MetaOptic Designer: Automated Design of Metalenses

Inverse Design Tool for Optimal Performance

Author

Chenglin Xu
RSoft Product Manager,
Synopsys

Introduction

Metalenses have the potential to revolutionize optical products by replacing bulky curved lenses with thin, flat surfaces. Metalenses are a key enabling technology for the next generation of compact imaging, sensing, and display applications [1].

Synopsys is supporting this new world of innovation with MetaOptic Designer, an unprecedented inverse design tool that takes user-specified criteria and generates metalenses/metasurfaces for optimal system performance.

Why Metalens Design Is Uniquely Challenging

A metalens usually consists of millions of subwavelength unit-cells called meta-atoms, which modulate light locally and coherently over the entire metasurface. The shape and/or size of each meta-atom is determined locally based on overall performance of the metalens. Designing such a metalens with millions of variables is a uniquely challenging task. As explained in the work of Prof. Federico Capasso's group [2], metalens design has traditionally been done manually and requires extensive design experience and a deep understanding of fundamental physics. The manual metalens design flow is illustrated in Figure 1[3].
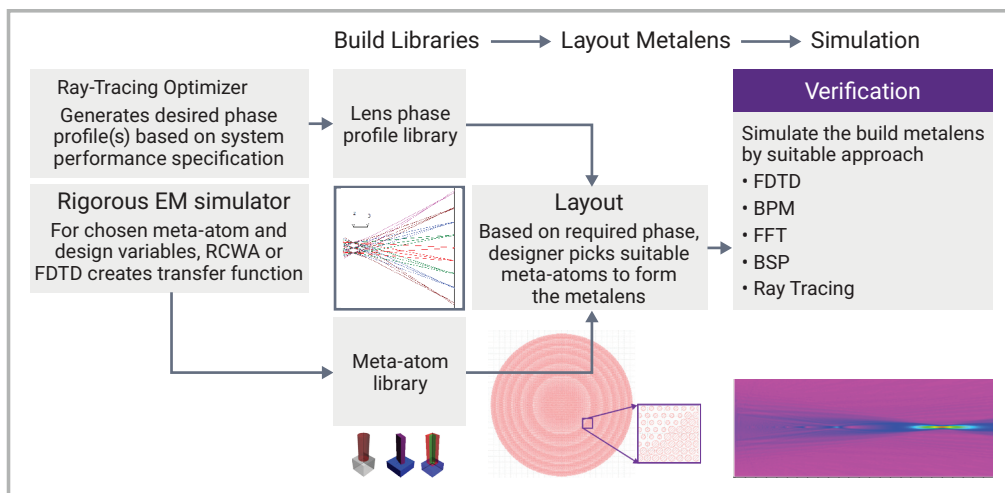

Figure 1: Metalens manual design flow

The manual design approach relies on a pre-defined phase profile, which is valid for a fixed incident condition only because the transfer function of the meta-atoms varies at different wavelength, incident angle, and polarization. Therefore, a phase profile optimized at a particular incident condition is not valid at others. As a result, it is very difficult to design a metalens with multiple functions, such as an achromatic lens for a wide spectral range or a large field of view (FOV) lens for wide incident angles.

MetaOptic Designer: Solving Metalens Design Challenges

To address the limitations of manual metalens design approaches, significant efforts have been made worldwide to develop automation flows with inverse design capabilities. Research groups have described their inverse design algorithms for applications on cascaded metasurfaces [4] and large metalenses [5]. Algorithms developed in academia are often used internally and by the developers for their specific applications. Therefore, an industrial, user-friendly design tool to automate metalens design is highly desirable. Such a tool would enable engineers with all levels of expertise to design metalens systems quickly and easily.

To meet this need, Synopsys has developed MetaOptic Designer. MetaOptic Designer is the first fully automated commercial tool for metaoptics that provides inverse design capabilities [6]. The optimization algorithm employs the well-known adjoint method, which can easily handle millions of design variables.

MetaOptic Designer's forward propagation is done with an efficient Fourier transform method -- also known as the angular spectrum method -- which is exact in homogenous media. The transfer function of each meta-atom is characterized by a parametric bidirectional scattering distribution function (BSDF) database built with the finite-difference time-domain (FDTD) method or rigorous coupled wave analysis (RCWA) using Synopsys products FullWAVE™ FDTD [7] or DiffractMOD™ RCWA [8]. RCWA can be ~100x faster than FDTD for most meta-atoms with similar accuracy.

