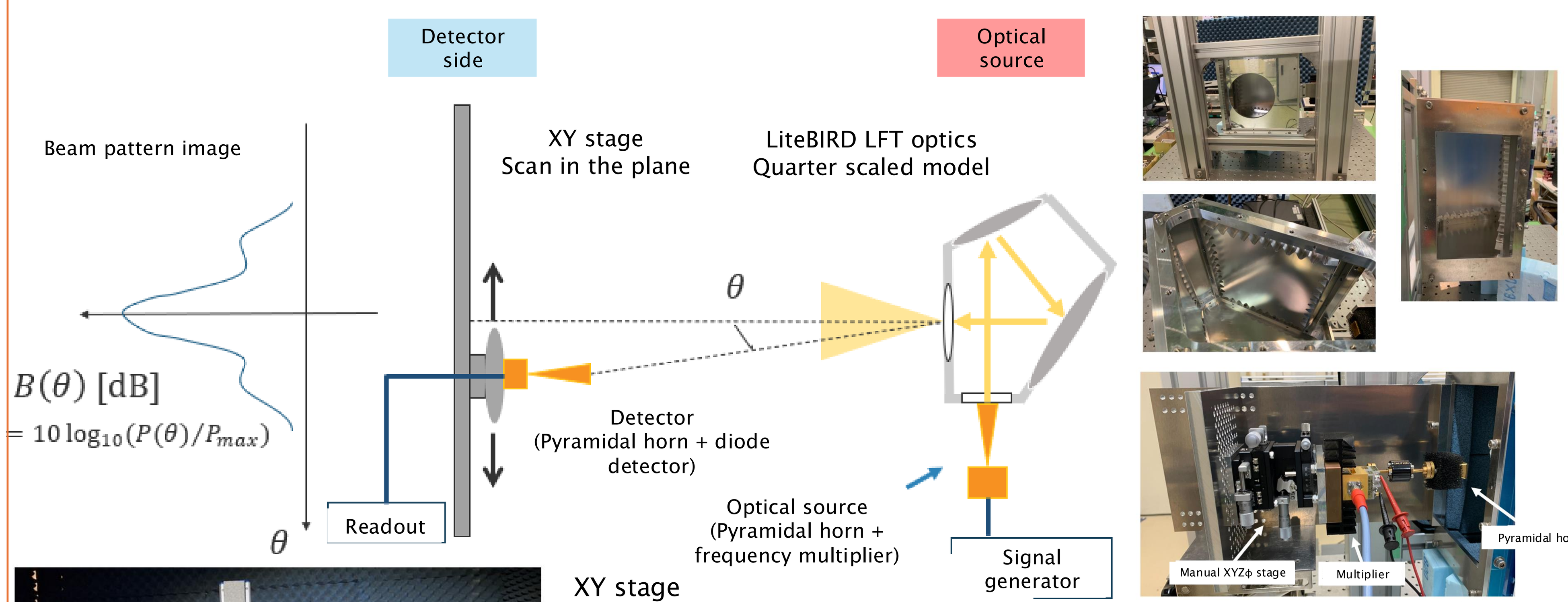
To get transmission ($T_{\max}$) and modulation efficiency (a_4/a_0) for two representative stacking configurations, symmetric and anti-symmetric design (K.Komatsu et al., 2020)



