Inverse-Designed Volumetric and Multi-Layer Silicon Metaoptics

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***Abstract*—Metaoptics made of near- or sub-wavelength patterned dielectric elements are a low loss platform for realizing advanced optical components which can control electromagnetic radiation based on its fundamental spatial, spectral, and polarization properties. Fundamentally this behavior arises from controlling the interference of multiple modes within the structure. 3D-patterned and multi-layer devices hold many modes, but controlling them requires complex geometries that presently must be identified with advanced algorithms. This talk will highlight the design, fabrication, and measurement results of metaoptics components being designed for space instrumentation, including interferometry systems and filters.**

***Keywords*— Metaoptics, inverse-design, volumetric**

I. Introduction

OPTICAL design has long relied on modular, linear arrangements of traditional optical elements like lenses, gratings, polarizers, waveplates, etc. A collection of these components can control all of the fundamental properties of light (frequency, k-vector, and polarization), but the physical size of the system grows immensely with the complexity of the system function. The reliance on modular system can be mitigated by encoding customizable and multi-functional behavior into individual components, effectively combining multiple basic components into one advanced component.

Broadly speaking, *metaoptics* are optical components with near- or sub-wavelength patterned features whose geometrical parameters substantially affect the optical modes within their volume [1]. Among their most appealing attributes is the multifunctional capabilities, such as the ability to prescribe independent high-transmission phase masks to orthogonal polarizations [2]. Most of metaoptics development has focused on thin and flat elements like transmit/reflect arrays and metasurfaces, which can only support a few modes within the volume of their individual elements. The effect is a fundamental limitation on the degrees of freedom in the design and the achievable complexity [3]. While thinness is often an appealing aspect of these devices, it is also the fundamental limitation on their efficiency and functionality.

Ideally, meta-optical component should be thick enough to contain as many modes as is necessary to achieve its prescribed task. However, the existence of enough modes is not the only requirement, since additionally these modes must be *controlled* via the geometry. To do this, the device typically must be patterned in all three dimensions which poses two main difficulties: 1) identifying the optimal 3D shape, and 2) fabricating the resulting 3D shape at the microscale.

II. Results and Applications

To identify a 3D shape that is both optically efficient and fabricable we use a adjoint-based inverse-design that incorporates fabrication constraints. The adjoint method offers an extremely efficient method for calculating the gradient of a figure-of-merit with respect to the permittivity of a design region, enabling gradient-based optimization of the device.

At terahertz frequencies, high-resistivity Si is an excellent material because of its low absorption loss and its ability to be fabricated with high precision. To fabricate 3D devices, we pattern the individual layers across a single wafer, separate the dies, and then stack them. Both layer-to-layer alignment and minimization of the air gap between layers is critical for realizing efficient devices, and this talk will describe the methods used to achieve this.

Some applications of volumetric Si metaoptics are extremely compact interferometer systems for spectroscopy, and components like orthomode transducers and filter, which can be used to substantially reduce size, weight, and power of Earth, planetary, and astrophysics instrumentation. In all cases, the volumetric nature of these metaoptics allows for much broader band performance than thin metasurfaces typically do.

References

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