Synthesizing High-performance Reconfigurable Meta-devices through Multi-objective Optimization

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***Abstract*—Metasurfaces offer the potential to realize large SWaP (size, weight, and power) reduction over conventional optical elements for their ability to achieve comparable functionalities in ultrathin geometries. Moreover, metasurfaces designed with phase change materials offer the potential to go beyond what is achievable by conventional optics by enabling multiple functionalities in a single reconfigurable meta-device. However, designing a single metasurface geometry that simultaneously achieves multiple desired functionalities while meeting all bandwidth requirements and fabrication constraints is a very challenging problem. Fortunately, this challenge can be overcome by the use of state-of-the-art multi-objective optimization algorithms which are well-suited for the inverse-design of multi-functional meta-devices.**

Keywords—inverse-design, metamaterials, metasurfaces, nanoantennas, optimization, reconfigurable.

I. INTRODUCTION

Metasurfaces are the two-dimensional counterparts to metamaterials in that that they enable designers to engineer the behavior of electromagnetic waves at surfaces and interfaces as opposed to volumetric wave manipulation more commonly associated with bulk metamaterials [1]. Moreover, due to their ability to replicate traditional optical functionality in an ultrathin geometry [2], metasurfaces have the potential to disrupt optical system design by achieving massive SWaP (size, weight, and power) reduction and enabling applications not previously possible with heavy conventional systems [3]. To this end, phase-gradient metasurfaces have garnered tremendous interest for imaging applications due to their ability to exploit the generalized form of Snell's law [4] and bend electromagnetic waves in ways not possible with traditional spherical glass lenses. Such metasurfaces achieve their behavior through an intelligent pattering of nanoantennae (also known as "meta-atoms"), which are designed to achieve a desired complex transmission and/or reflection behavior. For imaging applications, the need for highly transmissive applications has necessitated that the nanoantennae be composed of dielectric materials due to their low loss [5]. However, most dielectric metasurface designs typically achieve only a single functionality which can limit their ability to supplant conventional lenses in the system design process. Meanwhile, phase change materials (PCMs) possess tunable dielectric permittivities which can be exploited to synthesize reconfigurable metasurface devices such as beam-steerers, optical shutters, spectral filters, and adaptive focal length lenses [6]–[9]. While PCMs offer the ability to realize multi-functional meta-devices, they bring with them a significant expansion of the degrees of design freedom available to the designer. Consequently, the inclusion of PCMs in the system can significantly increase the difficulty of the inverse-design process making more traditional optimization approaches intractable for optical designers. Fortunately, there exists a number of optimization techniques for meta-device optimization including recent developments such as topology optimization [10], deep learning [11], and multi-objective optimizers [12]. In fact, multi-objective optimization (MOO) algorithms are the natural choice for the inverse-design of multi-functional meta-devices since all functionalities can be each represented by a single objective and simultaneously optimized [13], [14]. This paper presents a brief introduction to multi-objective optimization and its potential for synthesizing high-performance multi-functional PCM-based metasurfaces.

II. MULTI-FUNCTIONAL META-DEVICE OPTIMZIATION

Unlike traditional single-objective optimizers which only find a single optimal solution, MOO algorithms generate a set of optimal solutions called the Pareto set. When visualized in objective space, these solutions can help designers understand the tradeoffs inherent between competing design objectives (*e.g.*, size versus efficiency or bandwidth). For reconfigurable meta-devices, these objectives can be the desired optical functionalities at various states of the PCM (*e.g.*, amorphous and crystalline). Fig. 1 presents a hypothetical solution space for a reconfigurable PCM-based meta-device. The solid line is the Pareto front which is a continuous surface that contains all solutions in the Pareto set. In this example, there is a clear tradeoff between achievable performance in material states 1 and 2. While the ideal solution in which the device exhibits the maximum theoretical performance in both states is unachievable, the MOO algorithm is able to present the user with a range of solutions and their tradeoffs from which they can select the design that best attains their desired performances. When applied to optical metasurface design, the MOO algorithm can be assigned a unique cost function per available diffraction order allowing the user to simultaneously maximize the performance at each order while also providing tradeoffs for multi-diffraction order performance. For example, consider the metasurface supercell shown in Fig. 2. Due to the supercell

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periodicity the *m* = -2, -1, 0, +1, and +2 diffraction orders are available to couple into. When paired with PCM materials, such a supercell could steer into one order (*e.g.*, +1) in the amorphous state and into another order (*e.g.*, +2) in the crystalline state. In fact, switching between steering into single or multiple orders is possible if the optimizer is given an appropriate set of user-defined cost functions. Moreover, the supercell can also be optimized to switch between transmission and reflection modes which gives the designer tremendous flexibility in achieving functionalities that can disrupt conventional optical device design.

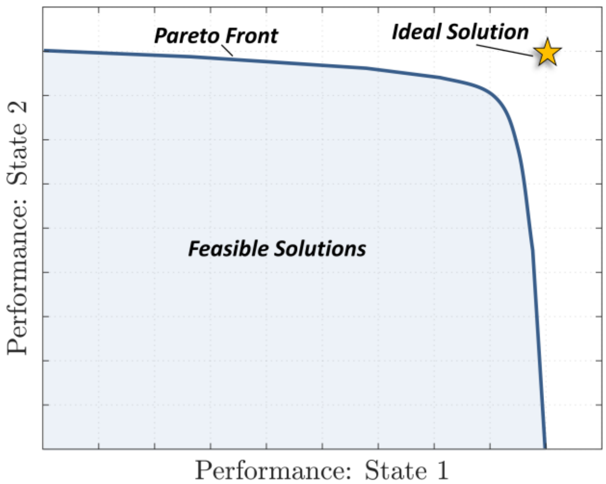

Fig. 1. Visualization of a hypothetical multi-objective optimization problem for a reconfigurable PCM-based meta-device.

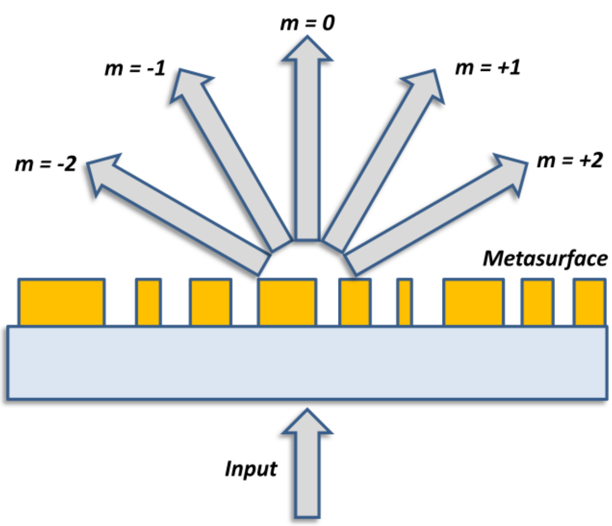

Fig. 2. Metasurface supercell concept with multiple pathways for the incident wave to couple into. Such a supercell is perfectly suited for a MOO algorithm as multiple performances can be simultaneously maximized.

III. Future Work

Note that, while multi-objective optimization is a generic paradigm, there are a number of unique multi-objective algorithms designers can employ in their inverse-design procedure. Moreover, different algorithms can offer designers with unique functionalities or geometrical creation capabilities. For example, the Multi-Objective Optimization with TOLerance (MOTOL) algorithm can yield designs with robustness as an explicit objective [15] while the Multi-Objective Lazy Ant Colony (MOLACO) algorithm [16] can synthesize contiguous three-dimensional structures to realize true bi-anisotropic metamaterial unit cells.

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