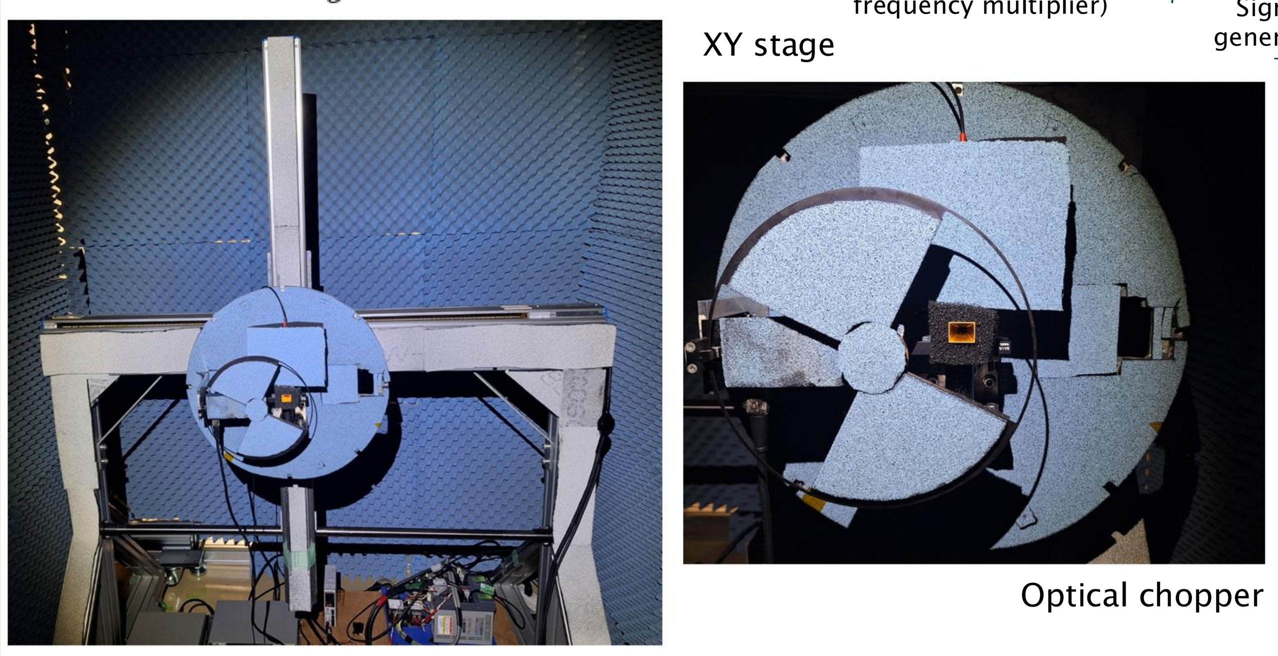
- Broadband characterization over the low frequency band
- We are going to construct the optical measurement which can measure
  - Modulation signal up to 14 degrees (maximum incident angle when we integrate it to LiteBIRD LFT)
  - Cross polarization of Jones matrix to obtain Mueller matrix
  - 2D beam pattern together with LFT



Beam pattern characterization



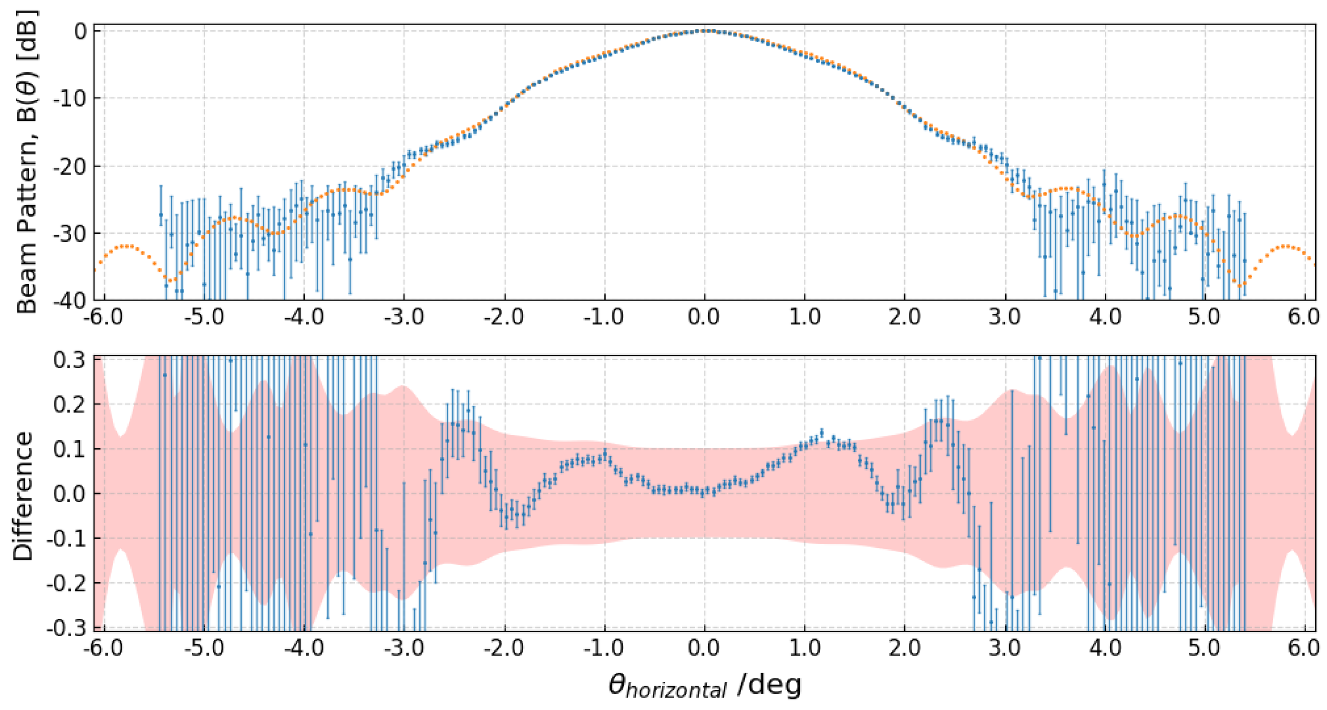
H. Mori, master thesis (2023)



