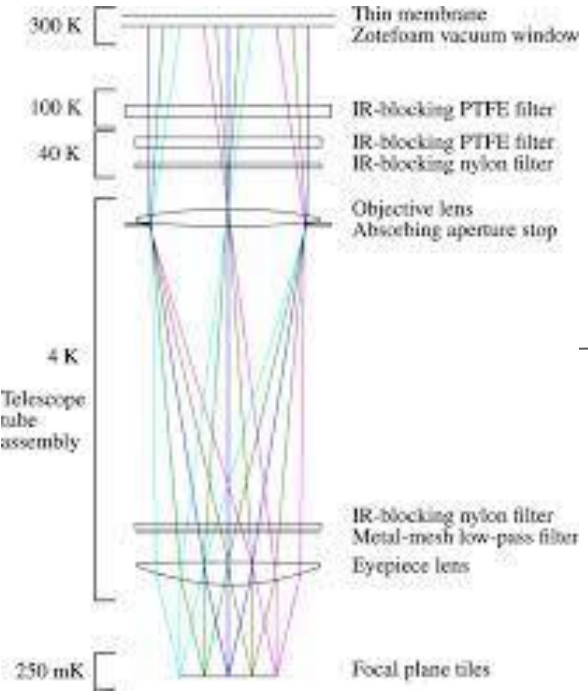
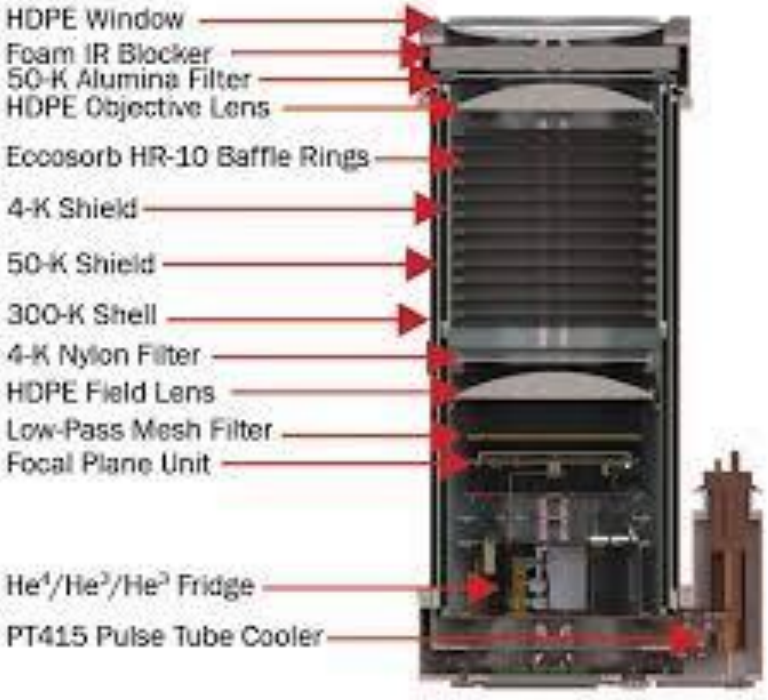
Cold Optics

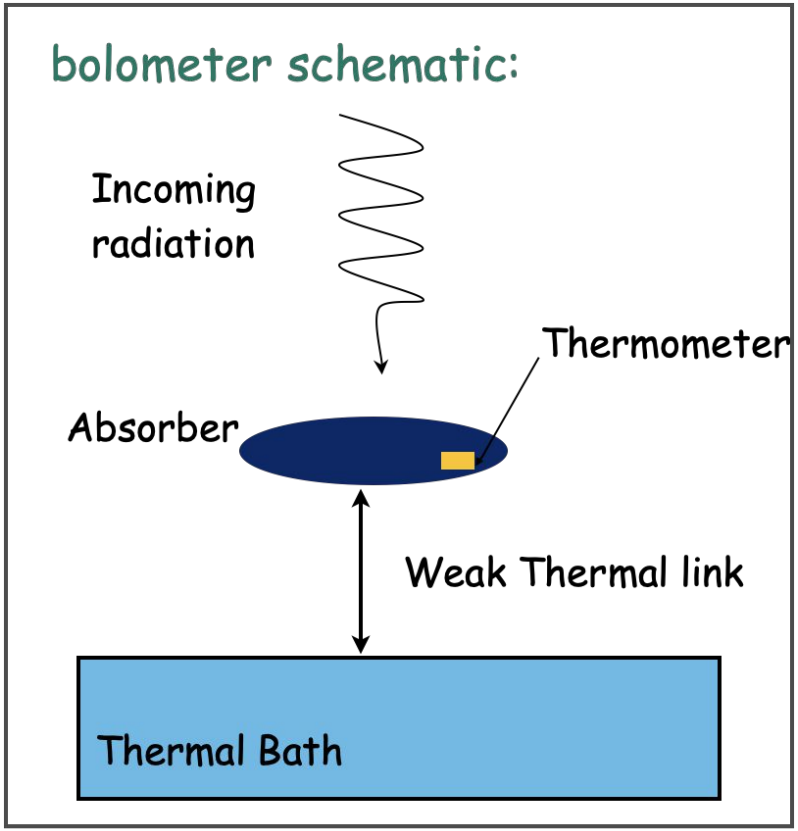
Jeff McMahon



This lecture discusses the components
Needed to implement the designs
From the previous lecture
(BICEP shown)



Maximizing Signal to Noise



- Two noise sources
  - Photons
    - The photons from the sky in the band of interest are the signal.
      - **Maximize transmission**
    - Any other photons are noise
      - **Avoid stray light and out of band signals as much as possible**
  - Phonons
    - Must operate cold
      - **Requires vacuum**
      - **Requires limiting out of band light to keep cold**

What these systems do:

(1) **Pass light into a vacuum space**
  (a) Critical for cryogenics to work
    (i) Necessitates a window
(2) **Filter out unwanted light, passing only the bands of interest**
  (a) Critical to minimize the power (aka loading) on the cryogenic stages
    (i) Infrared (IR) blockers are key here
  (b) Critical to reject out of band signals that we don't want to measure
    (i) Band defining filtres are key here
(3) **Focus light**
  (a) Critical to producing an imaging system
    (i) Typically requires lenses which muyst be anti-refleciotn coated
(4) **Limit stray light**
  (a) Critical to maximizing sensitivity
    (i) Requires baffling to absorb light that doesn't go where we want it
    (ii) Often demands a cold stop to block light that goes in the wrong direction
    (iii) Much carefully consider diffraction and scattering
(5) **Couple light onto detectors (this is the edge of the detector system)**
  (a) Critical to high coupling efficiency, and to minimize stray light
    (i) Requires feed horns, planar antennas, or phased arrays

Interactions of light with dielectric materials

The index of refraction (n) determines how much light is bent by a lens (or other optic) and how much light gets reflected at an interface.

