Optimization and Inverse-design Techniques for Metalens Synthesis

Sawyer D. Campbell, Eric B. Whiting, Ronald P. Jenkins, Pingjuan L. Werner, and Douglas H. Werner
Department of Electrical Engineering
The Pennsylvania State University
University Park, PA 16802, USA
sdc22@psu.edu

***Abstract*—Phase-gradient metasurfaces enable designers to tailor the behavior of electromagnetic waves at surfaces by exploiting the generalized form of Snell's law. This ability has led to the investigation of metalenses which have the potential to significantly reduce the size, weight, and power (SWaP) of conventional optical systems. While traditional lenses are made from individual glasses, metalenses are comprised of patterned meta-atom unit cells which are arranged in such a way so as to give the metalens its desired behavior. Therefore, any metalens's performance is ultimately determined by that of its underlying unit cell components. However, designing meta-atoms that simultaneously achieve high performance over wide frequency bandwidths and fields-of-view is an extremely challenging problem that is best addressed with powerful optimization and inverse-design techniques.**

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

I. INTRODUCTION

Metasurfaces have garnered lots of attention in recent years for their potential ability to disrupt conventional optical systems. By exploiting the more general form of Snell's law [1] metasurfaces can achieve relatively arbitrary optical performance by manipulating a spatially-varying reflection and/or transmission phase profile along a surface. When used in imaging systems, metasurfaces are known as "metalenses" and have been investigated at a number of frequency bands including the visible [2], mid IR [3], and terahertz [4] regimes. One of the most promising aspects of metalenses is their ability to achieve optical power comparable to traditional spherical glass lenses albeit in a thin planar geometry [5]. Moreover, due to their unique dispersion behaviors, metalenses can be paired with conventional optical elements to provide color correction while significantly reducing the number of lenses required compared to conventional optical systems [6]. Regardless of their targeted frequency regime or application of interest, all metalenses can benefit from optimization. To this end, there exist a number of optimization techniques for meta-devices [7], such as metalenses, that include local, global, and multi-objective [8], [9] algorithms and new approaches such as surrogate-modeling, topology-optimization [10], and deep learning [7]. All of these techniques have seen success in the design of meta-atom unit cells and supercells for a variety of beam-steering and focusing applications. These meta-atoms are the building blocks used to synthesize large diameter metalenses and finding high performance meta-atoms is paramount to realizing metalenses with imaging performance comparable to conventional optical elements. With respect to performance, metalenses are typically judged by their focusing efficiency over a specified frequency bandwidth and field-of-view. This efficiency is ultimately determined by the available phase options and transmission magnitudes of the meta-atom building blocks. For this reason, dielectric-based meta-atoms have seen tremendous interest in the optical regime due to their low intrinsic losses [11]. This paper presents a brief introduction to the optimization of meta-atom unit cells for high-performance metalens synthesis.

II. METALENS OPTIMIZATION

Nearly all meta-atom and metalens optimization strategies follow the same basic design flow which is summarized is Fig. 1. With the optimizer selected, an initial set of design parameters are generated which are then used to construct the unit cell geometry. At this stage, any and all fabrication constraints are applied to the geometry to ensure its manufacturability. Note, this may require constraints being applied both before and after the unit cell is generated, depending on the complexity of the geometry generation techniques being employed. Next, a suitable full-wave forward solver (*e.g.*, Finite-Element Method, Finite-Difference Time Domain, or Discontinuous Galerkin Time Domain) is used to simulate the meta-atom(s) under plane-wave illumination across a pre-determined range of frequencies and incidence angles. When the simulation is complete, reflection and/or transmission (*i.e.*, S-parameter) data is extracted and used to evaluate one or more user-defined cost functions which are constructed in order to find meta-atom geometries that achieve the desired performance(s). After this stage, the optimizer generally checks if it has converged to the optimal solution(s); if not, it uses feedback gained from the most recent evaluations to choose another set of design parameters and the process repeats until convergence or a stopping criterion has been met. When the optimization is complete, the user is presented with a finalized design or set of designs depending on whether a single- [12], [13] or multi-objective [14] optimization algorithm, respectively, is employed.