As illustrated in Figure 2, MetaOptic Designer optimizes the metalens system to achieve the best performance based on the desired targets, with only a few inputs from the designer.

Figure 2: MetaOptic Designer workflow

MetaOptic Designer requires the following inputs:

- Pre-built BSDF database of the meta-atoms to be used
- Incident field with any profile, wavelength, polarization, and incident angle
- Basic optical system information, such as number of metasurfaces, size of each surface, separation between surfaces, image plane position, as well as refractive lenses included
- The desired targets: either focusing spots or desired display images

MetaOptic Designer outputs include performance metrics, such as focusing efficiency and the optimized metalens designs, which are provided as both GDS files for fabrication and RSoft™ CAD files for further simulations.

MetaOptic Designer can also include refractive lenses within the metalens system. Refractive lenses can be specified through aspheric coefficients or imported from a file generated by Synopsys CODE V®, a market-leading imaging design tool.

MetaOptic Designer can also be used to evaluate the performance of an existing design at operating conditions other than what it was optimized for. An existing design can be used as an initial condition for further optimization.

As shown in the following examples, MetaOptic Designer can be used for many applications, such as achromatic and large FOV imaging, polarization conversion and splitting, and aberration correction.

Design Example: Achromatic Metalens

Designing achromatic metalenses for imaging systems is a difficult task that many researchers have been focusing on. A few designs have been reported that rely on manipulating both the phase and dispersion profiles, but these require extensive design knowledge [9]. MetaOptic Designer simplifies the design task and designers only need to specify the inputs and desired targets. MetaOptic Designer returns an optimized solution within the specified tolerance. As shown in Figure 3(a) for an achromatic lens, RGB tri-color inputs all focus on the same spot after the metasurface. The inputs and desired targets are scripted in Figure 3(b). Using the pre-defined (parametrized) TiO_2 meta-atom shown in Figure 3(c), MetaOptic Designer produces the optimized layout shown in Figure 3(d) within a few seconds on a 6-core laptop.
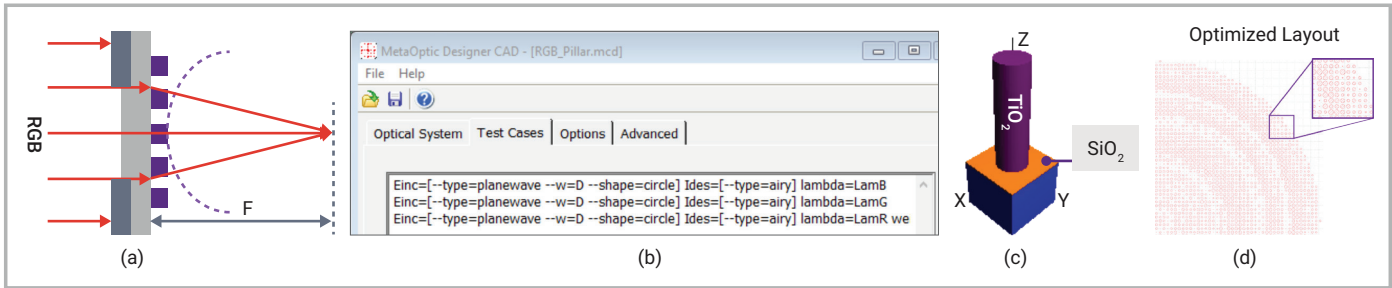

Figure 3: (a) Schematic diagram of an achromatic lens; (b) specified design targets; (c) schematic of the meta-atom used; (d) optimized metalens layout

