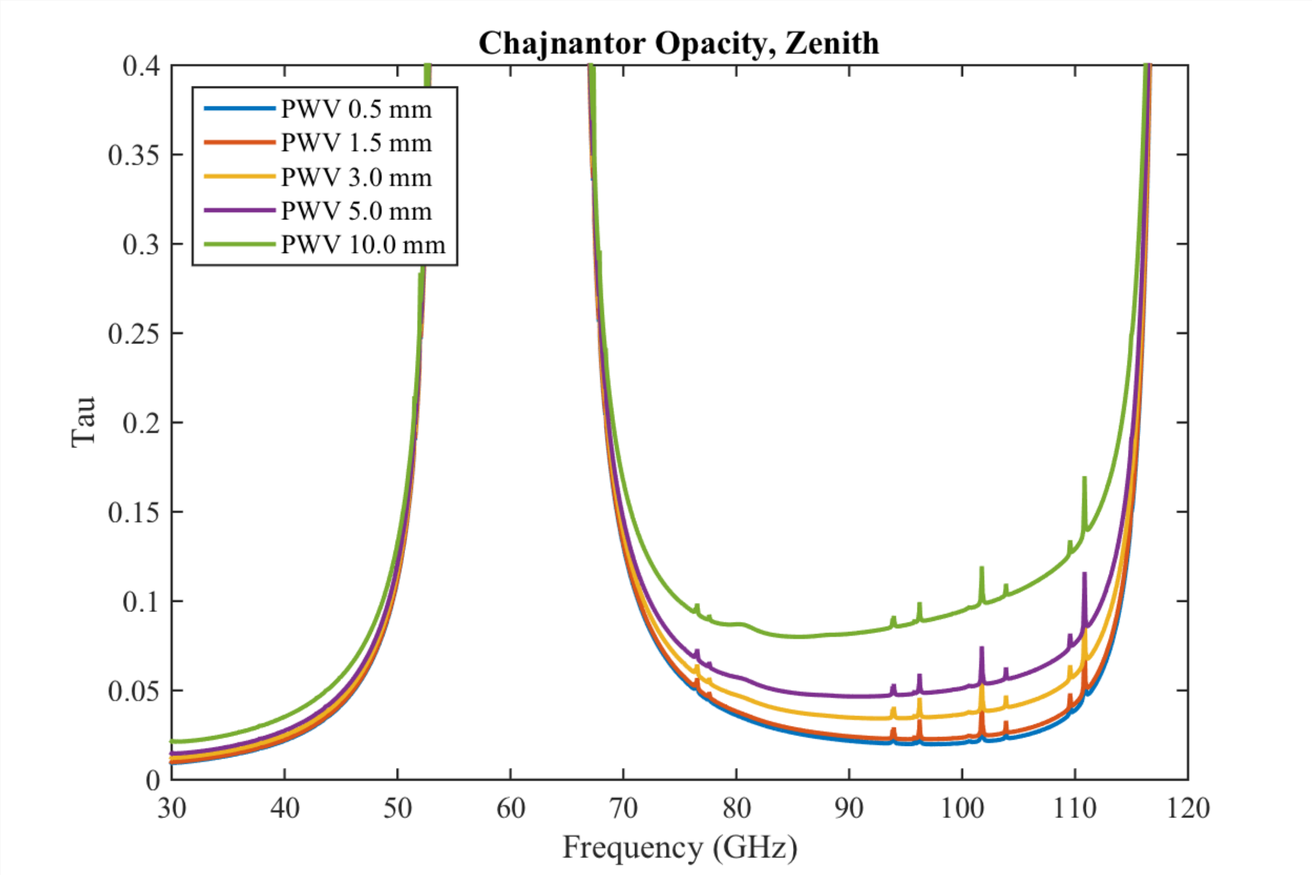
SILICON LENSES FOR BAND 2+3

TONY MROCZKOWSKI

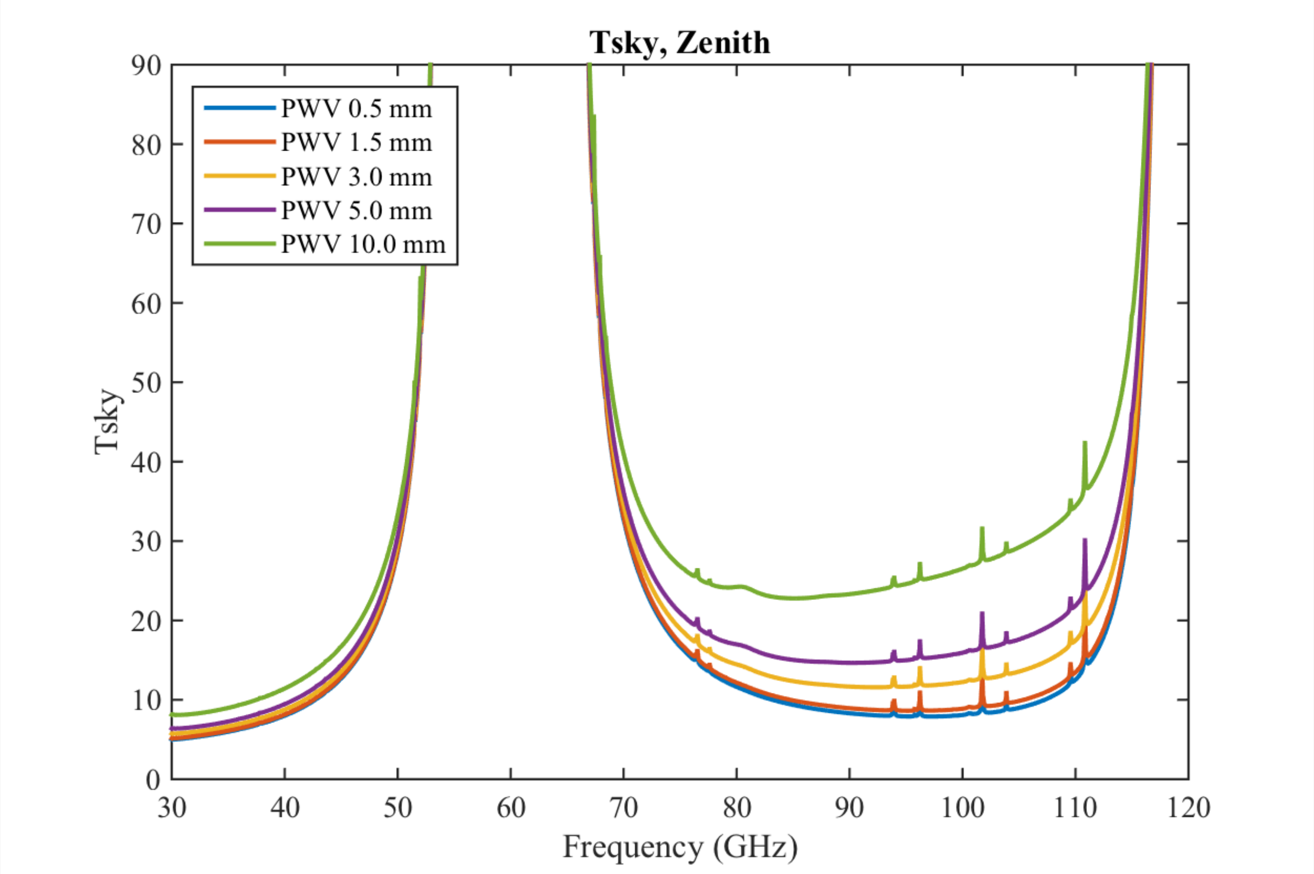
Or *What I learned about Lenses from the CCAT and CMB communities*

ALMA transmission for a range of conditions: 0.5-10 mm of Precipitable water vapour



Corresponding noise temperature of the sky

remains low (<20 K) for a broad range of conditions



Loss in the optics:

