Optimizing the Efficiency of Fabry-Perot Interferometers with Silicon-Substrate Mirrors

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Introduction

Interferometers in ground, airborne, and space observatories have spurred growth in astronomy and astrophysics for decades. We present the novel design of microfabricated, silicon-substrate based mirrors for use in cryogenic Fabry-Perot Interferometers (FPIs) for mid-IR to submm/mm instruments in ground (e.g. CCAT-prime [1,2]), airborne (e.g. HIRMES), and space-based instruments. To achieve high resolving power and optical throughput, we use a combination of inductive and capacitive gold meshes evaporated onto the silicon substrate. The other side of the substrate is plasma etched with a double-layer metamaterial anti-reflection coating (ARC). These silicon-substrate FPIs will enable spectroscopic observations with the upcoming large IR/submm/mm TES bolometer detector arrays. These broad bandwidth of these FPIs will:

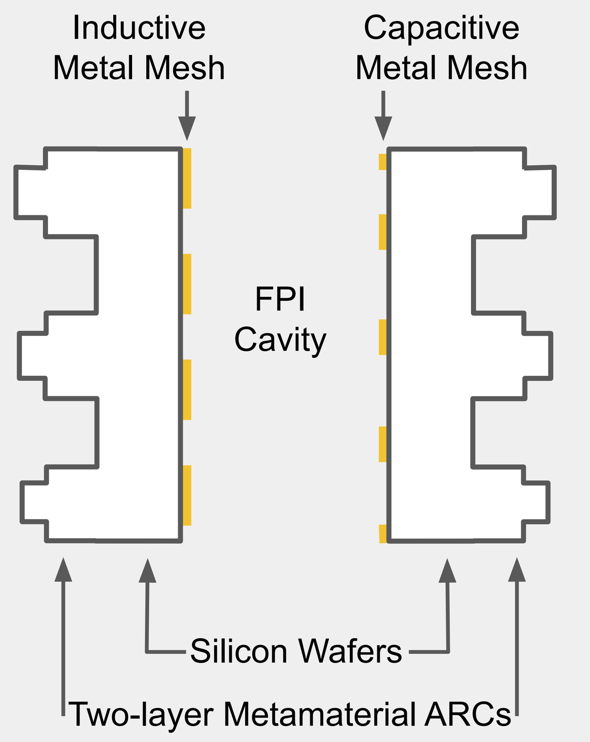
- Efficiently cover the octave bandwidth required for a [CII] intensity mapping spectrometer for Epic of Reionization investigations on CCAT-prime [1]
- Observe a broad set of diagnostic far-infrared fine-structure lines (e.g. [OIII] 52 um to [NII] 122 um) with a single FPI for airborne or space-borne spectroscopy (e.g. HIRMES) [4]

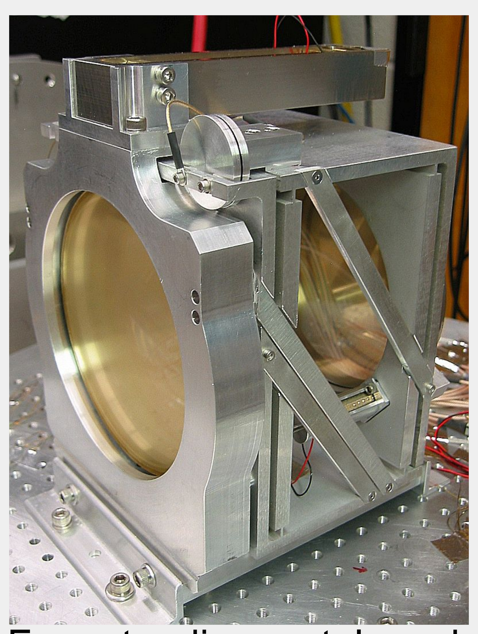
Silicon Substrate FPIs

Far-IR FPIs commonly use free-standing metal meshes as reflectors [6]. Silicon substrate based mirrors promise significant improvements in transmission, bandwidth, and mechanical stability.

