National Aeronautics and Space Administration

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

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Objective:

The objective is to develop and characterize an extremely compact and low-power terahertz spectrometer. The key to the reduction in volume and power centers around designing a wavelength-scale, passive optical element whose behavior is extremely difficult to realize with combinations of traditional optical elements like lenses and gratings, particularly in small volumes.

This component, referred to as a metaoptics component due its exotic behavior engineered through subwavelength patterning, allows us to revisit one of the simplest types of spectrometers; a tunable Fabry-Perot (FP) resonator. FP resonators can be compact and tuned accurately with low power, but they output a series of resonances that introduce ambiguity in measurement. Filtering out all but one resonance is an option, but this severely limits bandwidth. Instead, the resonances can be spatially separated to their own direct detector. This is possible with elements like gratings, but the continuous dispersion of a grating inevitably means that systems must be large to adequately separate the various frequencies.

Inverse-designed metaoptics have the ability to impose arbitrary transformations to signal with customizable frequency-dependent behavior, so the objective of its design is to design an element that efficiently sorts all resonances to their unique direct detector, independent of the position of the tunable cavity. Furthermore, the design must fabricable with currently available techniques.

Approach and Results:

Our approach is a resonator-based spectrometer with a compact, efficient metaoptics elements placed after the resonator to sort all the output resonance to their own unique direct detector. An illustration of the system is shown in Fig. 1.

The resonator consists of two curved mirrors. The mirrors are distributed Bragg reflectors (DBRs) made of cascaded Silicon and air/vacuum layers, each approximately λ/4 thick. The curvature of the mirrors is obtained by depositing a thin SiO2 layer on the mirrors, which deforms the mirror due to the stress of the film (Fig. 2a). This ensures a compact Gaussian mode exists in the cavity that does not diverge as the beam propagates back and forth. The measured curvature of the mirrors matches a Gaussian profile (Fig. 2c), and the resulting cavity has been demonstrated to have a Q of 104 (Fig. 2d-e). We intend to add more layers to the DBR mirrors to increase their reflectivity, and thus the cavity Q up to 105.

The metaoptics device is design with an inverse-design algorithm that seeks to maximize a figure-of-merit function (FoM) by altering the permittivity of a stack of Silicon wafers. This optimization is done by efficiently computing the gradient of the FoM with respect to the device permittivity using a technique referred to as the *adjoint method*. Once the gradient is computed, it can be passed through a series of filters to push the design towards a solution that can be fabricated. This processed gradient is then used to perturb the permittivity in a small step, and the process is iterated. Despite the efficient algorithm, the task of optimizing a 3D permittivity profile remains computationally challenging and thus limits volumetric metaoptics to device sizes of several wavelengths per side. A lens is placed after the resonator to focus the output beam to the metaoptics.