The power reflection is $R = \left(\frac{n-1}{n+1}\right)^2$

For HDPE (n = 1.5) R = 0.04, for Silicon (n = 3.4) R = 0.30

The loss tangent (tan∂) determines the transmission (T) and emissivity (E) of a material of thickness t

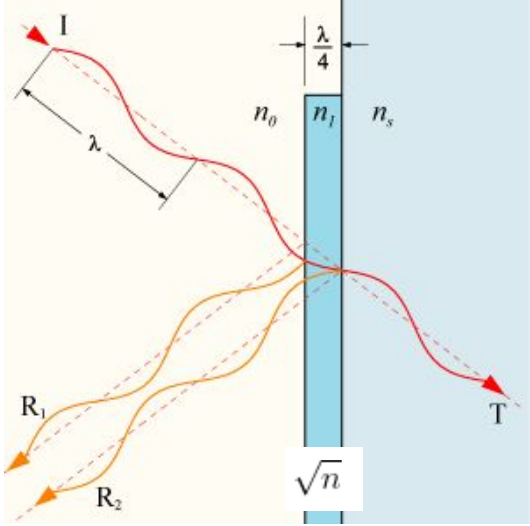
$$T = e^{-2\tan\delta\frac{2\pi}{\lambda}nt} \qquad E = 1 - T = 1 - e^{-2\tan\delta\frac{2\pi}{\lambda}nt}$$

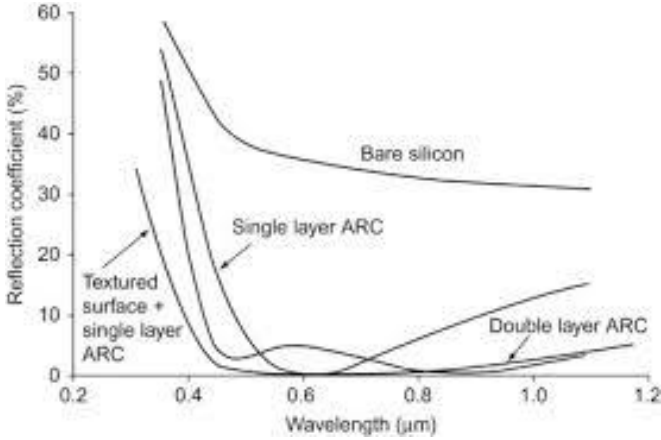
Inhomogeneities in the material lead to **scattering**. This is a harder calculation where the details matter, but Mie scattering is a useful model

For materials listings find a copy of James Lamb's "Miscellaneous data on materials for millimetre and submillimetre optics"

Anti-reflection Coatings

- Reducing reflections seems simple–
  - Put one or more materials with the appropriate index of refraction and thickness at a dielectric interface and reflections are eliminated at some frequencies and mitigated over a band
  - One lawyer works over a relatively narrow band
  - For more bandwidth multi-layer coatings can be implemented, or one can use a gradient index coating
    - In general the mutli-layer coatings are thinner for the same performance
- However, this is very hard
  - Requires finding (or engineering) the right material
  - The coating must be mechanically robust and support the thermal environment (eg cooling without falling apart)
  - A non-negligible fraction of experimental research effort goes into solving this problem for the materials we need to use.





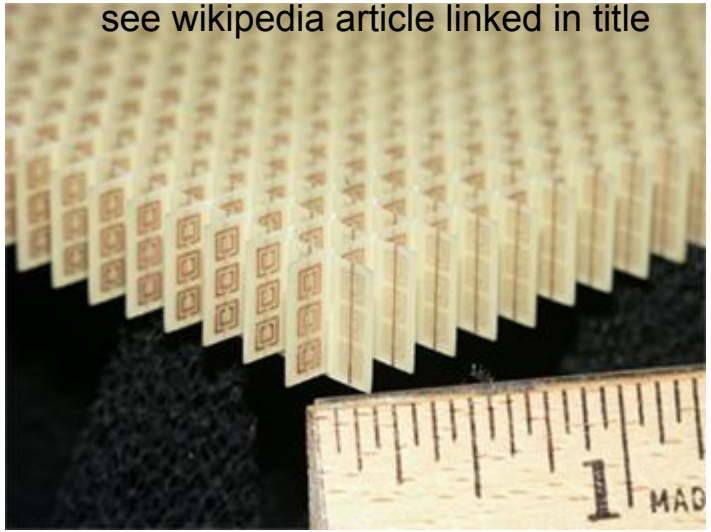
Metamaterials

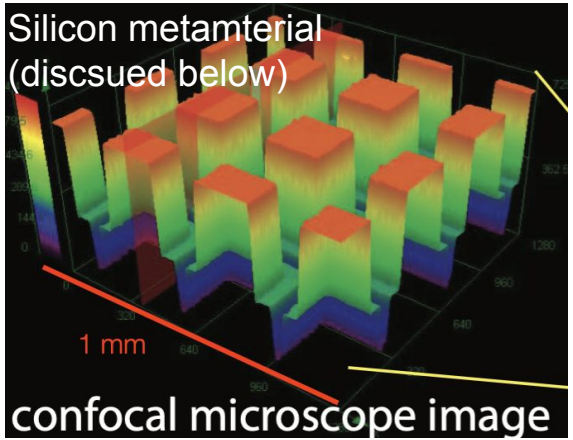
Concept:

- engineer the dielectric function with sub-wavelength features
    - Can be metal structures
    - Can be dielectric structures
- Example: index of refraction
    - The index of refraction is related to the polarizability of a medium
    - By removing material in regular sub-wavelength features we can lower index
    - Since this is a combination of the bulk material and vacuum it an be a very low loss approach
    - Also, these structures are perfectly CTE matched to the substrate

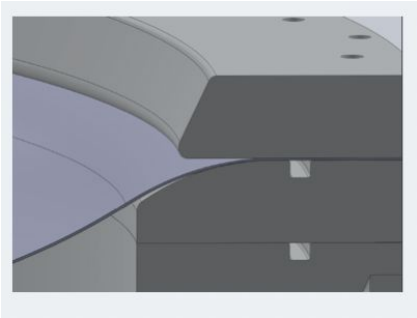
Negative index structure

see wikipedia article linked in title





Component: Windows



- 1 ATM ~ 15 PSI
  - A 40 cm window is ~19k lbs of force
  - This requires high strenght windows
- Typical Solutions
  - Zotefoam
    - A foamed plastic with a low index
      - It must be thick
      - The reflection is low
      - Scatteirng is ~1% for typical thickness due to inverse Mie Scattering
  - HDPE
    - A solid plastic
      - Strong so it can be relatively thin
      - Relatively low dielectric loss
      - Requires an anti-reflection coating
        - Laminated plastic
          - Turns out laminated coatings are hard and geting repeatable performance is tricky
        - Metamaterial
          - MUSTANG and SPT-3G have interesting implementations of this
        - BICEP developed a thin HDPE fabric window