The optimized meta-atoms can then be used to pattern a metalens to achieve a desired optical functionality. Fig. 2 depicts an optimized metalens that has perfect focusing at a desired focal plane. The metalens is comprised of square unit cells that

---

The work is supported in part by DARPA contract no. HR00111720032.

Submitted On: August 31, 2020
Accepted On: September 5, 2020

https://doi.org/10.47037/2020.ACES.J.351136

1054-4887 © ACES

provide the requisite transmission phase at their individual locations. In addition to optimizing the meta-atoms themselves, the phase-profile of the metalens itself can be optimized to best exploit the properties of the available meta-atoms. For example, optical systems comprised of conventional glass elements and metasurfaces will have complex combinations of mono- and polychromatic aberrations that will require both the refractive lens geometrical parameters and the metalens phase profile to be optimized in concert to achieve the best possible optical performance of the combined system. Moreover, the requisite metalens phase profile can be used to drive the meta-atom optimization procedure and *vice versa* where a library of meta-atoms is used to constrain the metalens phase profile range. Interestingly, the same optimization algorithms and techniques can be used to optimize both the nano-scale meta-atoms and the centime-scale metalenses.

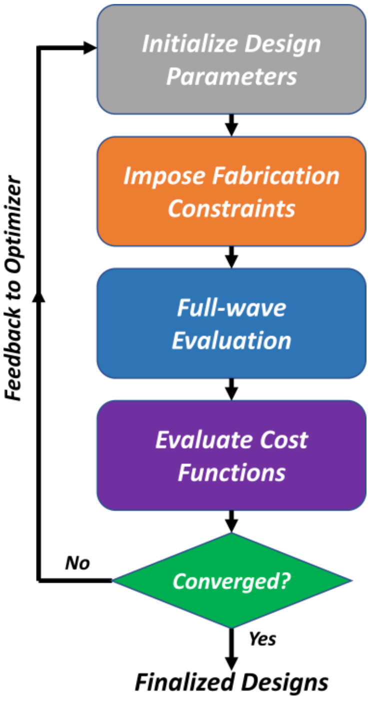

Fig. 1. Multi-objective optimization meta-atom inverse-design framework.

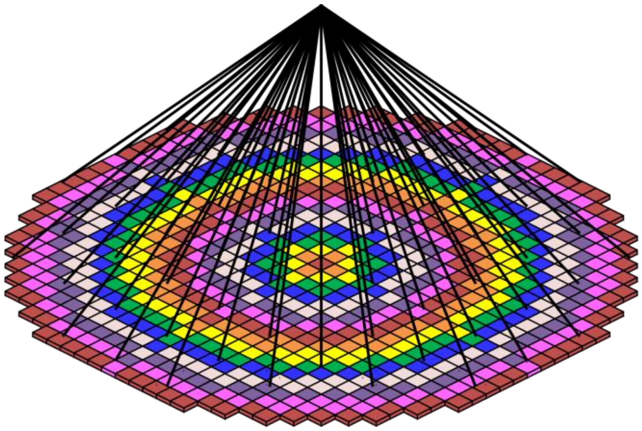

Fig. 2. Synthesized metalens comprised of optimized meta-atoms.

III. FUTURE WORK

High-performance meta-atoms should be robust to fabrication uncertainties, mechanical stresses, and thermal changes which may be experienced in real world operation. Thus, an inverse-design framework that enables the optimization of meta-atoms based on performance robustness is highly desirable. Future studies will investigate the potential for realizing robust meta-atoms and metalenses. Additionally, the ability to simultaneously simulate and optimize the meta-atoms and metalenses across all size scales is an active area of research.