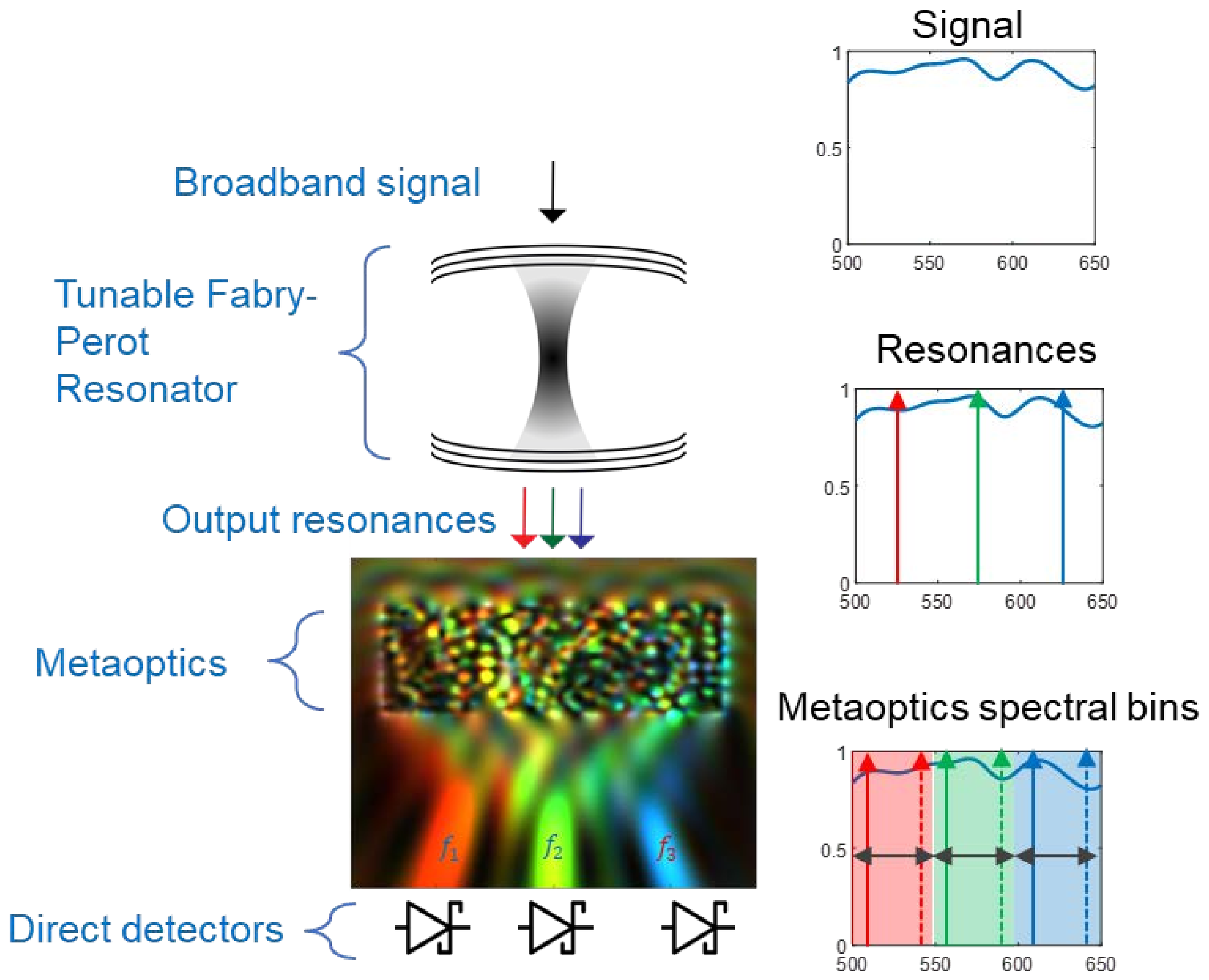

Figure 1. Basic illustration of the system. A resonator made of two curved mirrors outputs a series of spectral lines, which are coupled to a direct detector array by a metaoptics device. The output resonances can be tuned by changing the cavity length, and the metaoptics are designed to sort all frequencies efficiently independent of the cavity length.

The chosen FoM resembles a free-space, spectral demultiplexer. The device outputs three frequency bins, whose spectral width approximately matches the free spectral range (FSR) of the cavity. Every frequency in a given bin is routed to the same position, which behaves differently from a grating which would **continuously** separate frequencies to different angles. The simulated results of this device are shown in Fig. 3 for a 4-layer device and an 8-layer device, showing increasing performance with increased layers. The efficiency of the 8-layer device, defined as the fraction of power transmission through a desired square aperture, exceeds 80%

The device is fabricated by defining the pattern of each layer on the device layer of a Silicon-on-insulator (SOI) wafer, etching the pattern with deep-reactive ion-etching (DRIE), removing the handle layer beneath the device, then stacking all layers with their device layers in close contact. Currently, several directions for obtaining precise layer-to-layer alignment are being explored. We have already achieved adequate alignment by defining the released handle layer region to precisely fit the die beneath it, to within 10 um accuracy. A technique that uses compression pins for ~1 um alignment is regularly used at JPL but has not yet been demonstrated for thin layers.

Background:

Terahertz spectroscopy is a critical remote sensing tool for understanding phenomena at the molecular level, with broad applications in Earth, planetary, and astrophysics sciences. In particular, planetary instrumentation stands to benefit immensely from reducing the volume and power requirements of spectrometer to permit cost-effective, close-up observations of asteroids, comets, and planets.

Two techniques are typically used for spectrometry. The first technique uses a coherent-based detection scheme (i.e. heterodyning), which involves mixing the measured signal with a local oscillator. Current local oscillator limit the bandwidth of the system, and are difficult to scale to higher frequencies. The second technique uses conventional optics like gratings to disperse frequencies across an array of sensors. These systems can be low-power, featuring high resolution and hyperspectral imaging, but tend to be large and require a large number of detectors. The presented work is similar to the second approach but utilizes inverse-designed metaoptics to substantially reduce the size of the system.