Component: Metal Mesh filters

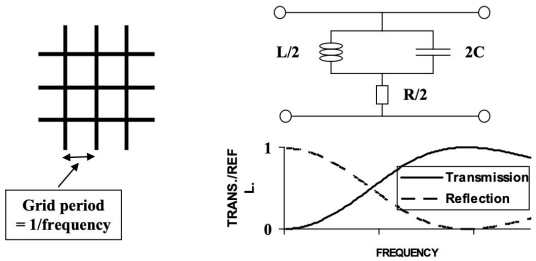


Figure 1a: Inductive grid geometry, equivalent circuit and spectral properties

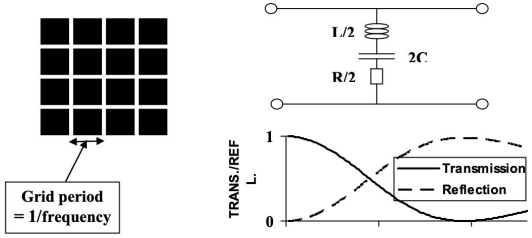


Figure 1b: Capacitive grid geometry, equivalent circuit and spectral properties

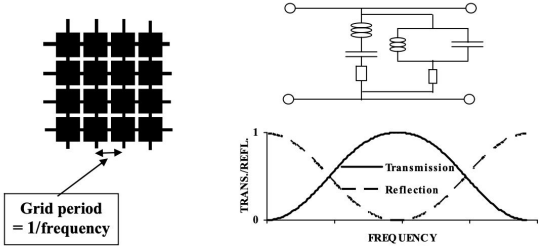
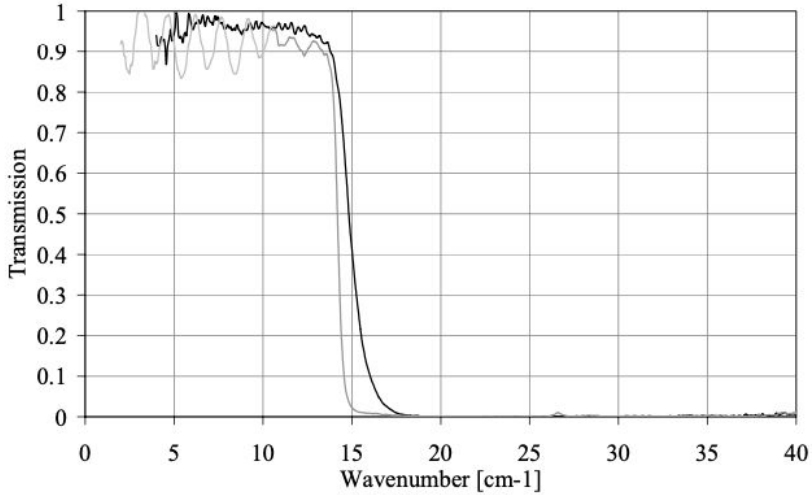


Figure 2: Resonant grid geometry, equivalent circuit and spectral properties

Stack multiple mesh layers together (with proper spacing) to get improved filter performance

- Cardiff makes many different types of filtres
  - LPE (low pass edge, shown below)
  - Band-pass
  - HPE (high pass edge)
  - IR blockng
  - Dicrhoics



Component: IR Blocking Filters

Reflective filters

Can reduce >99% of out of band power without absorbing it, however, adding a second filter doesn't square reduce this by the same factor again since it creates a relatively high Q cavity between the two. Also for mesh filters the large angle transmission can become large

Absorptive filters

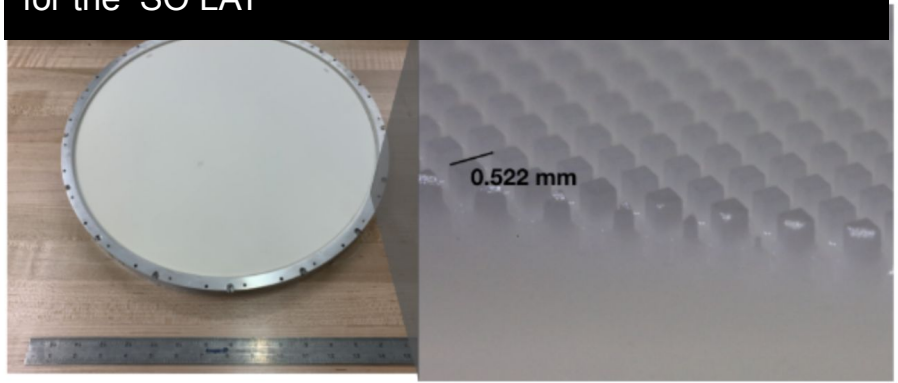
are a handy tool to augment reflective filters

- Nylon (n = 1.7) and Alumina (n=3.1) are typical materials since they are IR black
- Aluminum has a very high conductivity, but requires a good AR coating
- Require AR coatings which work well cryogenically

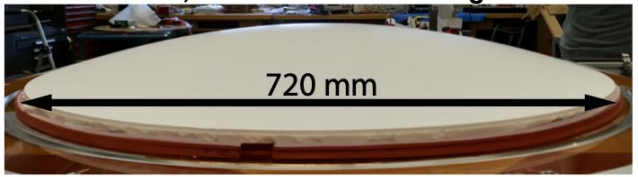
Alumina AR coatings

Laminated coatings for alumina
Saw Cut **metamterial AR coatings for alumina**
Laser cut metamterial coatings for alumina

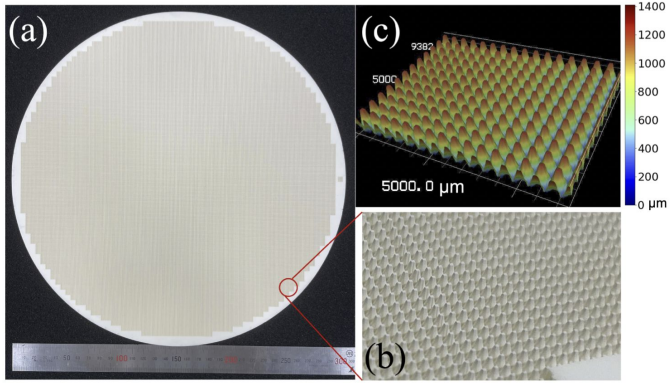
One of four complete metamterial AR coated MF filters for the SO LAT



