What is polarization modulator?

1. **1/f noise rejection**
   - Atmospheric noise, ground pickup
   - Detector / electrical noise
   - Long term instabilities

2. **Systematics mitigation**
   - Differential beam pointing, ellipticity
   - Differential gain
Modulation techniques

There are various polarization modulation techniques:

1. **Phase switch**: WMAP, CAPMAP, QUIET…
   - Modulation by switching the path length half-phase shifted
   ![Phase switch diagram]

2. **Faraday rotation modulator (FRM)**: BICEP1
   - Modulation using ferrite and coil by Faraday effect
   ![Faraday rotation modulator diagram]

3. **Half-wave plate (HWP)**: MAXIPOL, EBEX, SA, SO, ACTPol, NIKA, LSPE/SWIPE, LiteBIRD…
   - Modulation by rotating HWP
   ![Half-wave plate diagram]

4. **Variable-delay polarization modulator**: PIPER, CLASS
   - Install at front or rear of focal plane
   - Each pixel
   ![Variable-delay polarization modulator diagram]

References:
- QUIET Collaboration et al. (2011)
- S. Moyerman et al. (2013)
- A. Kusaka et al. (2014)
Do we need polarization modulator for LiteBIRD?

<table>
<thead>
<tr>
<th>Pros</th>
<th>Cons</th>
</tr>
</thead>
<tbody>
<tr>
<td>1/f noise rejection</td>
<td>HWP systematics</td>
</tr>
<tr>
<td>Systematics mitigation</td>
<td>Sensitivity effect</td>
</tr>
<tr>
<td></td>
<td>System risk</td>
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</tbody>
</table>

- LiteBIRD $f_{\text{scan}} = 0.05 - 0.1$rpm
- Do we have any guarantee for 1/f noise?
- 1/f is the main driver $\rightarrow$ continuously rotating HWP
- ABS, POLARBEAR successfully demonstrated $f_{\text{knee}} \sim 2$mHz.
- Concerns depend on hardware and calibration.
HWP systematics

Hardware development directly connects to systematics due to HWP imperfection

- HWP non-uniformity $\rightarrow$ AR and AHWP development
- Multiple reflections $\rightarrow$ AR development
- HWP phase freq. dependence $\rightarrow$ AHWP design optimization
- Beam effect through HWP $\rightarrow$ AR and AHWP development
- HWP temperature stability $\rightarrow$ rot. mech. thermal characteristics
- HWP wobbling $\rightarrow$ rot. mech. misalignment
- Angle reconstruction accuracy $\rightarrow$ encoder
- ...

HWP hardware development is key to achieve LiteBIRD full success
Continuously rotating HWP history

**MAXIPOL** (balloon)
- First CMB experiment using rotating HWP

**EBEX** (balloon)
- First experiment using cold rotating HWP with superconducting magnetic bearing

**ABS** (ground)
- First ground experiment with warm rotating HWP

**Simons Array, Simons Observatory SAT** (ground)
- First ground experiment with cold rotating HWP

**LSPE/SWIPE** (balloon)
- Balloon experiment with cold rotating HWP

**LiteBIRD** (satellite)
- Satellite mission with cold rotating HWP
HWP materials

Sapphire

- Birefringence single crystal material
- Maximum diameter $\leq 500\text{mm}$
- Need anti-reflection (AR) due to refractive index $\sim 3.3$
- Broadband of pol. eff. and phase difference are proportional to number of layer $\approx$ mass
- MAXIPOL, EBEX, SPIDER, ABS, SA, SO, LiteBIRD LFT

Metal-mesh HWP

- Based on metal-mesh filter technology
- Stack capacitive and inductive structure
- Bandwidth 3:1
- NIKA, ASTE, LSPE/SWIPE, LiteBIRD MHFT
- Reflective metal-mesh HWP is considered as backup solution.

G. Pisano et al. in press in PIER M (2012)
Toward satellite application

**Higher science goal**
- Wider frequency band
- Lower HWP temperature
- Reducing HWP imperfection

**Resource limitation**
- Cooling power
- Mass
- Volume …

**Space specific environment**
- Launch tolerance
- Cosmic ray
- No gravity

**System reliability**
- Risk management
- Redundancy
- Emergency operation
Polarization modulation unit (PMU) for LiteBIRD low frequency telescope (LFT)
LiteBIRD overview

Two telescopes: LFT (34 - 161GHz), MHFT (89 - 448GHz)
Focal plane unit: >4000 superconducting detector (TES) array
Scan strategy: L2 precession 45 deg. (10⁻²-10⁻³ rpm), spin 50 deg. (0.05-0.1 rpm)
Cooling chain: V-groove → 20K-2ST → 4.8K-JT → 1.75K ADR → 300/100mK ADR
Continuous rotating half-wave plate at the aperture of LFT and MHFT
## Representative requirements

