Development of silicon lens array for MKID camera

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Motivation

Wide-field sub-millimeter camera
- survey of the distant galaxy

The Dome Fuji Station
Tsukuba University planning to construct the 7m submillimeter telescope at the Dome Fuji

<table>
<thead>
<tr>
<th>Temperature</th>
<th>Altitude</th>
</tr>
</thead>
<tbody>
<tr>
<td>- Average : $-54$ °C</td>
<td></td>
</tr>
<tr>
<td>- Minimum : $-79$ °C</td>
<td>$3810$ m</td>
</tr>
</tbody>
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Comparison of $220$ GHz optical depth (Ishii et al, 2010)

- Transmittance
  - Dome F (summer)
  - Atacama (winter)$\rightarrow$same value
- very stable
- Dome F in winter$\rightarrow$expect to better transmittance

\[
\tau\text{(Ave)} = 0.045 \\
\text{(T = 97 \%)}
\]
NAOJ Camera Design

- Target Frequency
  - 220 GHz & 440 GHz

- Number of pixel
  - 220 GHz → 9 pixel demo camera
  - 440 GHz → 102 pixel camera

- Camera design

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Readout

Kinetic Inductance Detectors

Lens & Antenna coupling

Lens

102 pixel KIDs Camera

Day et al., 2003
Yates et al., 2009
Neto et al., 2009
Development of Silicon lens array
Lens Design with Double Slot Antenna

* Extended hemispherical lens

- Lens Diameter
- Extension Thickness

- considering the integration and dielectric loss, we decided to $D = 3\lambda$
  - Lens diameter: $D = 3 \times 1.36\,\text{mm} \,(=220\,\text{GHz}) = 4.09\,\text{mm}$
  - Symmetrical beam pattern and low side-lobe level
    - Extension thickness: $\text{Ext} = 0.65\,\text{mm}$
Machining by High-speed spindle

- Prototype 220 GHz Silicon Lens Array
  - 3×3 array
  - Lens diameter : D=4.09 mm
  - Extension thickness : L=0.35 mm
  - Machining time → 9 hours for machining 1 pixel
  - R0.15 mm TiAlN coated ceramic end-mill

- Error from the radius of lens (R=2.045mm)

- Surface roughness

  - Measurement of 6 lenses
    - P-V : 20 um
  - Measurement of 5 lenses
    - Center of lens
    - Ra : < 0.48 um

- Completed 9 pixel silicon lens array
Development of 440 GHz lens array

- 440 GHz 102 pixel camera design

- Lens Diameter: 2.04 mm
- Extension thickness: 0.2 mm
- Machining Setup: high speed-spindle & R0.1 mm TiAlN coated ceramic end-mill
- Machining Time: 1 hour for machining 1 pixel
Beam pattern measurement of Antenna coupled KID
**Measurement Setup**

- He3 sorption cooler
  - $T_{\text{min}} : 300$ mK
  - hold time : about 10 hours
  - IR filter

- 9 pixel Si KIDs mask design
- 300 mK stage
- 9 pixel Si lens array
- 4 K stage

**Antenna Coupled KIDs**

- 9 pixel Al KIDs
  - film thickness : 150 nm
- silicon substrate
- double slot antenna

(Monfardini et al, 2010)

![Graph of Total Transmittance]

Total Transmittance

$\sim 55 \%$ @ 220 GHz
Measurement Setup

beam pattern measurement

- measurement at magnetic shield room outside of the shield room inside of the shield room

- 220 GHz radiation source was scanned around the window
- recorded the amplitude variations of the S21 response
Beam Pattern Measurement

*Far-field beam pattern*

- frequency: 220 GHz
- dynamic range: 20 dB
- contour: 3 dB step
Future Work
Antireflective Structure

Antireflection coating
- conditions for zero reflectivity

\[ n_{AR} = \sqrt{n_{air} \cdot n_{Si}} = 1.84 \]
\[ d = \frac{\lambda}{4 \cdot n_{AR}} \]
- AR coating could separate from lens in thermal cycling.

Antireflective structure
Form a cyclic structure smaller than the target wavelength on the silicon surface

\[ \rightarrow \text{Possible to replace the ARS with the effective medium of the refractive index (Effective Medium Theory)} \]

\[ \rightarrow \text{same effect of one layer AR coating} \]

\[ \text{It is possible to get an anti reflective effect with only one material} \]
Groove Design of 220 GHz band

Because the structure is different at the vertical or horizontal direction of the groove.

Groove has polarization dependence

Λ = 0.36 mm
W = 0.14 mm
W’ = 0.22 mm
d = 0.185 mm

average reflectance between 200 - 240 GHz is about 12%.
Summary

1. Development of Si lens array for MKID camera
- 9 & 102 pixel silicon lens array was machined with the high-speed spindle at NAOJ
- measurement of 9 pixel lens’ shapes
  - shape error: \( \sim 20 \text{ um (P-V)} \)
  - surface roughness: \( \sim 0.48 \text{ um (Ra)} \)

2. Beam Pattern measurement of antenna coupled KID
- measurement of 220 GHz beam pattern using antenna coupled Al KID
- Simulation and measurement are well conformed

3. Future work
- fabricate the AR structures on the lens surface
- beam pattern measurement of 102 pixel KIDs array