Silicon substrate FPIs are comprised of:

- Metal mesh reflectors on silicon wafers [7]
  - Provide frequency dependent reflectance
  - Provide control of FPI resolving power
- Metamaterial anti-reflection coatings [10]
  - Sub-wavelength structure etched on silicon
  - Mitigate strong Fresnel reflections of silicon
  - Multiple layers → wider bandwidth



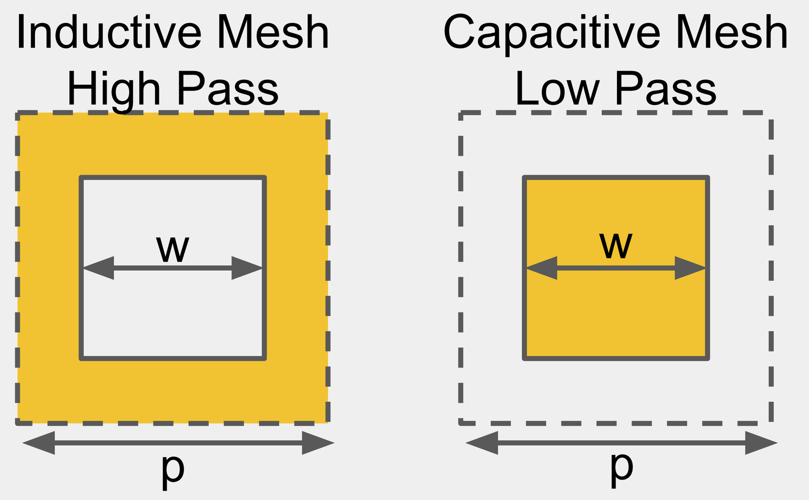


Free standing metal mesh scanning FPI

Design and Modeling

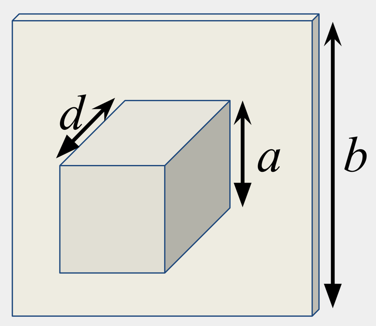
Metal Meshes

- Inductive and capacitive meshes [5]
  - Form high and low pass filters
  - Diffraction occurs for λ < p
  - Filter response depends on w/p
- Combining inductive and capacitive
  - Band-pass or band-stop filters
- Filters simulated in CST Microwave Studios