REFERENCES

[1] N. Yu, P. Genevet, M. A. Kats, F. Aieta, J.-P. Tetienne, F. Capasso, and Z. Gaburro, “Light propagation with phase discontinuities: Generalized laws of reflection and refraction,” Science, New Series, vol. 334, no. 6054, pp. 333-337, 2011.

[2] M. Khorasaninejad, W. T. Chen, R. C. Devlin, J. Oh, A. Y. Zhu, and F. Capasso, “Metalenses at visible wavelengths: Diffraction-limited focusing and subwavelength resolution imaging,” Science, vol. 352, no. 6290, pp. 1190-1194, June 2016.

[3] H. Zuo, D.-Y. Choi, X. Gai, P. Ma, L. Xu, D. N. Neshev, B. Zhang, and B. Luther-Davies, “High-efficiency all-dielectric metalenses for mid-infrared imaging,” Advanced Optical Materials, vol. 5, no. 23, p. 1700585, Dec. 2017.

[4] D. Jia, Y. Tian, W. Ma, X. Gong, J. Yu, G. Zhao, and X. Yu, “Transmissive terahertz metalens with full phase control based on a dielectric metasurface,” Optics Letters, vol. 42, no. 21, p. 4494, Nov. 2017.

[5] N. Yu and F. Capasso, “Flat optics with designer metasurfaces,” Nat. Mater., vol. 13, no. 2, pp. 139-150, Feb. 2014.

[6] J. Nagar, S. D. Campbell, and D. H. Werner, “Apochromatic singlets enabled by metasurface-augmented GRIN lenses,” Optica, vol. 5, no. 2, pp. 99-102, 2018.

[7] S. D. Campbell, D. Sell, R. P. Jenkins, E. B. Whiting, J. A. Fan, and D. H. Werner, “Review of numerical optimization techniques for meta-device design [Invited],” Opt. Mater. Express, vol. 9, no. 4, pp. 1842-1863, Apr. 2019.

[8] S. D. Campbell, D. Z. Zhu, E. B. Whiting, J. Nagar, D. H. Werner, and P. L. Werner, “Advanced multi-objective and surrogate-assisted optimization of topologically diverse metasurface architectures,” in Metamaterials, Metadevices, and Metasystems 2018, vol. 10719, p. 107190U.

[9] S. D. Campbell, E. B. Whiting, D. H. Werner, and P. L. Werner, “High-Performance Metasurfaces Synthesized via Multi-Objective Optimization,” in 2019 International Applied Computational Electromagnetics Society Symposium (ACES), pp. 1-2.

[10] D. Sell, J. Yang, S. Doshay, and J. A. Fan, “Periodic dielectric metasurfaces with high-efficiency, multiwavelength functionalities,” Adv. Opt. Mater., vol. 5, no. 23, p. 1700645, Dec. 2017.

[11] A. Arbabi, Y. Horie, M. Bagheri, and A. Faraon, “Dielectric metasurfaces for complete control of phase and polarization with subwavelength spatial resolution and high transmission,” Nat. Nanotechnol., vol. 10, no. 11, pp. 937-943, Nov. 2015.

[12] N. Hansen, S. D. Müller, and P. Koumoutsakos, “Reducing the time complexity of the derandomized evolution strategy with covariance matrix adaptation (CMA-ES),” Evolutionary Computation, vol. 11, no. 1, pp. 1-18, Mar. 2003.

[13] M. D. Gregory, Z. Bayraktar, and D. H. Werner, “Fast Optimization of Electromagnetic Design Problems Using the Covariance Matrix Adaptation Evolutionary Strategy,” IEEE Transactions on Antennas and Propagation, vol. 59, no. 4, pp. 1275-1285, Apr. 2011.

[14] D. Hadka and P. Reed, “Borg: An auto-adaptive many-objective evolutionary computing Framework,” Evol. Comput., vol. 21, no. 2, pp. 231-259, May 2013.