National Aeronautics and Space Administration

Volumetric Silicon Metaoptics for Highly-Compact and Low-Power Terahertz Spectroscopy

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Program: FY23 Topical R&TD

Objective:

To develop and characterize an extremely compact and low-power terahertz spectrometer using:

- Passive volumetric meta-optics elements, designed with inverse-design algorithms and fabricated by stacking patterned silicon wafers
- A high-Q resonator, whose output resonances are sorted to sensitive direct detectors by the volumetric device

Approach and Results:

- A **resonant cavity** is made with **metasurface-stabilized distributed Bragg reflectors** made of cascaded Si membranes.
- A metaoptics device made of stacked Si layers designed through topology optimization and patterned with micromachining techniques **sorts the cavity resonances to their own direct detectors.**
- The cavity outputs multiple **10^4-10^5 spectral resolution** lines separated by a **free spectral range (FSR)**. **Future work will target >10^6 resolution** by increasing cavity length. The FSR decreases, but by increasing the number of spectral bins that the meta-optics sorts the bandwidth can remain the same.

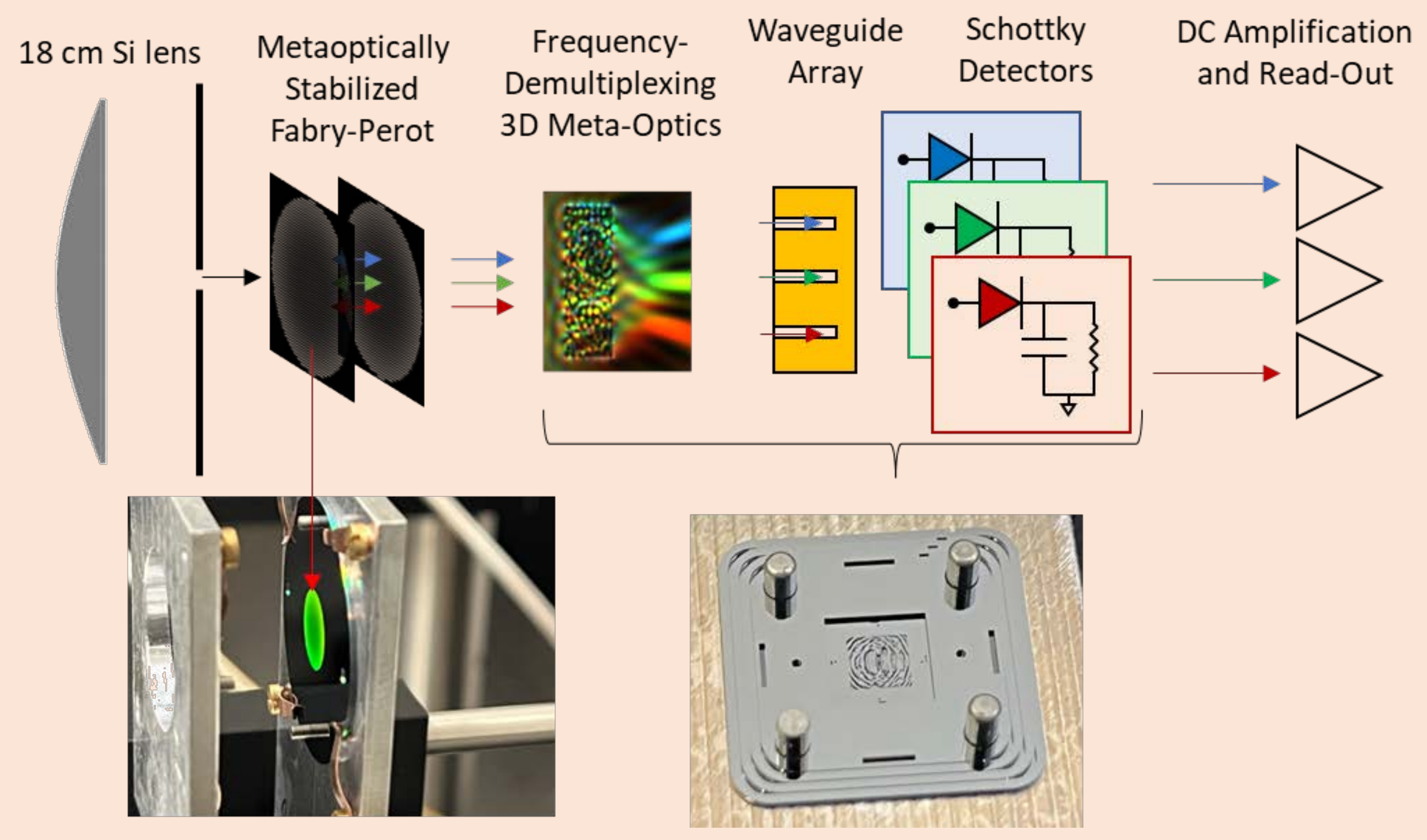

Figure 1. Basic illustration of the system. A resonator made of two metasurface-stabilized DBR mirrors outputs resonances that can be tuned by changing the cavity length. The metaoptics sort these resonances to different direct detectors, which are then processed as low-frequency signals.