<table>
<thead>
<tr>
<th>Items</th>
<th>Requirement (LFT)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Frequency band</td>
<td>34 GHz - 161 GHz</td>
</tr>
<tr>
<td>Transmittance</td>
<td>&gt; 98% (depend on freq.)</td>
</tr>
<tr>
<td>Polarization efficiency</td>
<td>&gt; 98% (depend on freq.)</td>
</tr>
<tr>
<td>Rotation frequency</td>
<td>0.8 Hz (48 RPM)</td>
</tr>
<tr>
<td>HWP diameter</td>
<td>&gt; ~ 480 mm</td>
</tr>
<tr>
<td>HWP temperature</td>
<td>&lt; 20 K</td>
</tr>
<tr>
<td>Total heat dissipation</td>
<td>&lt; 4 mW</td>
</tr>
<tr>
<td>Mass</td>
<td>&lt; 30 kg</td>
</tr>
<tr>
<td>Encoder specification</td>
<td>&lt; 0.2 arcmin</td>
</tr>
</tbody>
</table>

- The requirement values are not yet fixed because the detail system design and the trade-off study are in progress.
- Main development items are broadband achromatic HWP and a cryogenic rotation mechanism.
Current design of LiteBIRD LFT PMU

- Anti-reflection structure
- Cryogenic holder mechanism
- Sapphire stacked Achromatic HWP
- HWP holder
- Launch lock mechanism
- Rotation mechanism
Development roadmap

- **BBM**
  - Φ = 380mm
  - ~2020

- **DM/EM**
  - Φ = 500mm
  - 2020~2024

- **FM**
  - Φ = 500mm
  - 2024~launch!

![Diagram](image_url)
Broadband anti-reflection structure

• Broadband antireflection (34-161GHz): moth-eye based sub-wavelength structure by laser machining

• Fabricated Φ70mm small sample with height 2.34mm, pitch 0.54mm (~4:1)

• > 90% transmittance with good agreement between data and simulation

• The expected processing time for Φ=450mm is < 1 month using 40W femto-second pulsed laser
Sapphire AHWP development

✓ Single sapphire plate has pol. eff. $\varepsilon = 1$ for the only single frequency.

✓ We adopt Achromatic HWP (AHWP) consists of multi-stacked sapphire with the different optic axis for each HWP.

✓ We optimize the AHWP design with 5 layer to cover 34-161GHz.
Rotation mechanism

• All components at 5 K stage
• Heat dissipation < 4 mW due to cooling power
• Rotor (HWP) must be operated < 20 K to reduce thermal emission

Stable continuous rotation at cryogenic temperature with small heat dissipation

Breadboard model (Φ=380mm)

• Superconducting magnetic bearing
  Rotor: SmCo magnets + yoke for uniformity
  Stator: YBCO (Tc < 95 K)
• DC brushless motor with speed feedback control measured by optical encoder
• 3 grippers actuated by linear actuators (stepping motors)
Rotation mechanism
Thermal characteristics

- Total heat dissipation $\leq 4.0$ mW
- Rotor heat dissipation $\leq 1.0$ mW from thermal simulation
- Heat sources are hysteresis loss, eddy current due to magnet inhomogeneity $\Delta B$

$$P_h \propto k_h f \frac{\Delta B^3}{J_c}, \quad P_e \propto k_e f^2 \Delta B^2$$

- Total loss at nominal rotation speed (46 rpm) is $\sim 10$ mW, dominated by eddy current loss
- There is much room for improvement.
  - de-metallization, reduce weight …
  - Uniform magnet with yoke

Yoshiki Nomura (Saitama U.)
Angular encoding

- HWP angle reconstructed by incremental encoder consists of LED and Si photodiode
- Calibrate bias component (not change with each rotation).
- The angular error (random component changed per rotation) is calculated as $< 0.2$ arcmin.

$\Delta f \approx 2\text{mHz}$
Other activities toward flight model

- Cosmic ray effect: radiation damage, heat input, charging
- AHWP gluing and holder design for launch tolerance.
- System optimization including baffle and stop
- Fault tree analysis (FTA) to identify critical risks and components required redundancy.
- Development of low loss cryogenic motor
- Cryogenic optical measurement system
- Small integrated test system of TES and HWP
Summary

✓ Polarization modulator helps to reject 1/f noise and systematics.

✓ Continuously rotating HWP is employed to LiteBIRD with the main driver as 1/f noise.

✓ We presented the development status of LiteBIRD LFT PMU.

✓ Optical performance of AR and AHWP is successfully demonstrated by small samples.

✓ Cryogenic performance test of BBM rotation mechanism is in progress toward flight model.
Otsukare!