Significant Benefit to JPL and NASA:

Inverse-designed volumetric metaoptics can drastically reduce the size and power requirements of spectrometers. At terahertz frequencies, where we are able to pattern Silicon and stack wafers with deeply subwavelength accuracy, the behavior of metaoptics can be both efficient and multi-functional. The usefulness of this is not unique to spectrometers. We believe radar system and beam-scanning systems stand to benefit substantially from this technology in the future, and that improvements over basic components like filters can be achieved with higher transmissions and steeper cutoffs than state-of-the-art. These technology enhancements will allow NASA missions to utilize much smaller, potentially CubeSat-sized terahertz equipment.

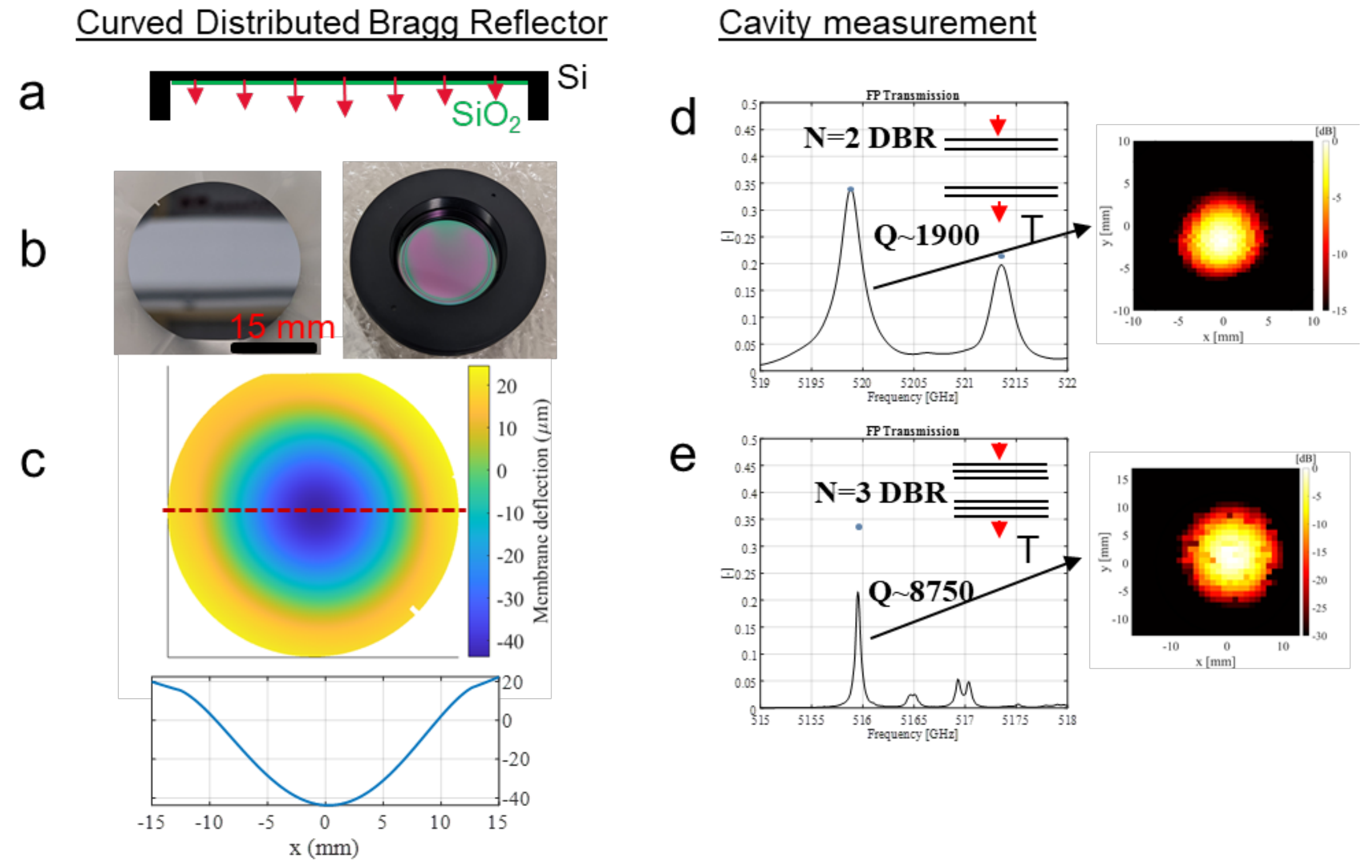

Figure 2. Fabrication and measurement results of the FP cavity. a) The curvature of the DBR mirror elements is obtained by depositing SiO_2. b) Photos of the front and back (mounted in optical adapter) of a DBR element. c) The curvature of the mirror element, measured in the Zygo Zemapper. d) A cavity is formed with two DBRs mirrors, each made of N=2 Si-air layers. The Q-factor of the fundamental Gaussian is ~1900. e) The number of DBR layers increased to 3, and the Q increased to ~8750.