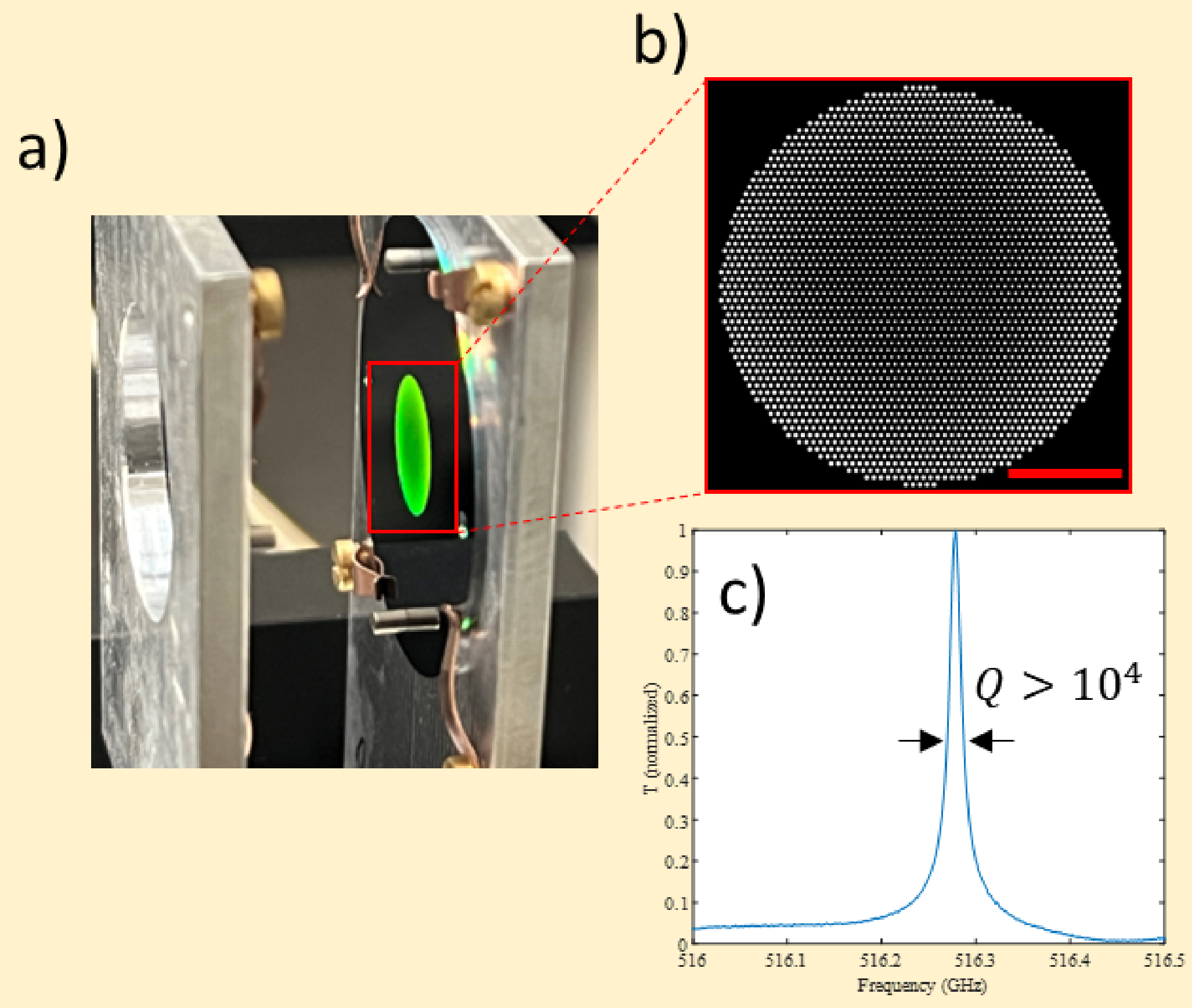

Figure 2. Fabry-Perot cavity. a) DBR placed in piezo-electric fixture. b) The metasurface pattern. The red scale bar is 2.5 mm. c) An example of a resonant feature of the cavity. Here the quality factor is approximately 10^4, which is limited by absorption from water in the atmosphere. The resonance contains no higher-order transverse modes, enabled by controlling the spillover efficiencies of the various cavity moves using metasurface aperture size.