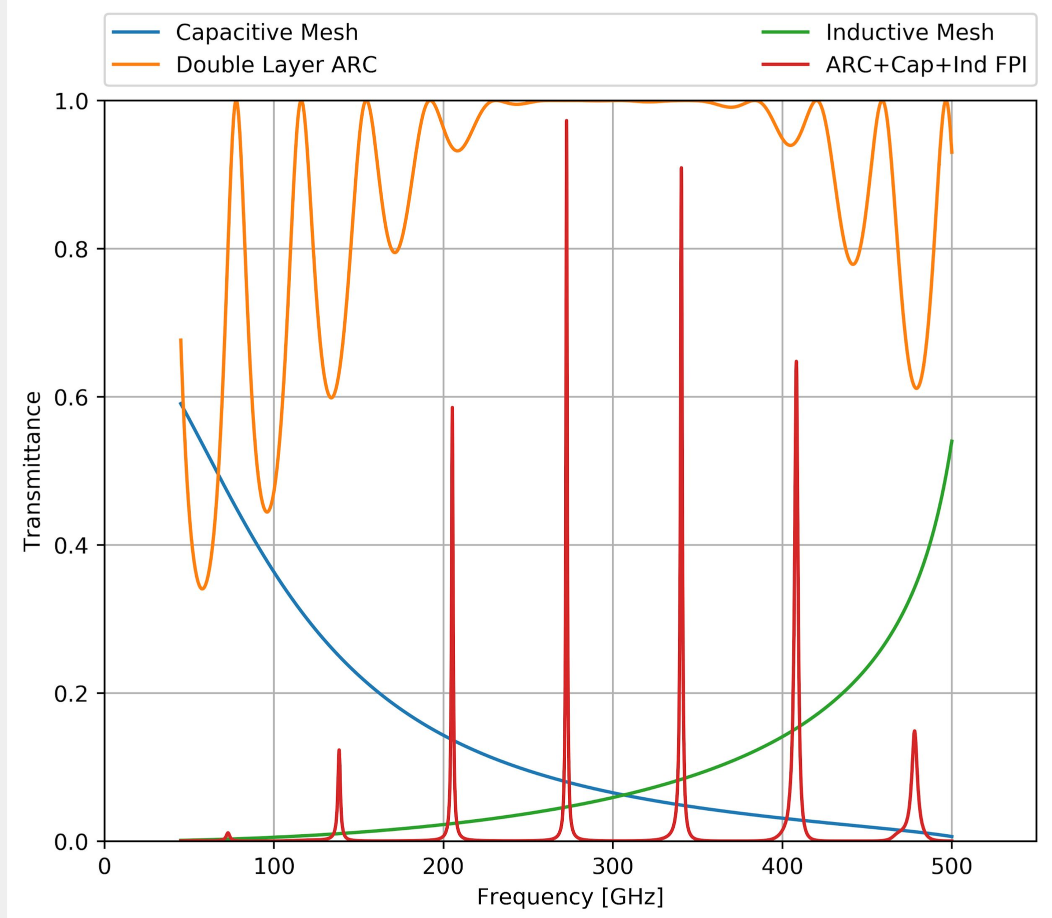
Metamaterial Anti-Reflection Coatings

- Broadband, sub-percent reflections required by FPI
  - To mitigate parasitic resonances
  - To optimize throughput
- Metamaterial benefits:
  - Precision control of ARC efficiency
  - Eliminates thermal contraction issues
- ARC depths, indices, and metamaterial geometry determined using:
  - Theory of layered dielectrics [8]
  - Equivalent circuit model theory [9]
  - Optimized with CST Microwave Studios



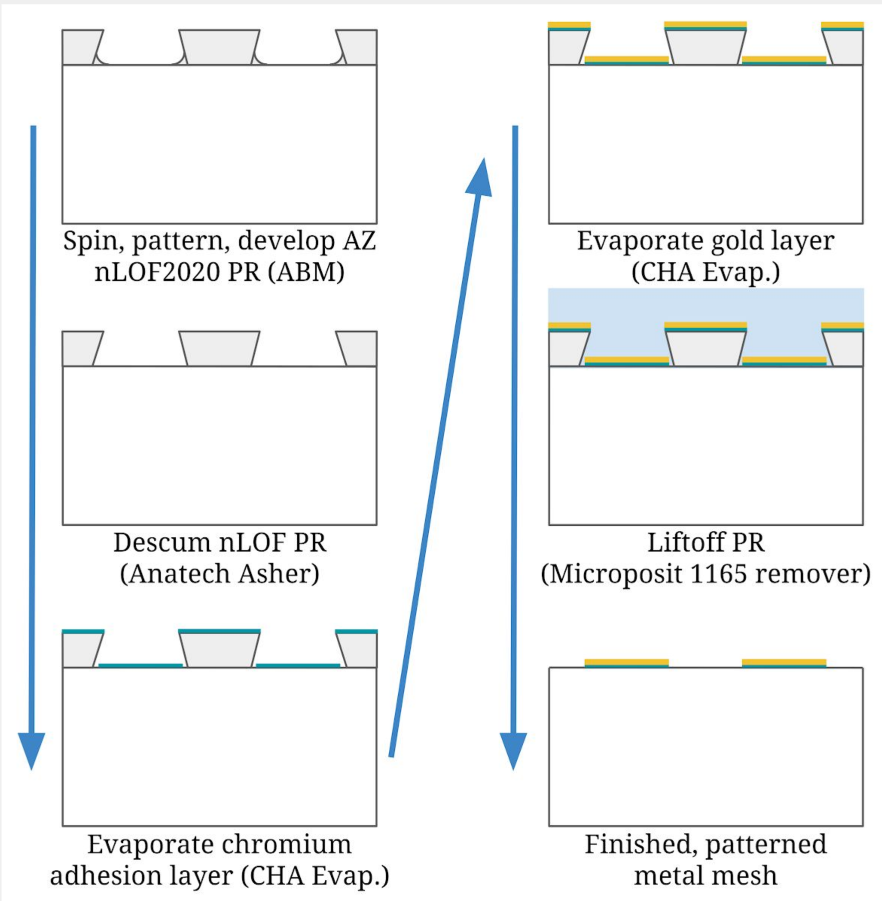
$$\epsilon_r^{\mathrm{eff}} = \left(\frac{a-b}{a} - \frac{b\epsilon_r^{\mathrm{Si}}}{b+(a-b)\epsilon_r^{\mathrm{Si}}}\right)$$