While T_{sky} is typically 10-20 K, an HDPE lens with an average thickness t≈17mm and an estimated loss tangent tan(δ) ≈ 2.4e-4 contributes T_{sys} ≈ 2.6 K (but this could vary by a factor of ~2 either way).

Diffractive/fresnel lenses could improve this, but an HDPE lens+vacuum window must be kept thick to avoid distortion.

See Alvaro's studies of the Band 2+3 optics for a more thorough review.

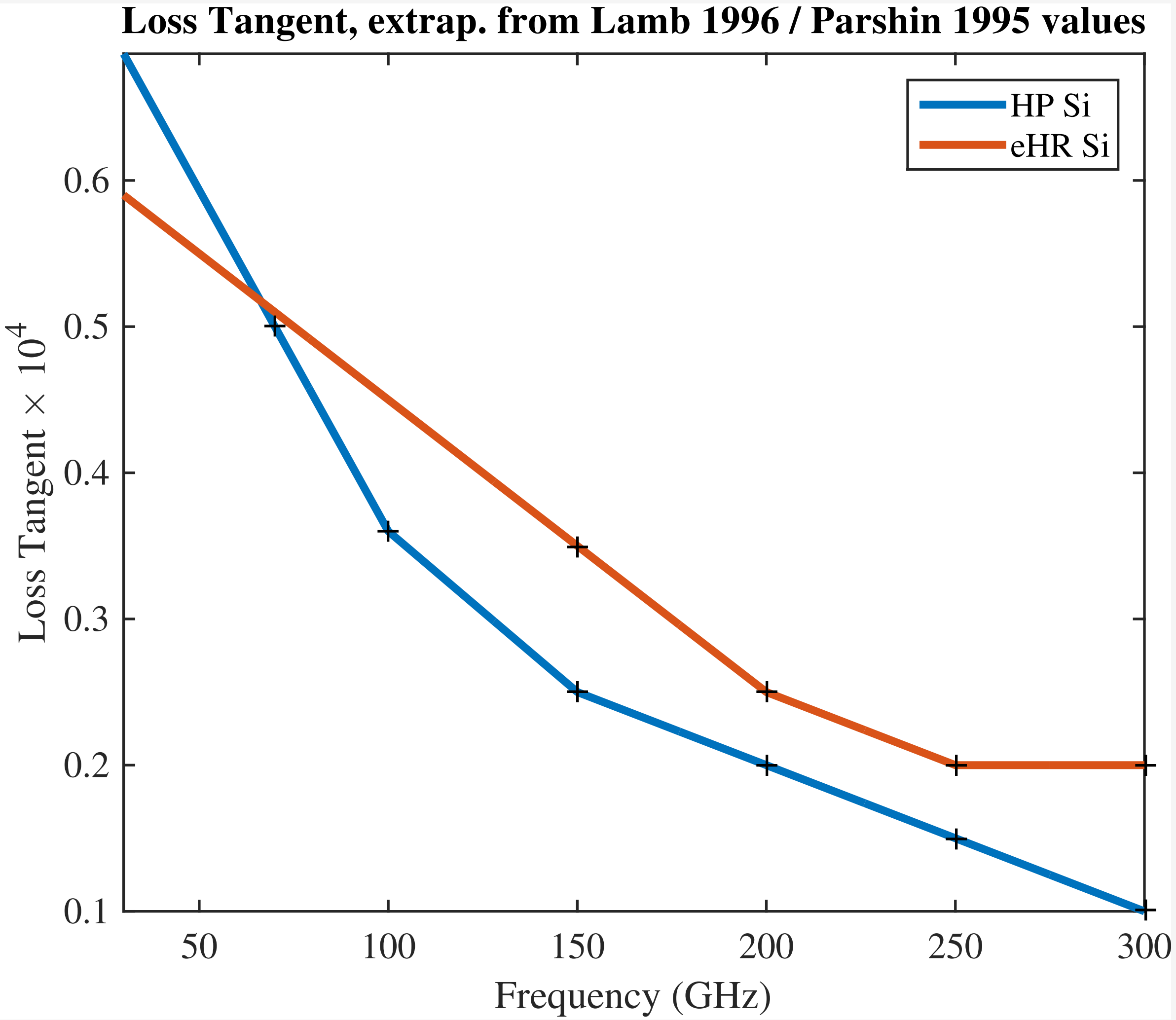
$$T_{\text{sys}} = T_{\text{phys}}(L - 1)$$