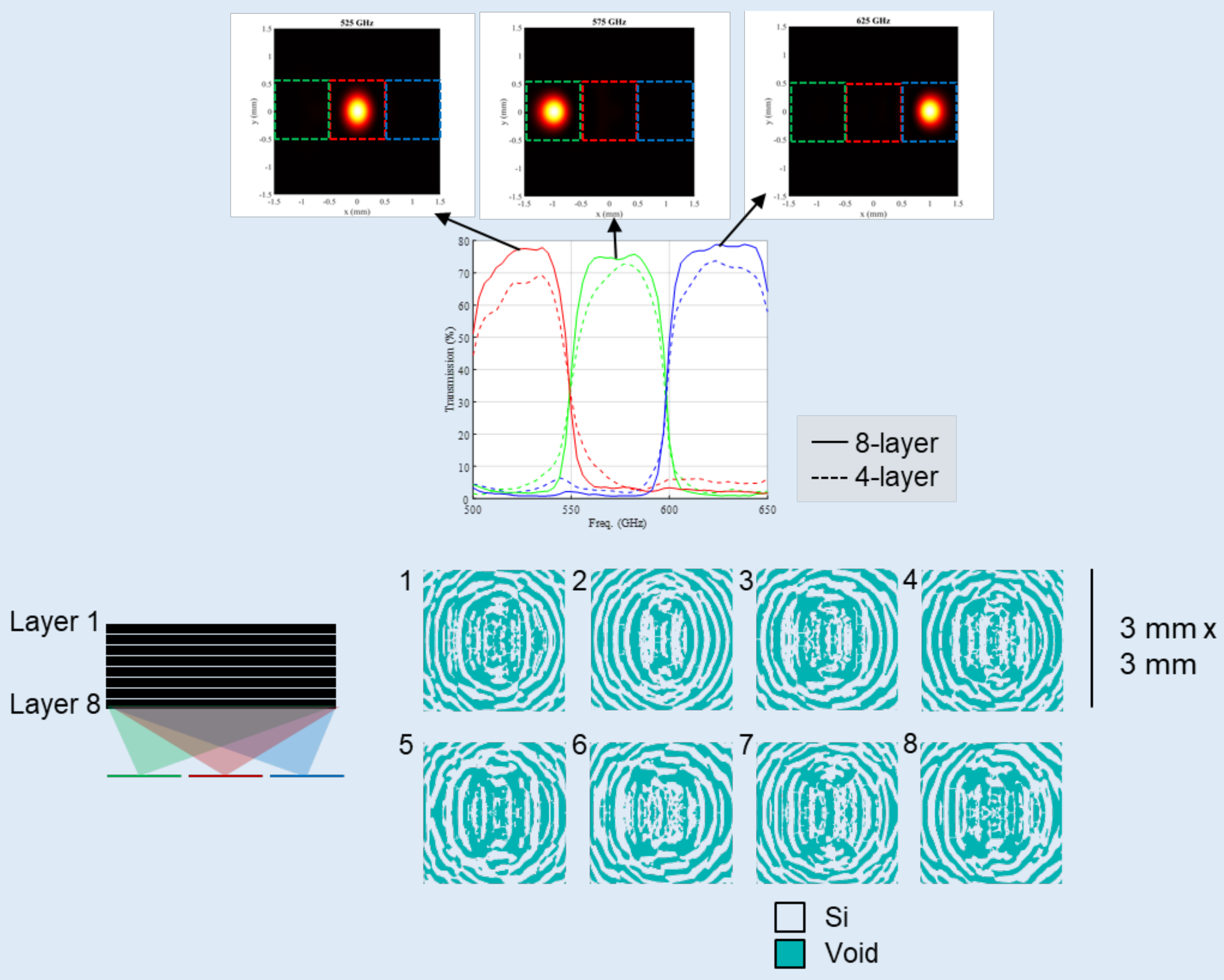

Figure 3. The simulated metaoptics device. The red, green, and blue curves correspond to the power transmission through the pictured red, green, and blue apertures. The dashed lines are for a 4-layer device, while the solid are for an 8-layer device showing an efficiency improvement due to the increased degrees of freedom in the design. The index profiles for the 8-layer device are shown. The individual layers are 3 mm × 3 mm, with a thickness of 40 um.