Equivalent Capacitive Circuit Model

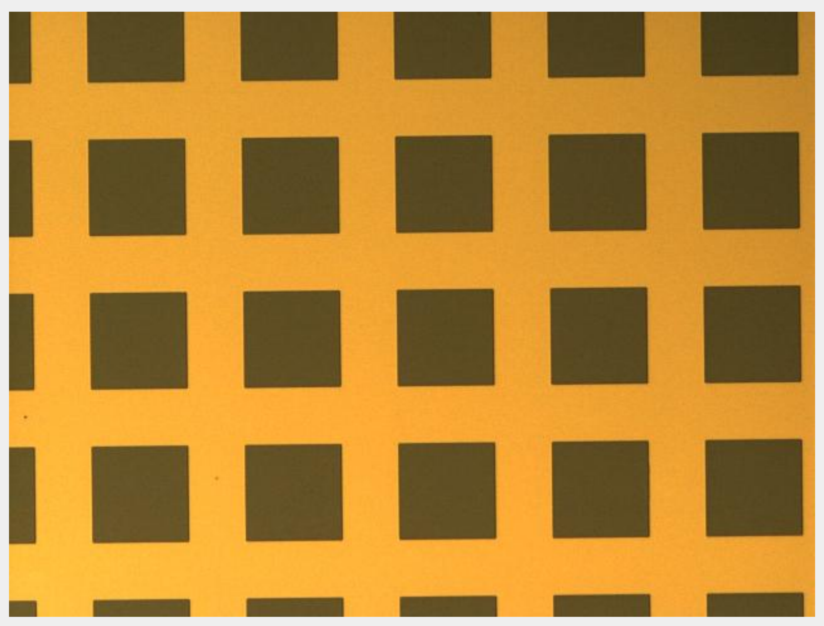


Simulated transmittance of a FPI and comprising two-layer ARC and inductive/capacitive metal meshes calculated with CST Microwave Studios