$$L = e^{2\pi n \tan(\delta) t/\lambda_0}$$

Silicon offers an alternative that can be thinner and less lossy.

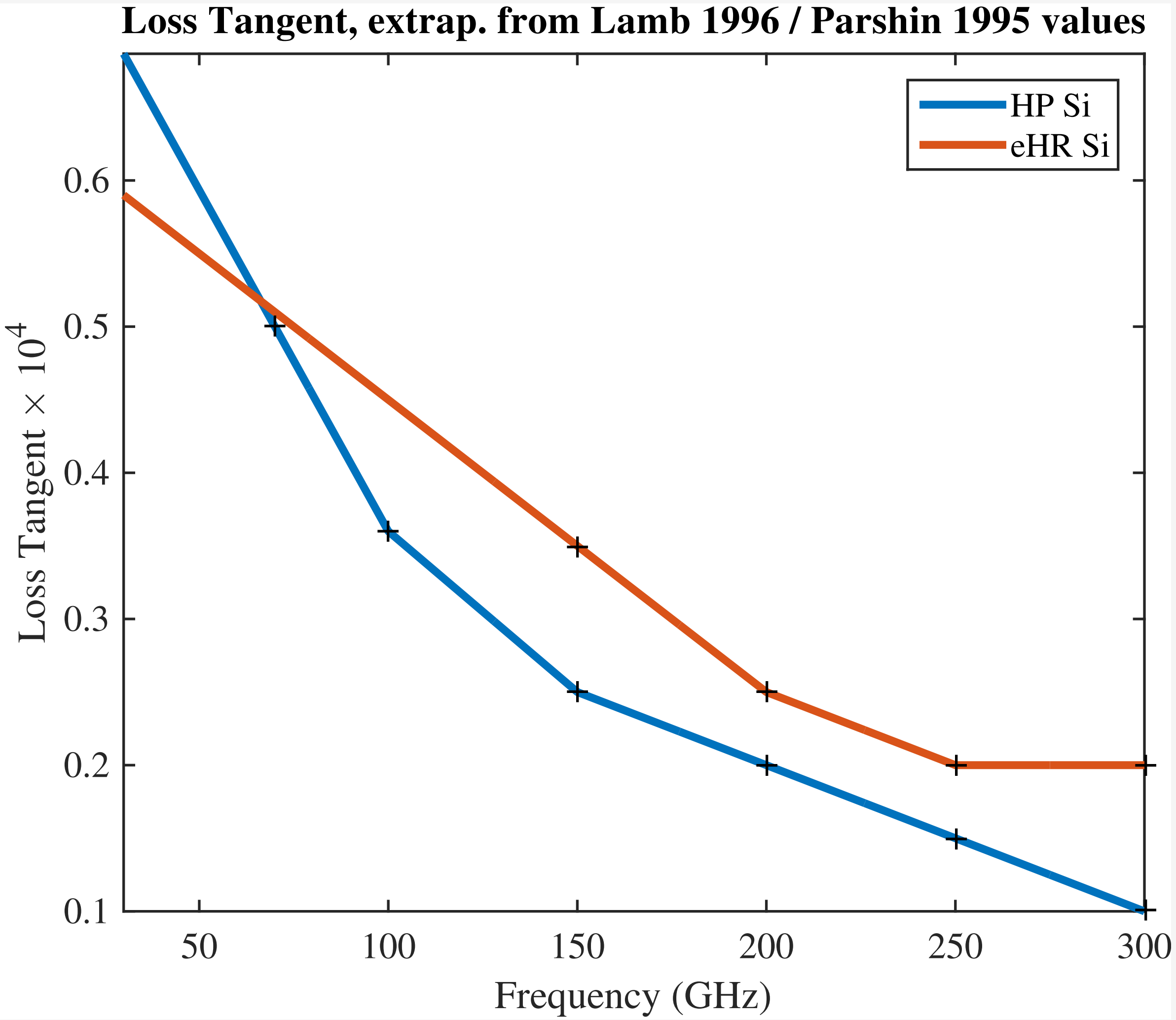
Plotted here is the loss tangents for 2 types high-resistivity Silicon (from Lamb 1996, compiled from Parshin 1995). Black + are measurements, lines are linear interp/extrapolations.

These results are already 20 years old.