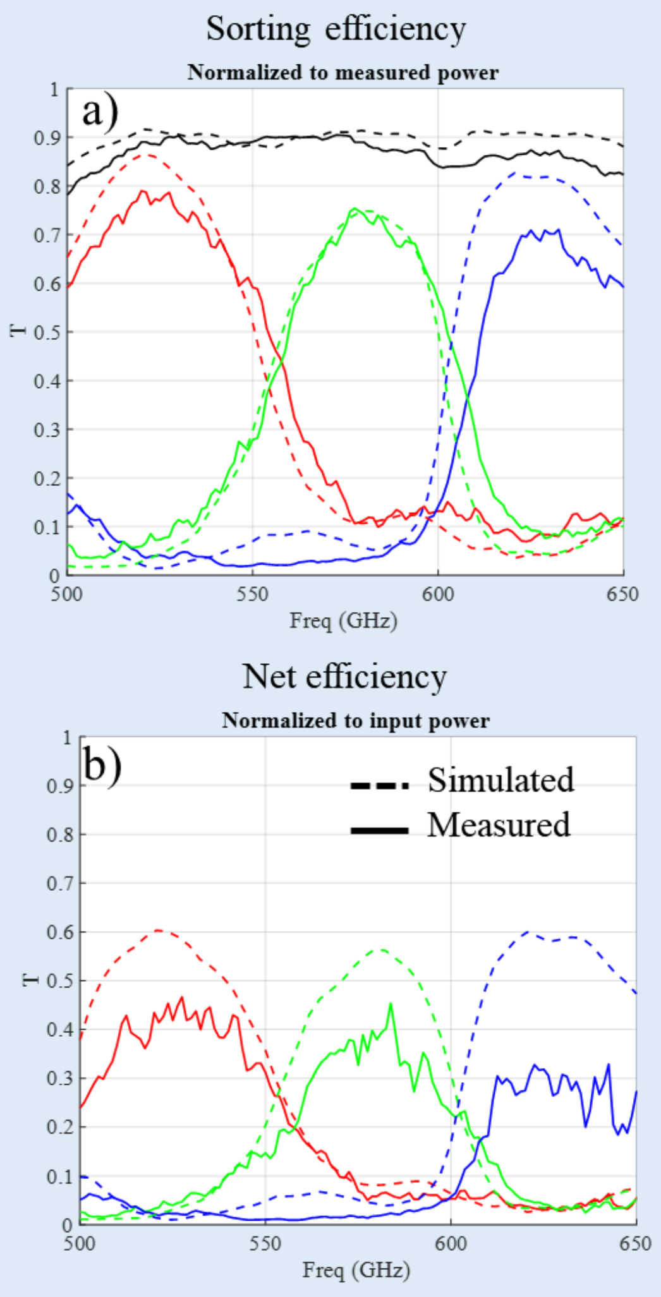

Figure 4. Measurement results of a 4-layer. (a) The sorting efficiency, and (b) the net efficiency.

Significant Benefit to JPL and NASA:

Our results are significant to NASA for two primary reasons. First, this is the first demonstration of volumetric meta-optics at terahertz frequencies and the resulting efficiencies are better than our previous RF polypropylene devices and mid-IR IP-Dip devices. Second, the work done in stabilizing the cavity mirrors and identifying key sources of error in the meta-optics has led to the subsequent design of a compact spectrometer exceed 106-107 spectral resolution which could feasibly out-compete state-of-the-art heterodyning instruments for planetary missions by offering similar spectral resolution at substantially reduced size and power requirements.

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This work was carried at the Jet Propulsion Laboratory, California Institute of Technology, under a contract with the National Aeronautics and Space Administration

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Clearance Number: CL#23-5679
RPC/JPL Task Number: R22120