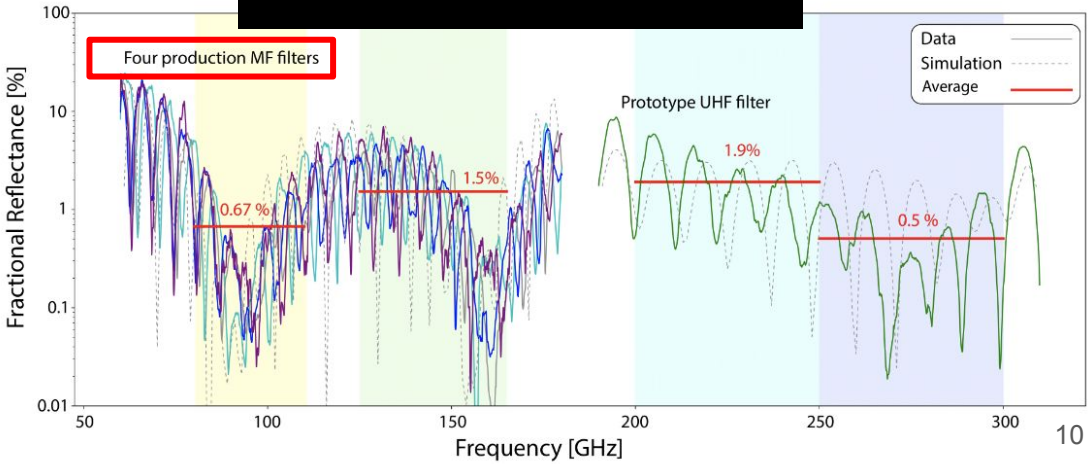
SPT 3G Lens, with laminated coating from UIUC



MUSTANG Lens with LASER AR



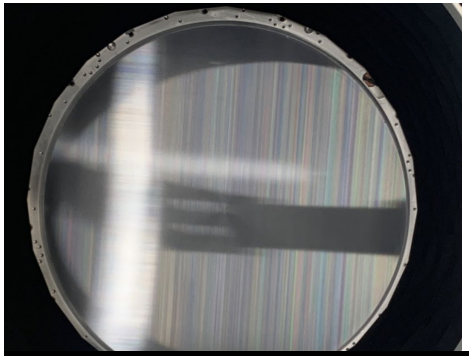
Measured Performance



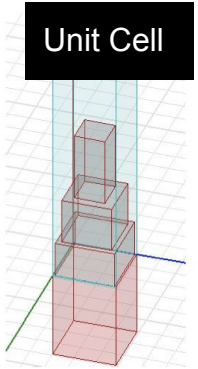
Silicon AR coatings

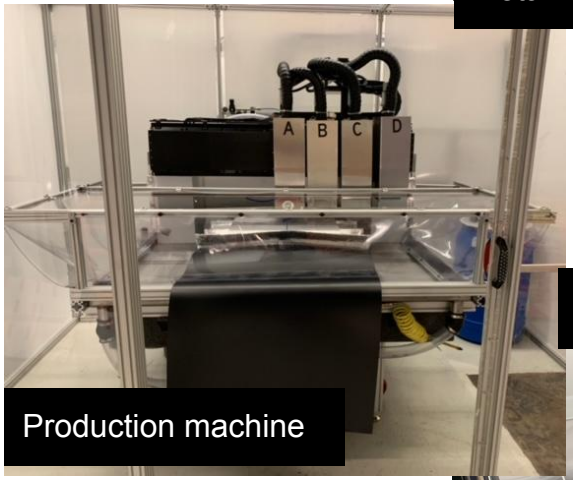
AR coating for silicon, production at scale
AR coatings for alumina
Baffling materials to control sidelobes

- We developed a new machine design which cuts the production time from one month per lens to one week
- We built a facility with two of these production machines so we could produce silicon and alumina (see next slide) simultaneously.
- This facility is ready and available for ASO
- See https://arxiv.org/abs/2101.10298 for performance



Metamaterial coated Si lens





Production machine

Production facility @ FNAL

Silicon AR coatings

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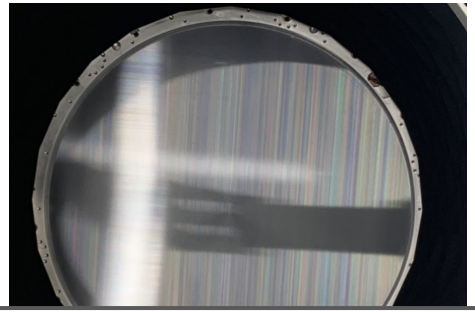

Unit Cell

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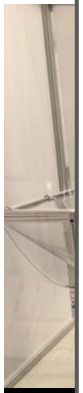
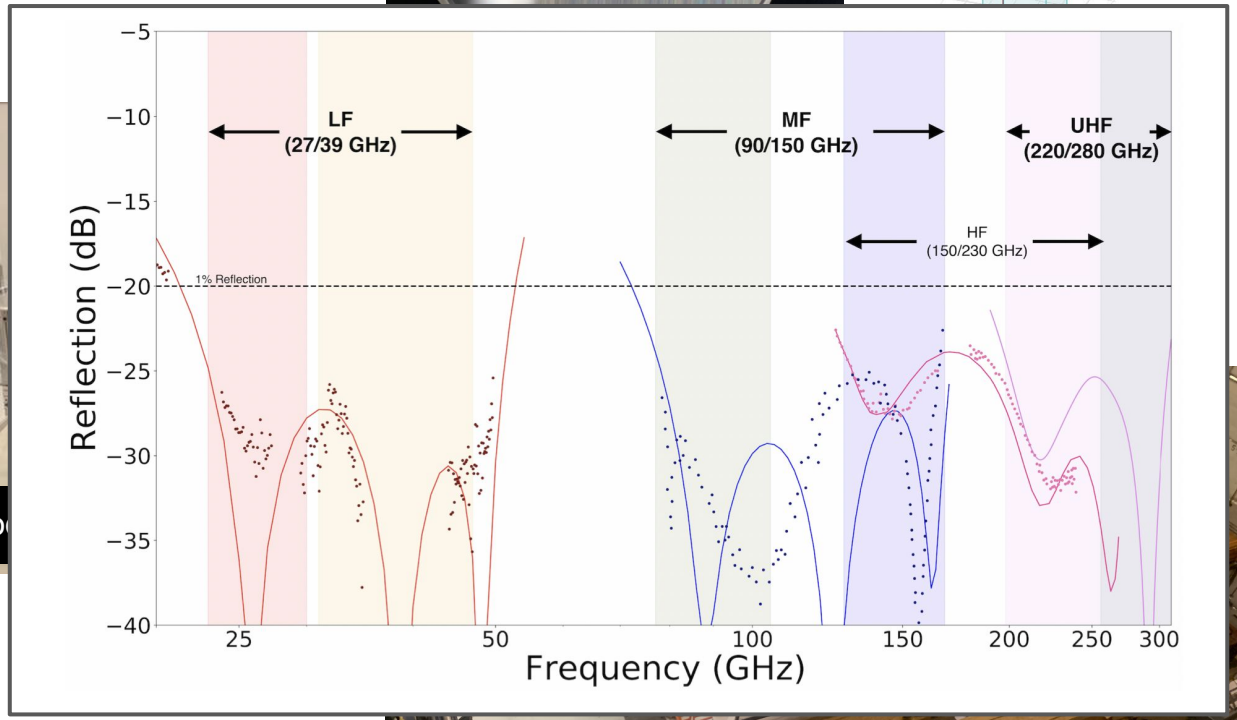