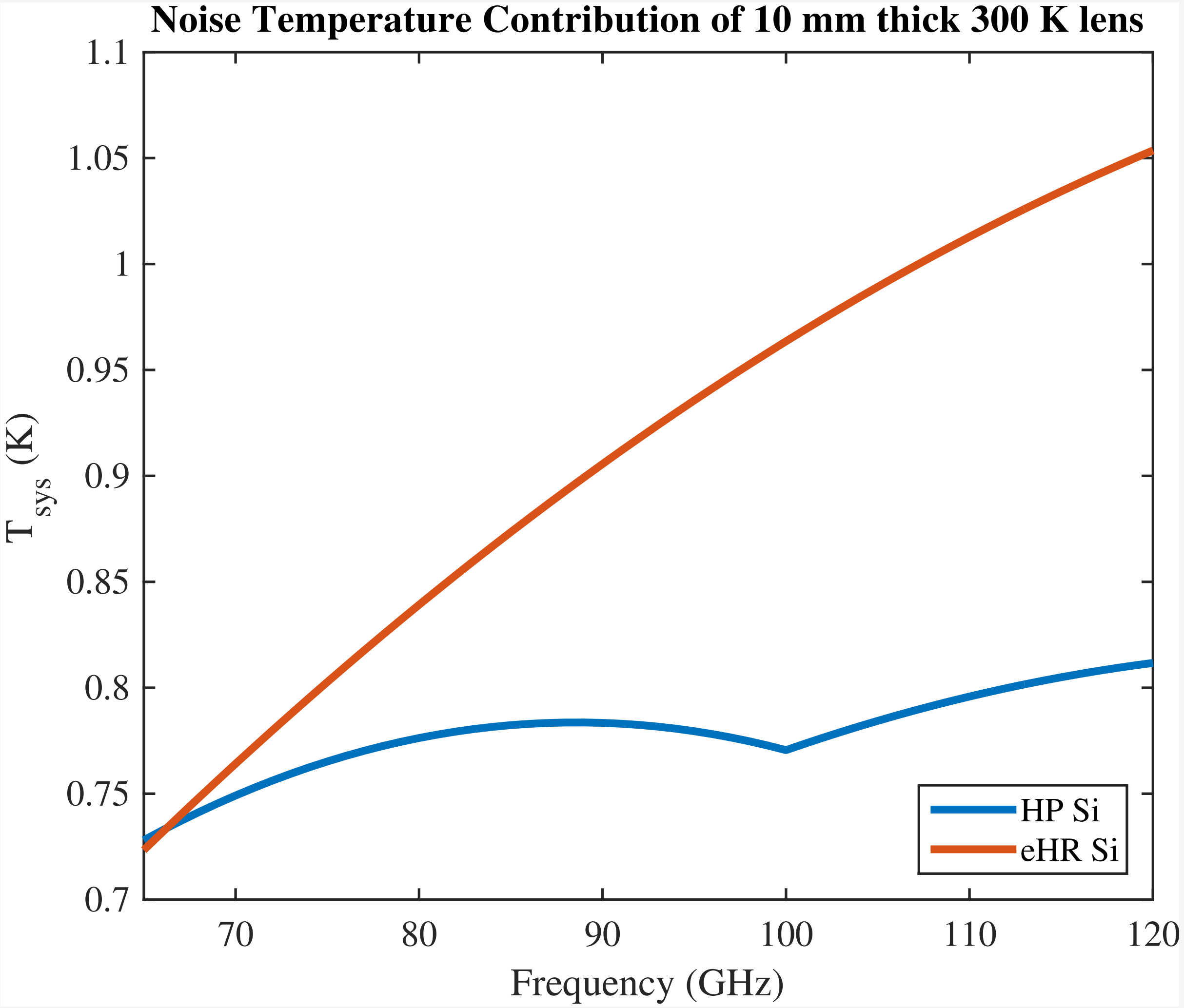
"At 35 GHz the loss tangent is ~0.004 for a Si wafer having a bulk resistivity of 1 kΩ cm." from Topsil's *APPLICATION NOTE: HIGH RESISTIVITY(HiRes™) SILICON FOR GHz & THz TECHNOLOGY* (http://www.topsil.com/media/123119/hires_application_note_v1.1_january2014.pdf).

Prediction: At resistivity > 10 kΩ-cm, the loss tangent should scale to < 0.4 x 10^{-4} at 35 GHz, and falls as 1/frequency.



Corresponding noise temperature contribution for 10 mm thick Si lens (with Parshin et al. 1995 / Lamb 1996 silicon).

Silicon could also be made thinner (3-4 mm) as a diffractive lens



Developments in recent years

- Up to 70kΩ-cm ultrahigh purity float zone (FZ) silicon is widely available in up to 200 mm diameters (e.g. from Topsil).
- The loss tangent scales inversely with resistivity, so we should be able to reduce the loss by a factor of 10 immediately from the Topsil 2014 measurements.
- Jeff McMahon (from Datta et al. 2013 ACTPol lens paper) has measured warm loss tangents of $\tan(\delta)<8\text{e-}6$ at 150 GHz. Scaling to Band 2+3, this will yield $\tan(\delta)< 2\text{e-}5$ (or Tsys<0.2 K).
- Silicon has a very high index of refraction (n=3.4), making it attractive for thin lenses with less extreme curvatures.
- Impedance matching over the wide bandwidths *used to be* more challenging, using multiple layers of plastics. Plastic coatings are lossy, can de-adhere from the lens surface, and we cannot choose the precise index/indices of refraction necessary.
- Thanks to recent work in the CMB community (and later, in CCAT development studies), wide bandwidth AR surfacing techniques have been realized (e.g. Datta et al. 2013 ACTPol lenses). This takes advantage of better machining (multi-axis milling and dicing saws) as well as advances in desktop computing for E&M simulations/optimizations.

Advanced AR techniques (Datta+ 2013)

Dicing saw approach to removing enough volume at subwavelength scales to tune the impedance.

Grid geometry avoids birefringence in the index (unlike concentric grooves). Geometry shown on right.

Nested grooves are optimized in HFSS to provide nearly an octave of bandwidth.

One can do even better with more layers.