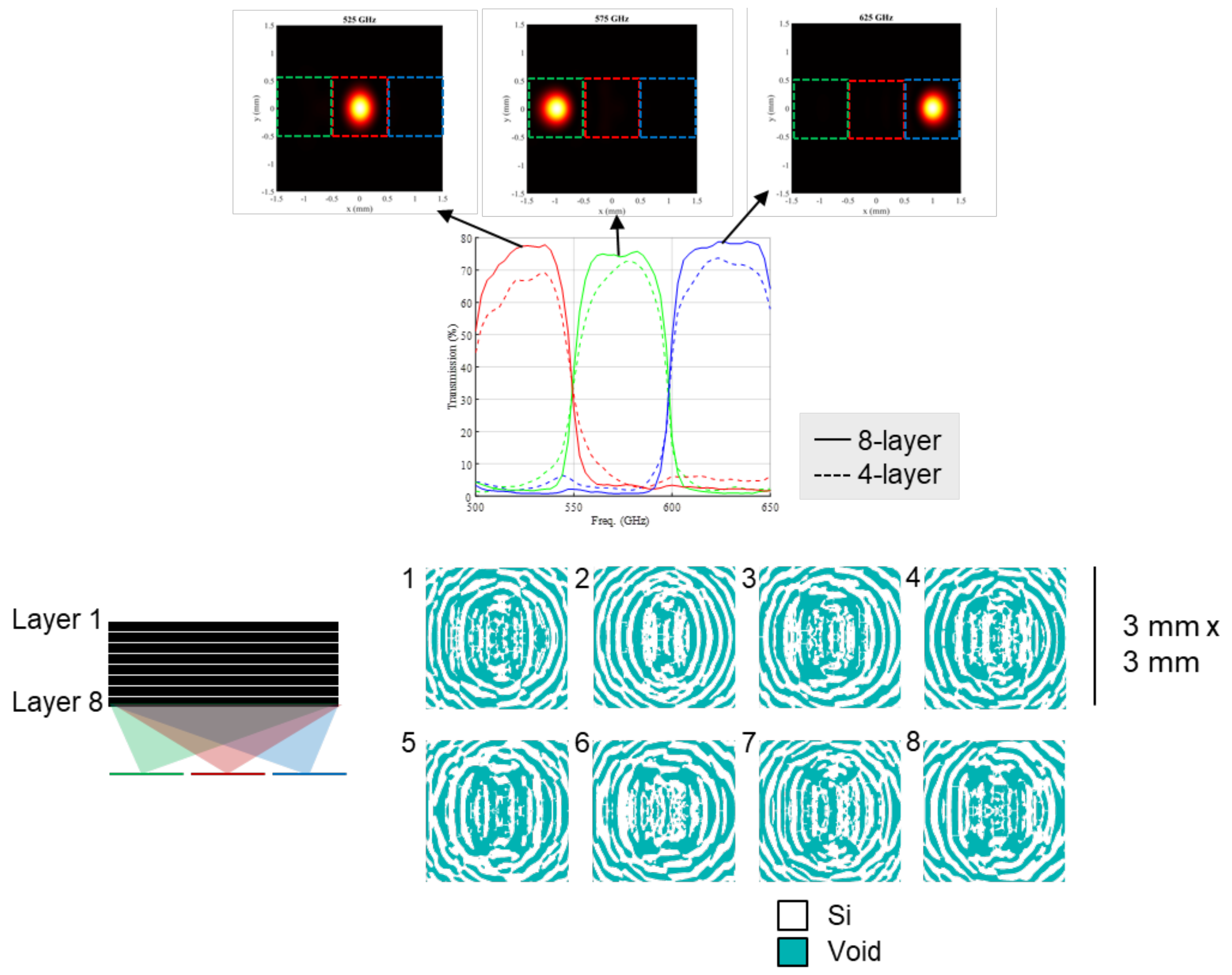

Figure 3. The simulated metaoptics device. The red, green, and blue curves correspond to the power transmission through the pictured red, green, and blue apertures. The dashed lines are for a 4-layer device, while the solid are for an 8-layer device showing an efficiency improvement due to the increased 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.

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