Pro



Baffling materials to control sidelobes

- Reflections from the outermost walls of the optics tube identified as a driver for spill to 300K (and our sensitivity)
- Developed metamaterial microwave absorbing tiles (MMAs)
- Achieve extremely low reflectance, low cost, and excellent heat sinking properties
- Reflection and scattering less than 1% at all relevant angles

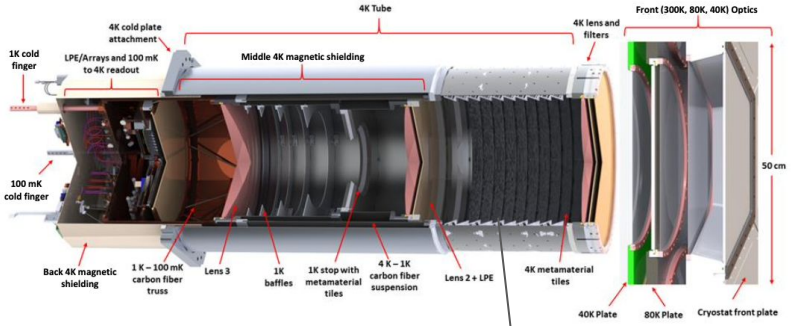
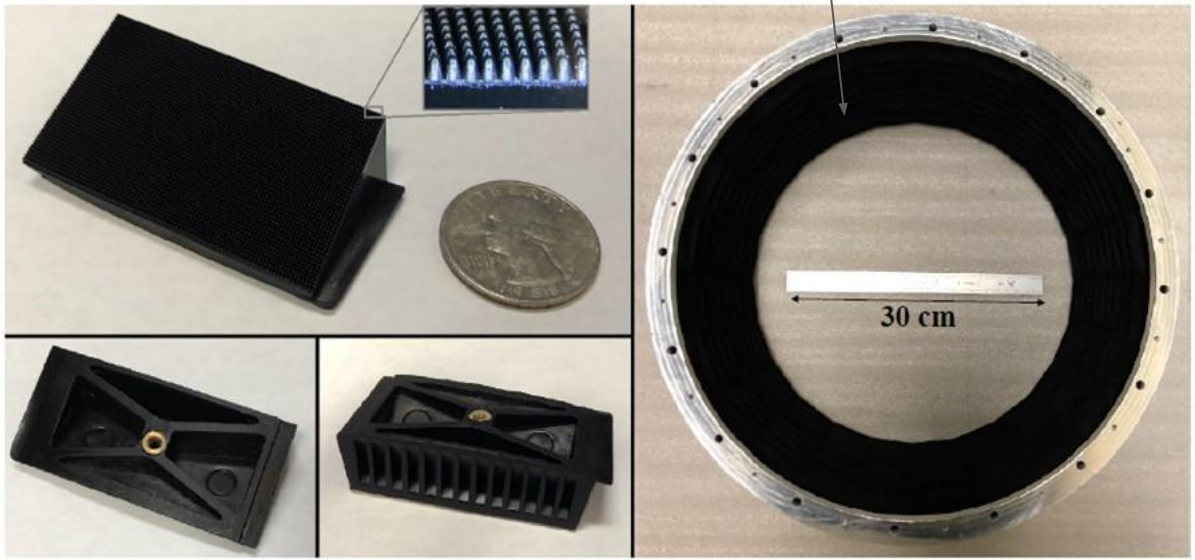
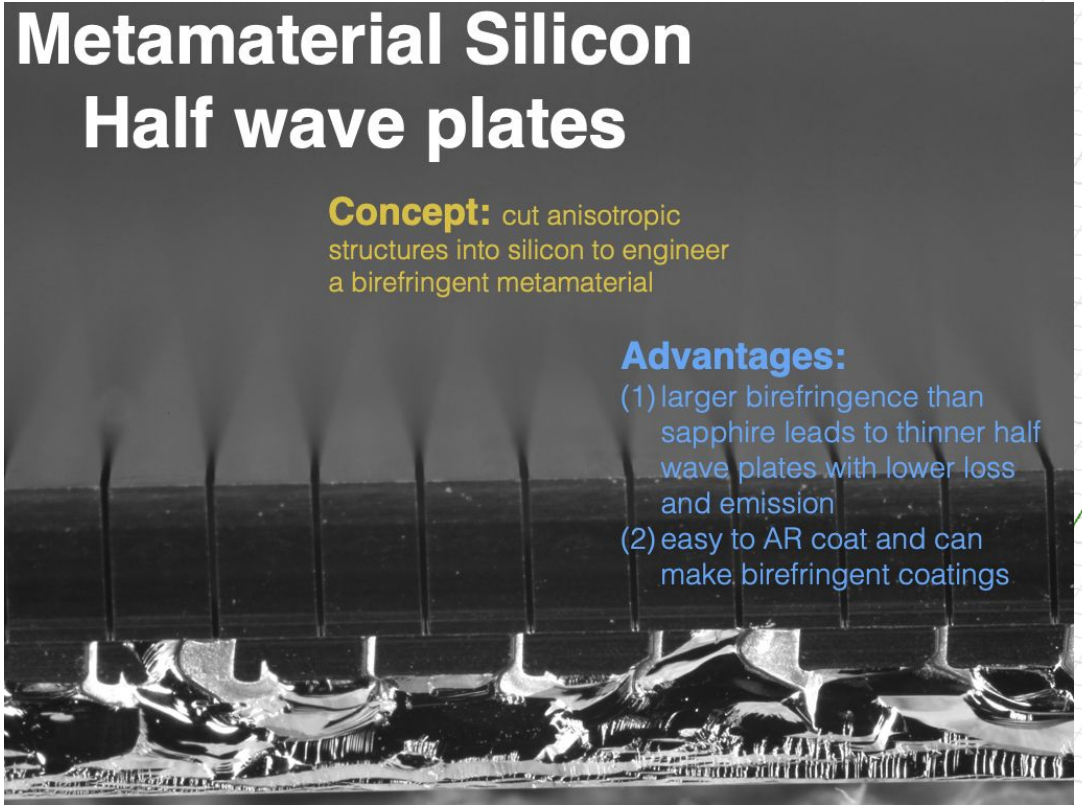