Will scale easily to Band 2+3, where features are larger

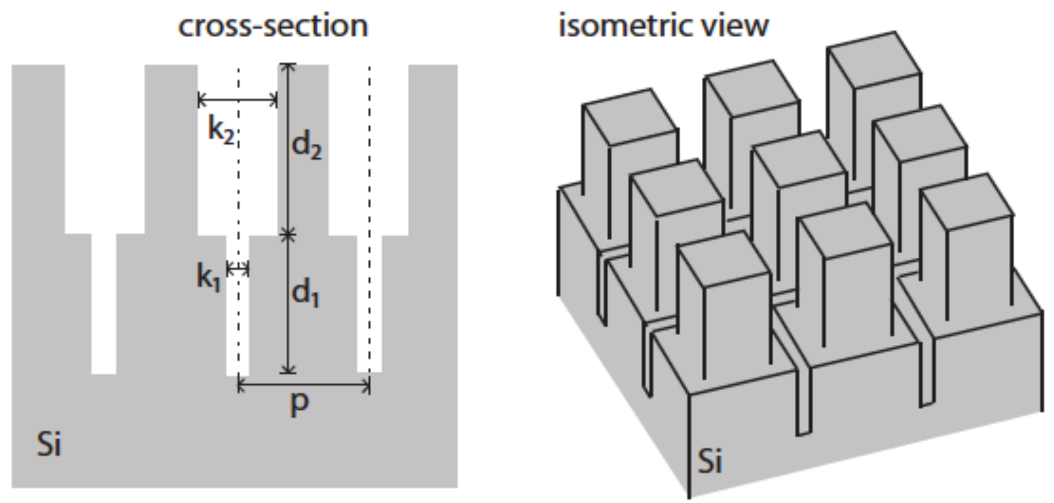


Fig. 2. The geometry of the two layer simulated dielectric AR coating. The left side shows a cross section through the center of the pillars and shows the design parameters discussed in the text. The right side shows an isometric view of the structure resting from making cuts along two perpendicular directions. In both drawings grey represents silicon and white represents vacuum.

Advanced AR techniques (Datta+ 2013)

Simulated performance at normal incidence for a **single** groove depth.

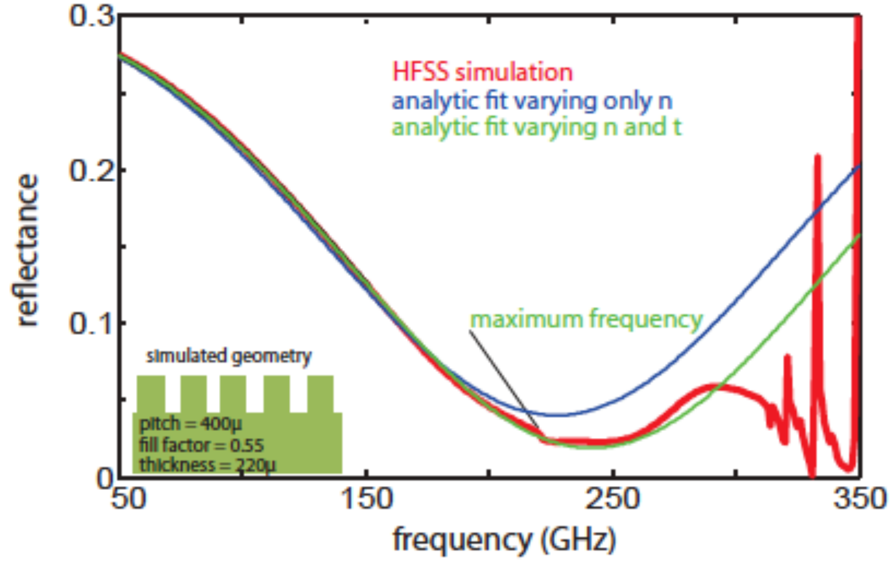