Metal Mesh Deposition

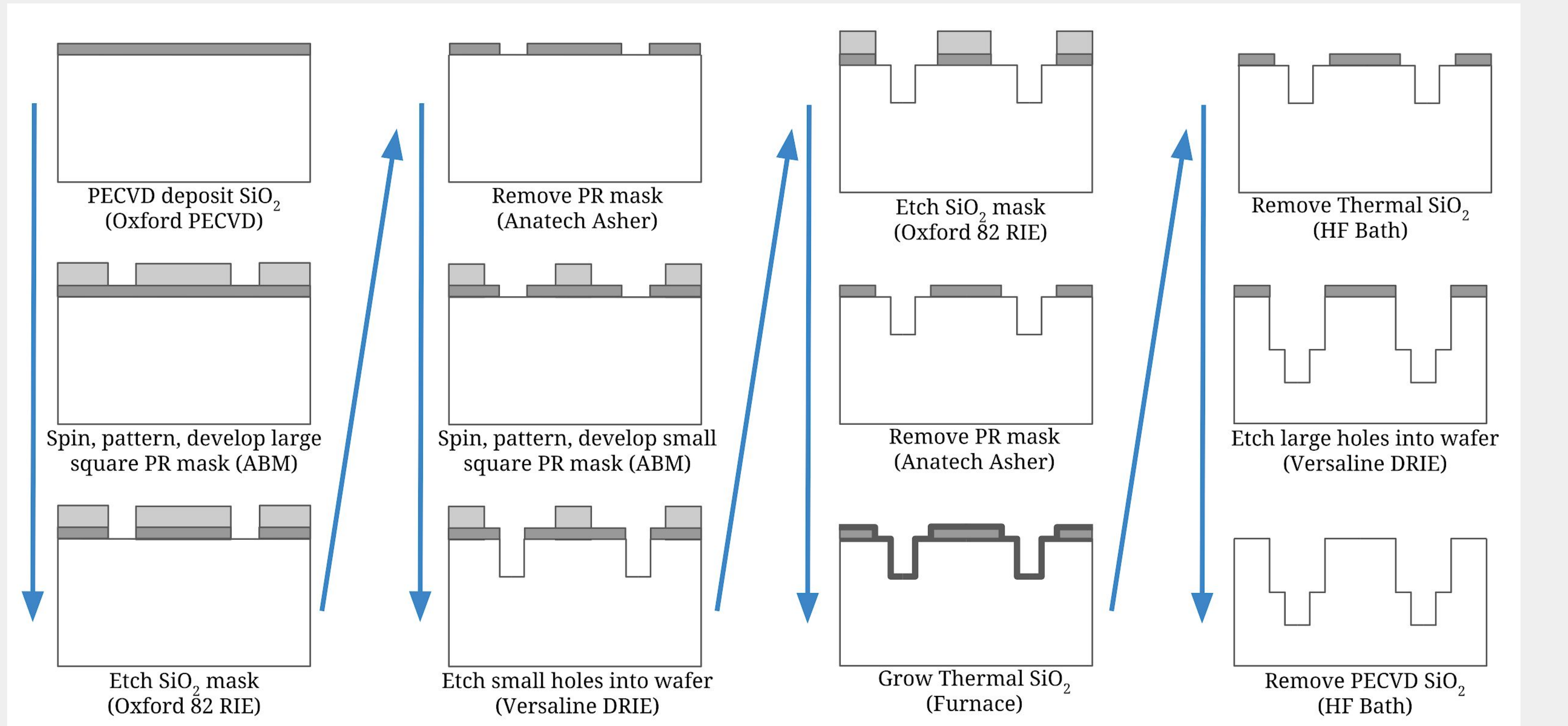


Standard negative liftoff photoresist patterning of metal mesh

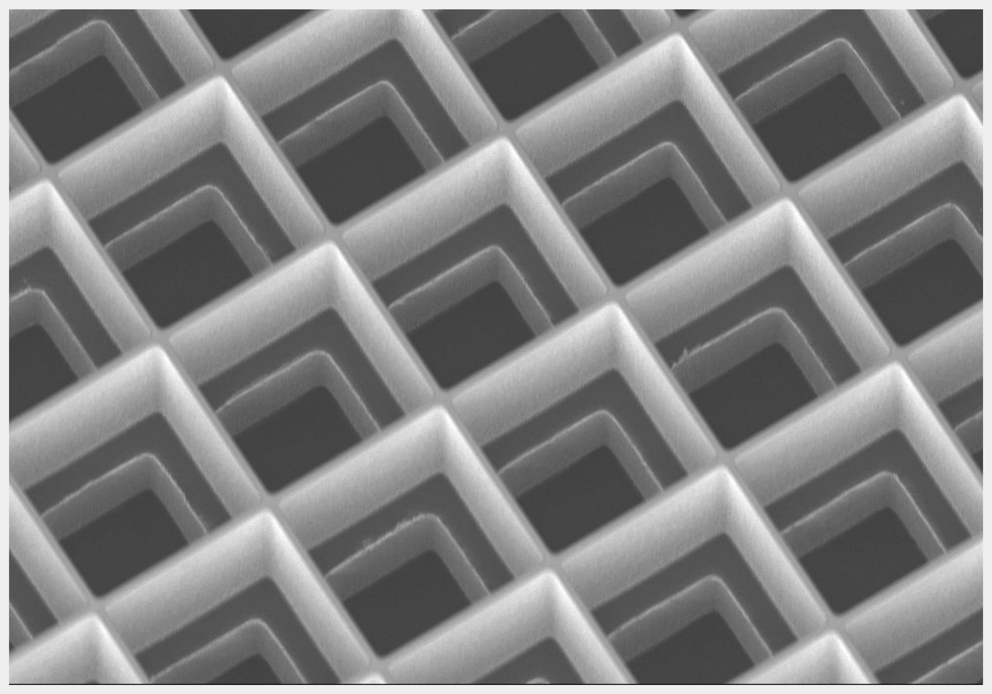


Microscope photo of patterned inductive gold mesh

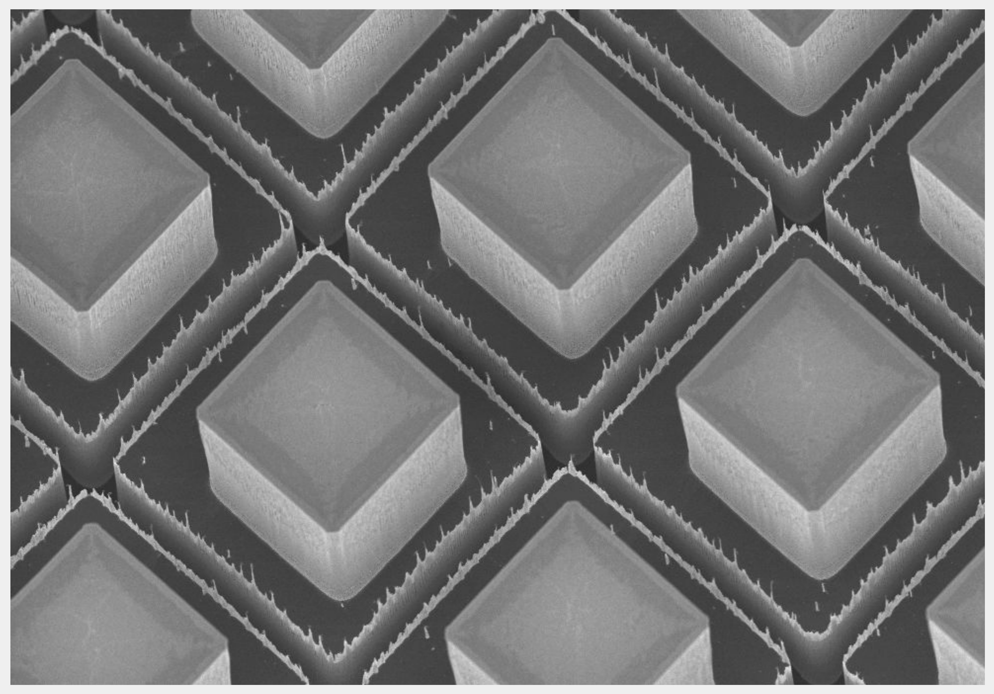
Metamaterial Anti-Reflection Coating Fabrication



Double layer metamaterial ARC recipe based on deep reactive ion etching (DRIE) [11].



SEM image of double-layer holes ARC optimized for 100um



SEM image of double-layer pillars ARC optimized for 350um

Future Work

- Currently fabricating on optical silicon
  - 1mm broadband double- layer ARCs
  - 1mm metal mesh reflectors
- FTS measurements coming soon.
- "Fixed" FPI of metal meshes on either side of optical silicon wafer, this summer.
- Scanning FPI with pair of mirrors, this fall.
- Exploring super conducting meshes to reduce ohmic losses in mesh filters.

References

1. Stacey G., et al., SPIE, 2018, 10700-53
2. Parshley S., et al., SPIE 2018, 10700-220
3. Vavagiakis E., et al., SPIE, 2018, 10708-64
4. Douthit G,. et al., SPIE, 2018, 10708-59
5. Dicker S., et al., SPIE, 2018, 10700-122
6. Ulrich R., Infrared Phys. 1966, DOI: 10.1016/0020-0891(67)90028-0
7. Sakai K., Genzel L., Review of Inf. and mm. Waves, DOI: 10.1007/978-1-4615-7766-9_5
8. Ade P., SPIE, 2016, DOI: 10.1117/12.673162
9. Yeh P., *Optical Waves in Layered Media*, Wiley, 1988
10. Biber S. et al., 33rd European Microwave Conference, 2003, DOI: 10.1109/EUMA.2003.341134
11. Datta R., et al., Appl. Opt. 2013, DOI: 10.1364/AO.52.008747
12. Gallardo P. A, et al., Appl. Opt. 2017, DOI: 10.1364/AO.56.002796

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