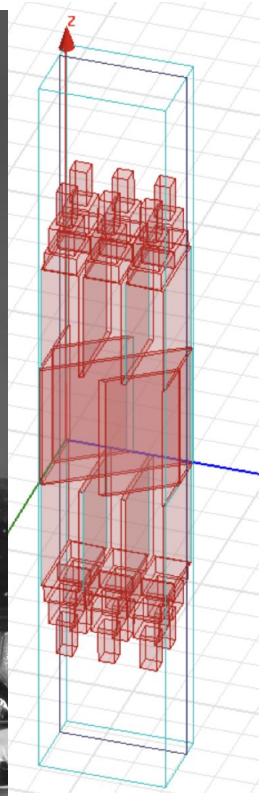
Figure 3: LATR OT Cross Section

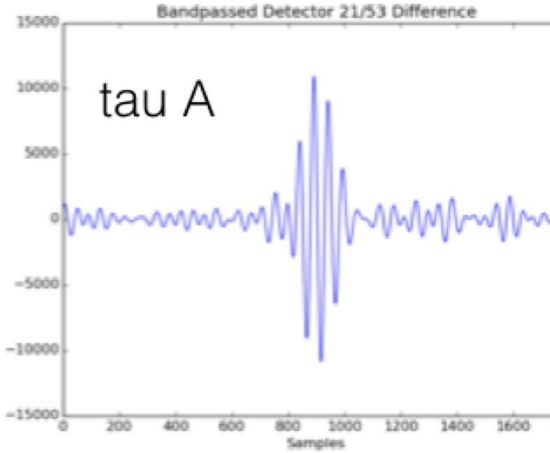
Metamterial AR coating tiles



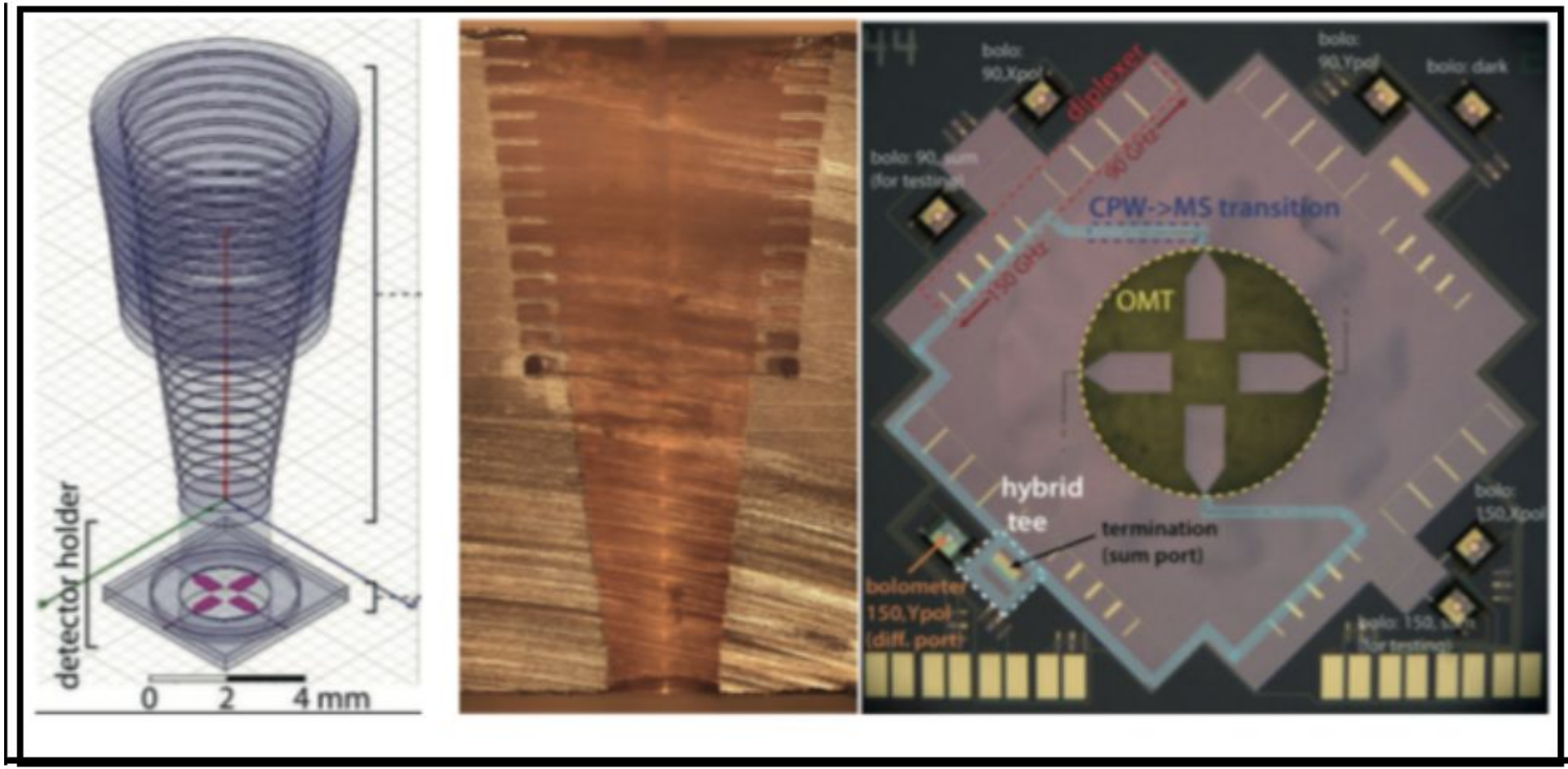
Wave plates– silicon metamaterial example, Sapphire is the commonly used material– but this model explains how the materials work