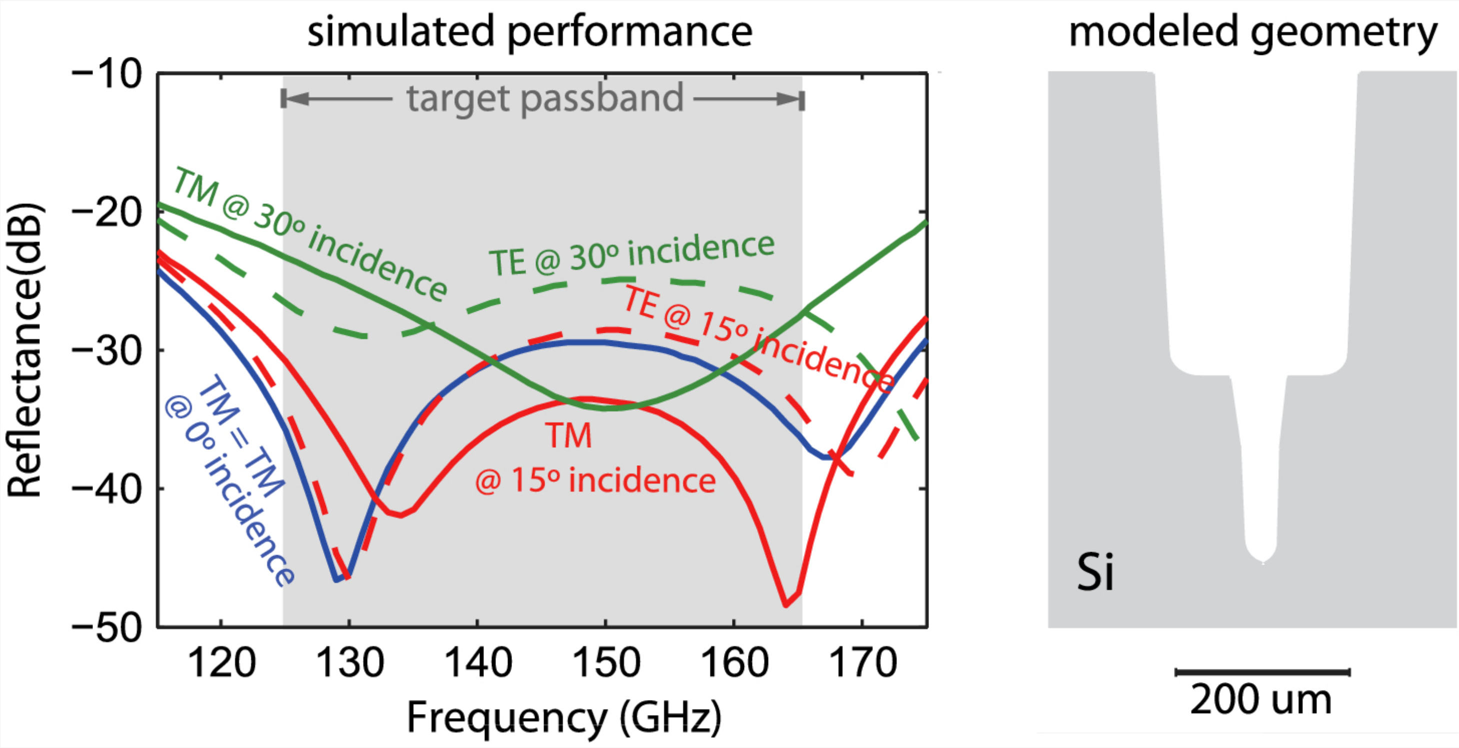
Fig. 3. A comparison of the reflectance calculated from an HFSS numerical simulation of a pillar geometry to fits based on a model of a simple dielectric layer. The geometry is specified in the inset in the lower left. A comparison between fits where the index n is free and where both the index and thickness are varied is shown. The HFFS simulation and the best fit curve differ by 5% at 220 GHz ($\sim$ **1.36 mm**). This is labeled as the maximum frequency and corresponds to the frequency at which the coating no longer behaves as a simple dielectric layer.