Combine the quarter scale of LFT, optical source and detector and a large xy stage to scan the beam.

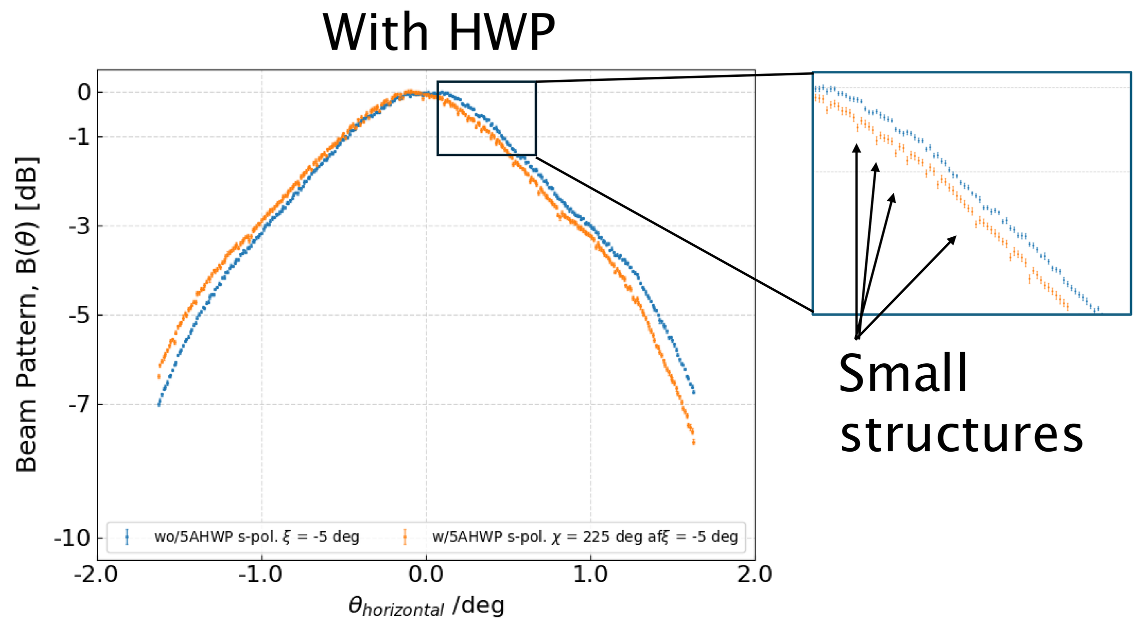
Measurement and its setup: H. Mori

Beam pattern measurement without HWP



- Near field (up to 3 degrees) measurement is consistent with the simulation.
- Side-lobe is also close to the simulation, however it has a large uncertainty because of the limited accuracy of the system

With HWP



- The beam pattern with HWP agrees with one without HWP, but the center of the beam is shifted due to the refraction in the tilted HWP (in 5 degrees in this plot)
- Tiny spikes are observed in the beam pattern with HWP, which can be due to the standing wave

- The next step is to measure the beam pattern more accurate for both near and far-sidelobe with and without HWP, satisfying the target accuracy of -56 dB using VNA
- Measure the diffraction effect at higher frequency due to SWS
- Propagate the actual beam pattern with HWP to the beam systematics simulation, which is the collaboration work with Okayama University