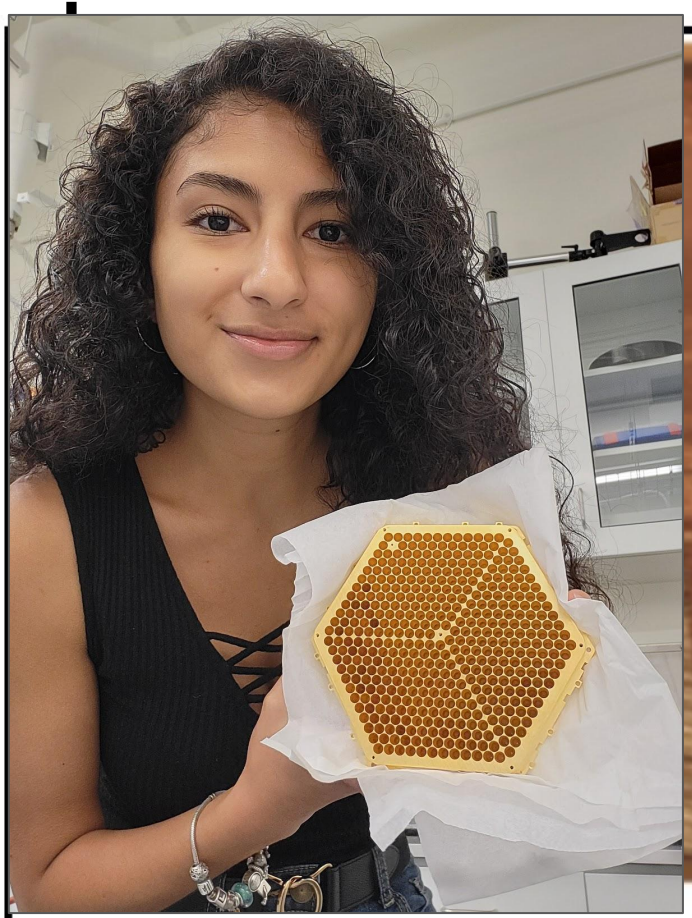


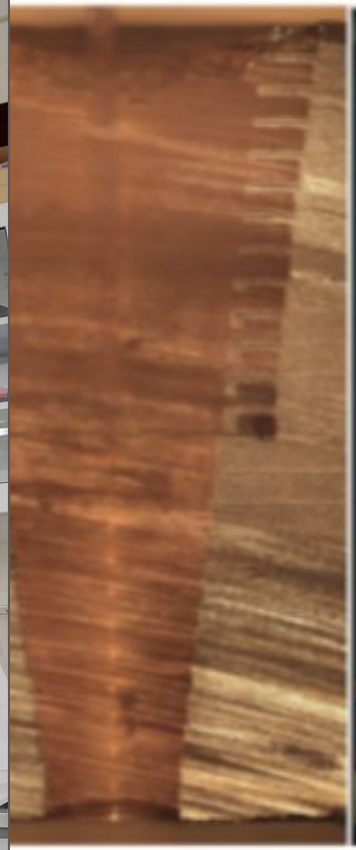


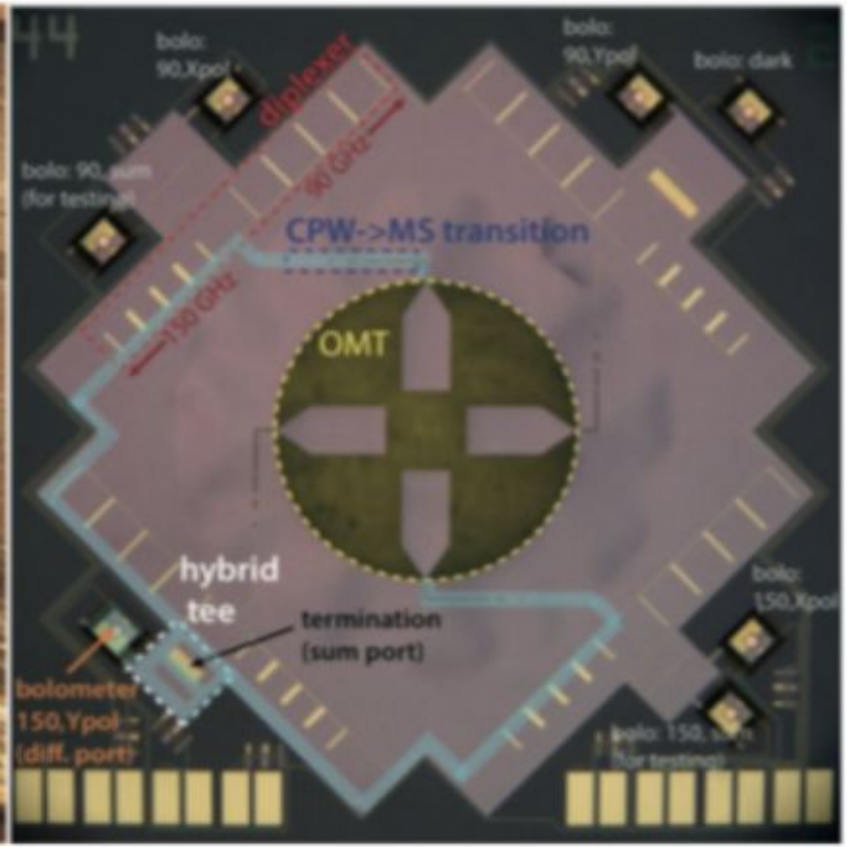
Optical coupling – for modern horns see Simon et al