Advanced AR techniques (Datta+ 2013)

Simulated performance using 2 nested groove depths.

Performs well even at 30 degrees incidence.

Broadband AR is appealing for Bands 2+3 as well as any future wideband ALMA receivers requiring lenses.



Datta et al. 2013 measurements

Measured performance closely matches the simulation

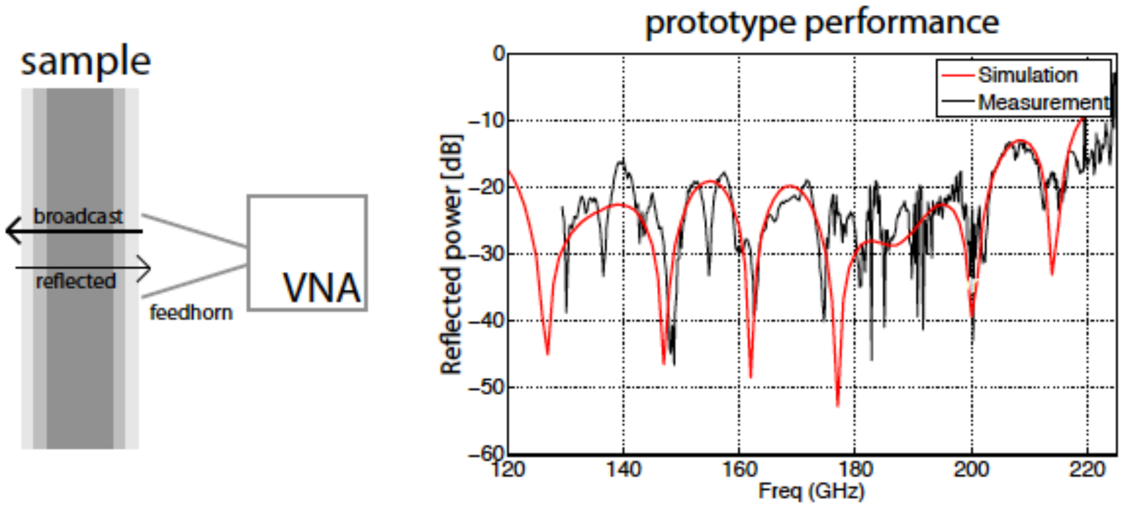


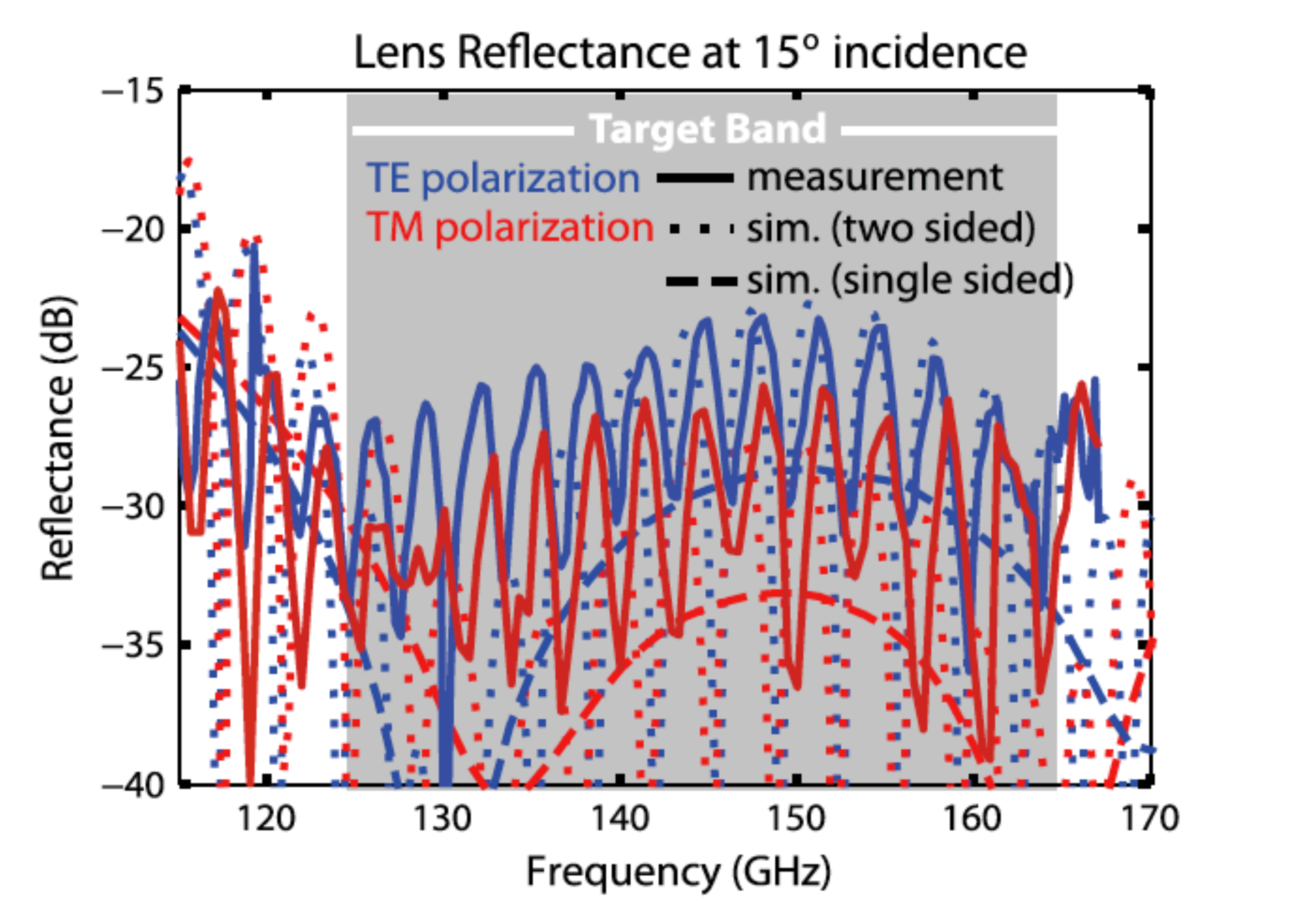
Fig. 10. *Left:* The setup used to measure the reflection from a two flat prototype sample. This consists of a VNA coupled to a feed horn with the sample placed at the mouth of the feed. *Right:* Comparisons between simulations and measurements of this sample. The simulations include the AR coating on both sides of the wafer and the measured thickness of the silicon. The measurements were performed using a vector network analyzer by placing the sample flat against a corrugated feed horn. Given the crudeness of this measurement, the agreement is excellent.

Effect of non-normal incidence

At the edge of a Band 2+3 lens, the angle will be 7.5 degrees for a double-sided lens, or 15.1 degrees for a single sided lens.

Datta et al. 2013 found little impact on the AR band and reflectivity due to non-normal incidences at small angle (and even somewhat acceptable performance for a 30 degree angle of incidence).

Plots (from Datta+13) show simulations including 1 and 2 sides, vs measurements



CCAT Short Wavelength Camera (SWCam) optical design

Parshley et al. 2014 design for 350-2000 micron set of cameras for CCAT first light.

SWCam uses warm 30-cm diameter Si lenses as vacuum windows

SWCam lens design has 25 mm central thickness and 9 mm edge thickness (adding 5 mm to ensure the 30-cm lens could safely hold vacuum).

Scaling for Band 2+3, this could be 2.7 mm thin, or 2.5 mm from Alvaro's estimates.

The Parshley paper even provides a mounting scheme to avoid fracturing the lens when vacuum is pulled.