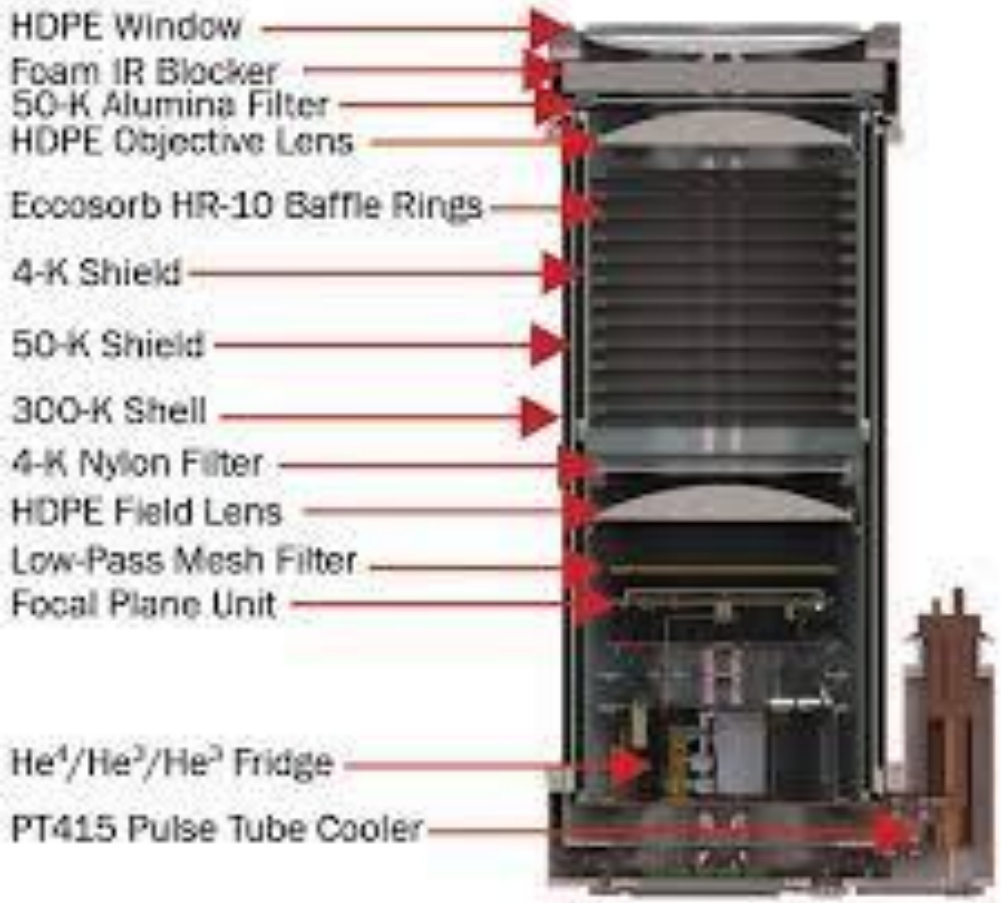
Optical coupling



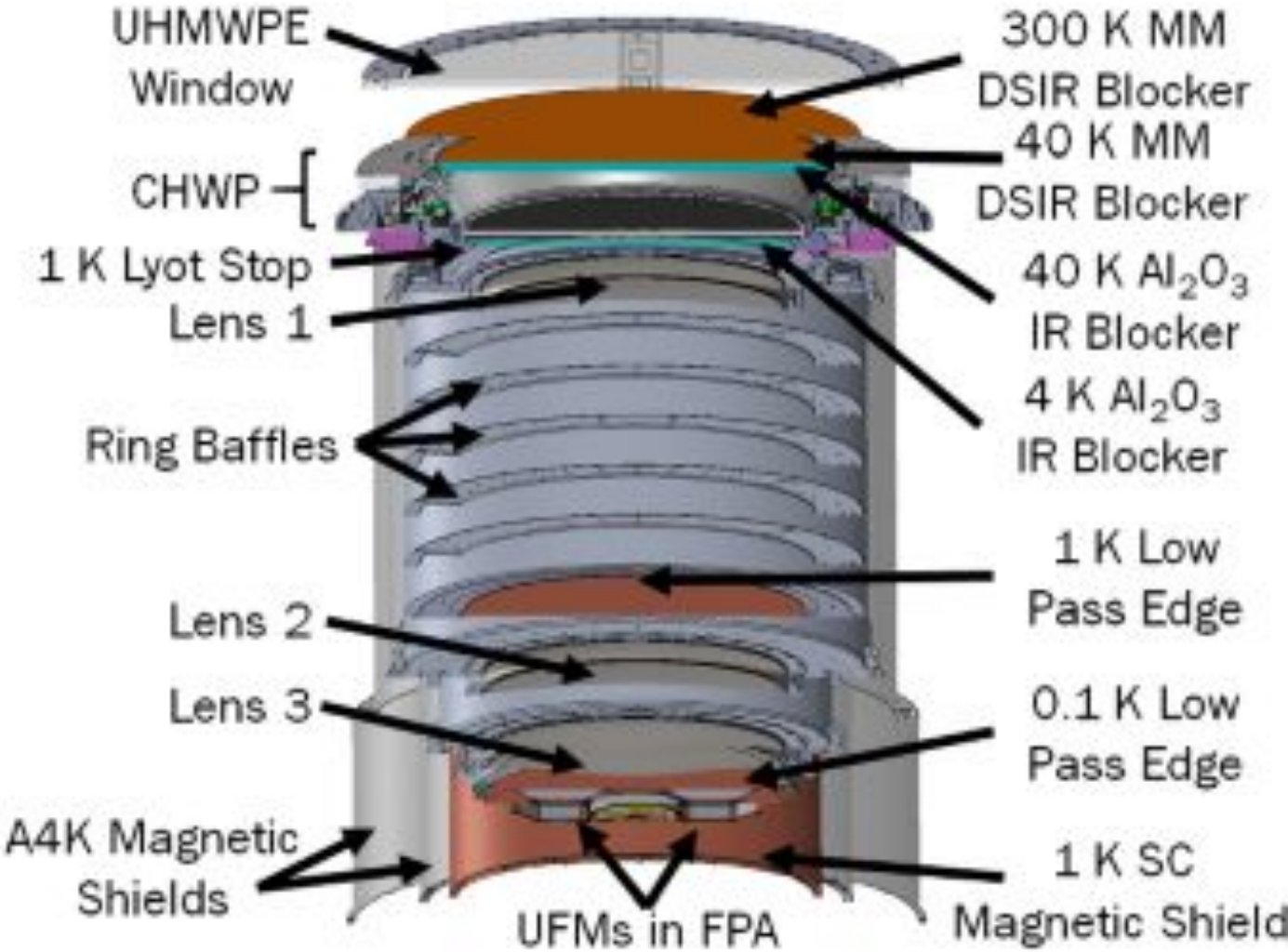




Example BICEP



Example:
SO SAT



Example: SO LAT

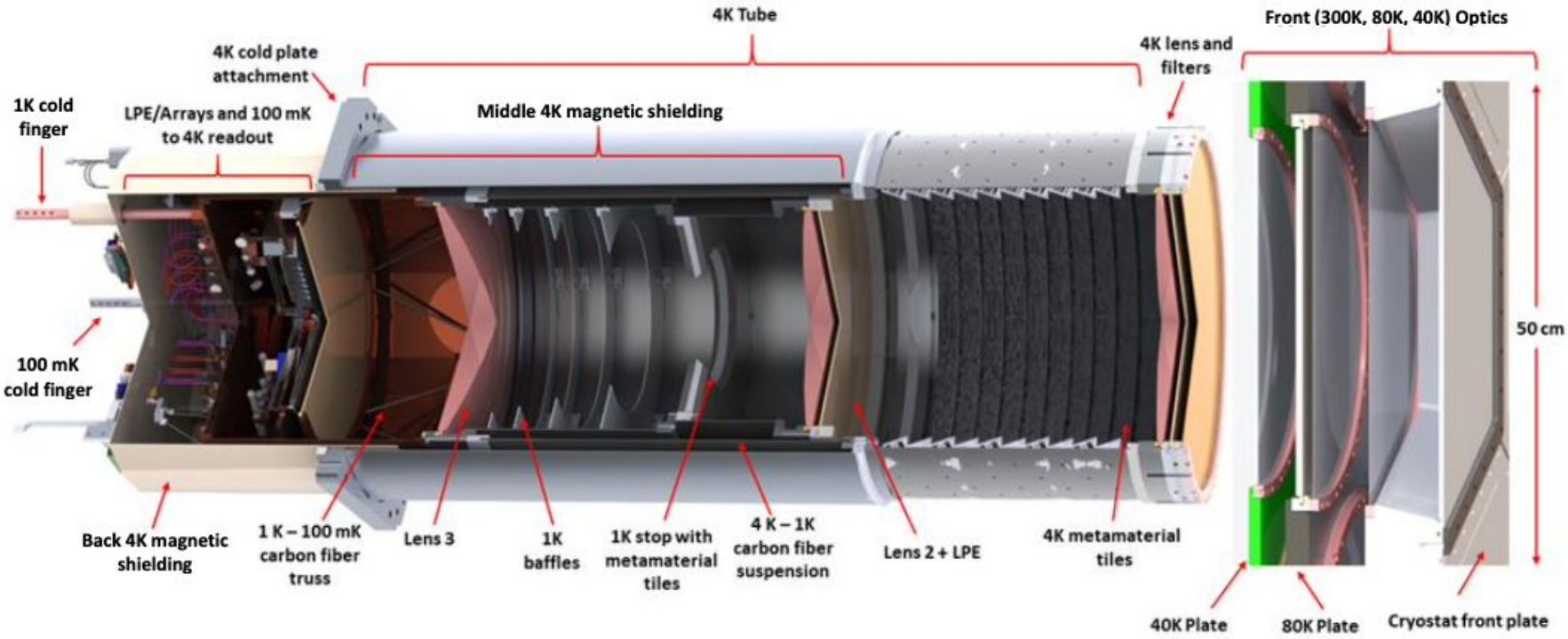


Figure 3: LATR OT Cross Section

Example SPT 3G