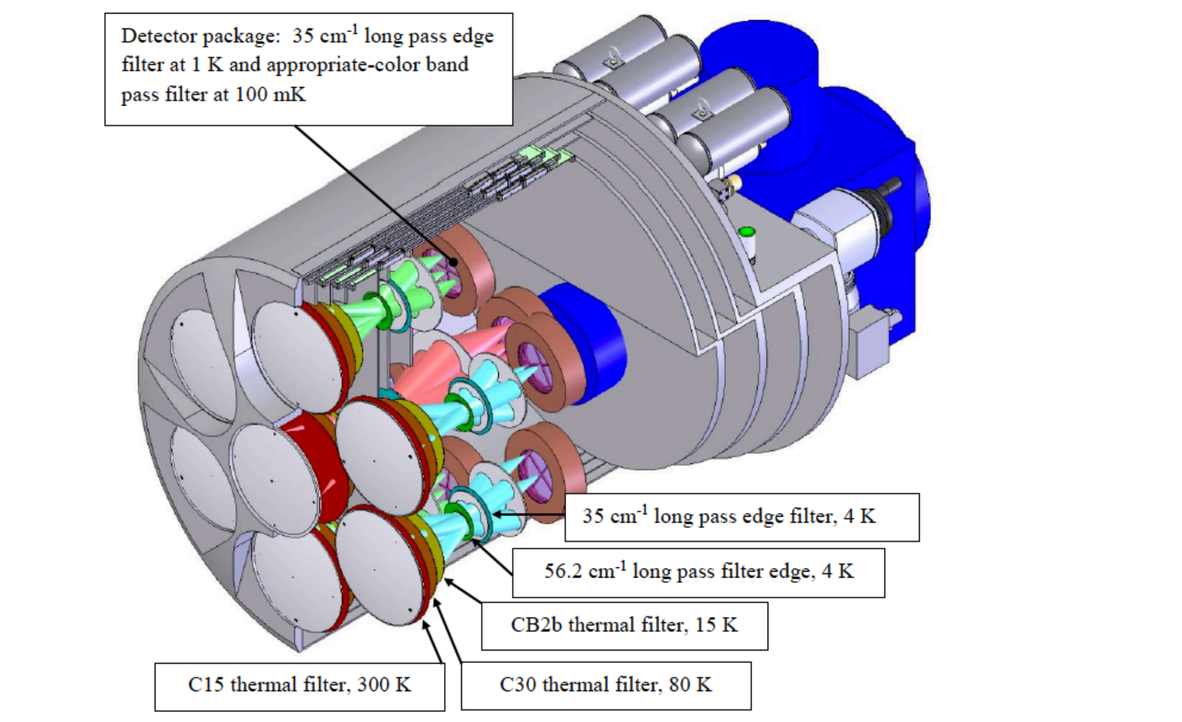


Figure 8. Isometric partial section view of the SWCam cryostat highlighting the filtration sequence. Sub-camera optical beams are shown as solids for some center and field-edge positions (pink = 850 μm, lime = 350 μm, & cyan = 450 μm, 2 mm). The seven filter sequence is color coded by operating temperature – warm (red) to cold (violet).

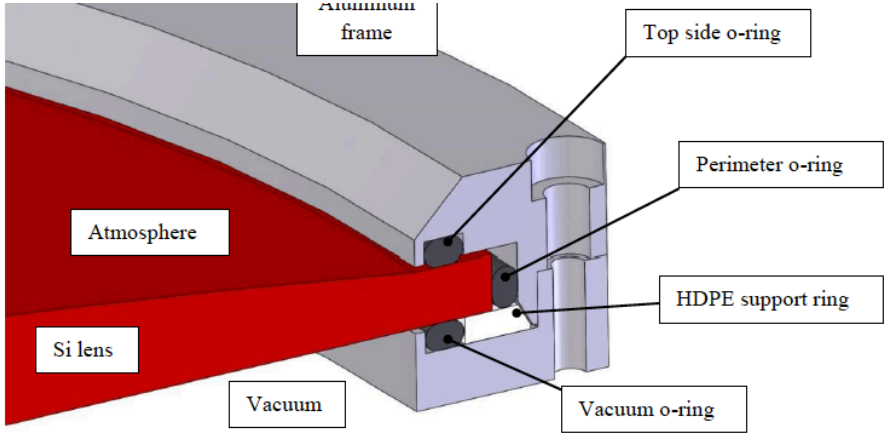
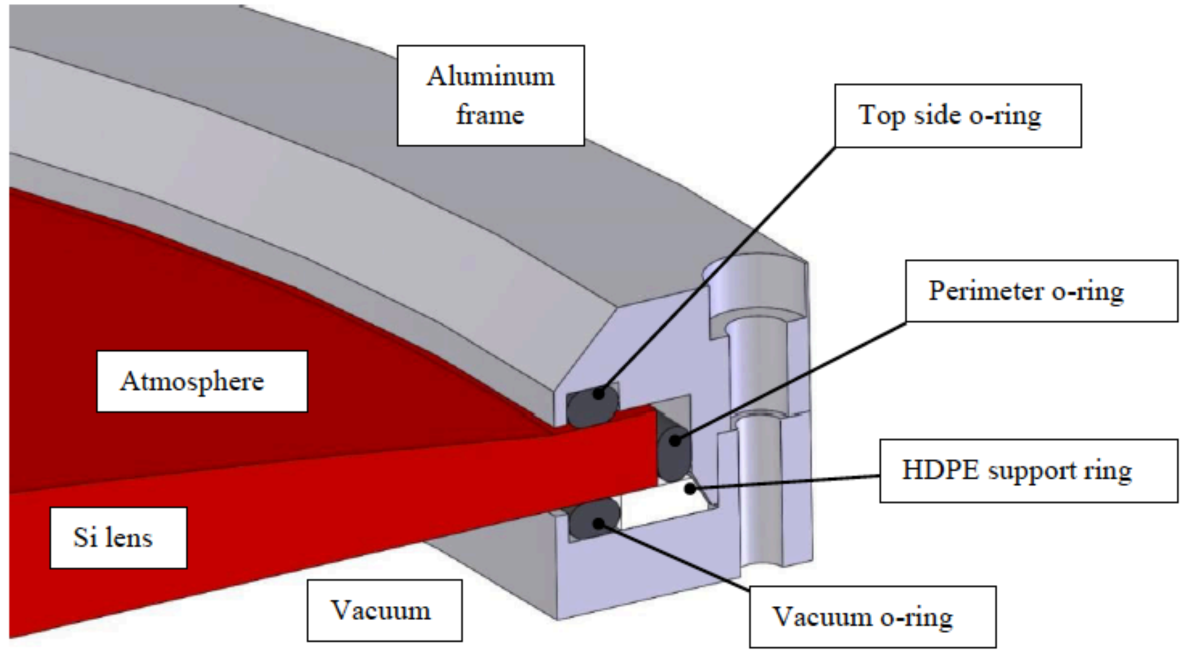


Figure 11. A detail cross section of the field lens mounting system (850 μm sub-camera shown). Note that the silicon is prevented from directly contacting the aluminum frame to avoid potential edge-induced fracture of the silicon. Not shown are channels to the o-rings on the perimeter and the top-side for venting.

CCAT Short Wavelength Camera (SWCam) optical design

SWCam mounting scheme to avoid fracturing the lens when vacuum is pulled.



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References

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- **"Large-aperture wide-bandwidth anti-reflection-coated silicon lenses for millimeter wavelengths" Datta et al. 2013**
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- Parshley et al. 2014 SPIE
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