The optimized metalens simulation results along the optical axis are shown in Figure 4(a). RGB inputs all focus approximately on the same focal plane. The absolute focusing efficiencies, defined as the amount of incident power focused within a circle with 2x the diameter of the Airy disk, are 35%, 28%, and 32% for RGB lights, respectively. Because of the TiO_2 meta-atom used, this metalens suffers strong reflection and only 66%, 58%, and 44% powers are transmitted for RGB lights. This is a small lens, only 20μm in diameter, and focusing should improve for larger lenses.
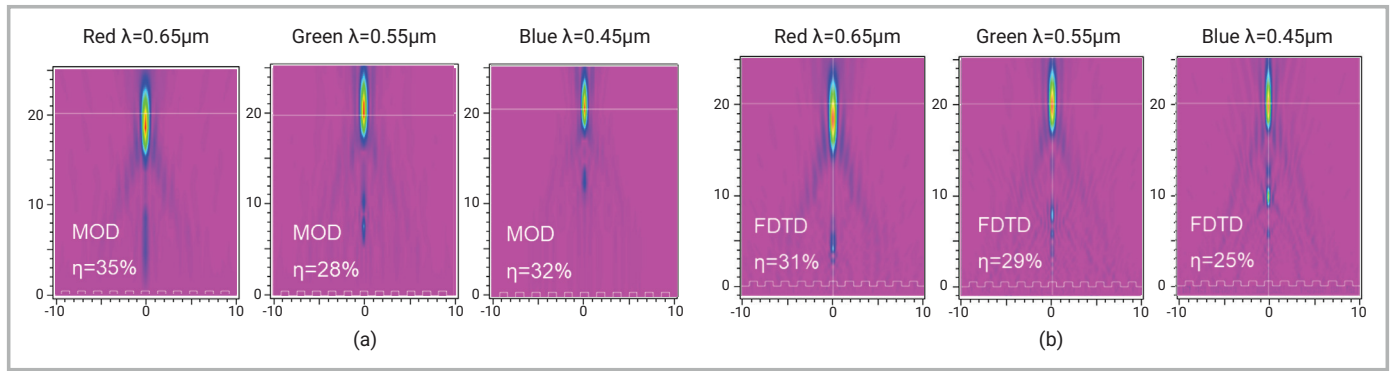

Figure 4: (a) Optimized results from MetaOptic Designer; (b) validation results from FDTD simulation

The purpose of using a small lens was to make validation of the MetaOptic Designer results against FDTD tractable, since FDTD takes about 100G RAM and ~4 hours on a 16-core computer for a single simulation. As shown in Figure 4(a) and (b), MetaOptic Designer gives results that are very close to those of FDTD for both the focusing patterns and focusing efficiencies.

Design Example: Large FOV Metalens

Large FOV is another challenging application for metalens design [10]. Significant design expertise can be required to ensure that the metalens will perform over a large FOV. MetaOptic Designer makes this process much easier. Designers specify the shifted focal positions corresponding to incident angles and the tool produces the optimized layout in about 1 minute on a 6-core laptop.
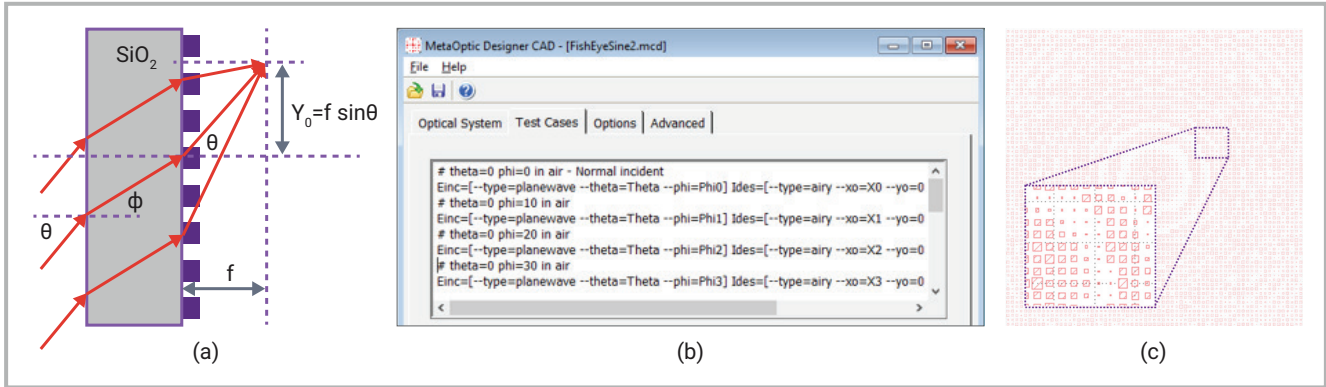

Figure 5: (a) Schematic illumination of a large FOV lens; (b) specified design targets; (c) optimized metalens layout

The optimized results from MetaOptic Designer, shown in Figure 6, clearly indicate that the metalens focuses the incident light at the image plane over a wide angular range. The design includes 9 discrete target angles at $10°$ intervals. Shown here are the results for $0°$, $40°$, and $80°$, only.
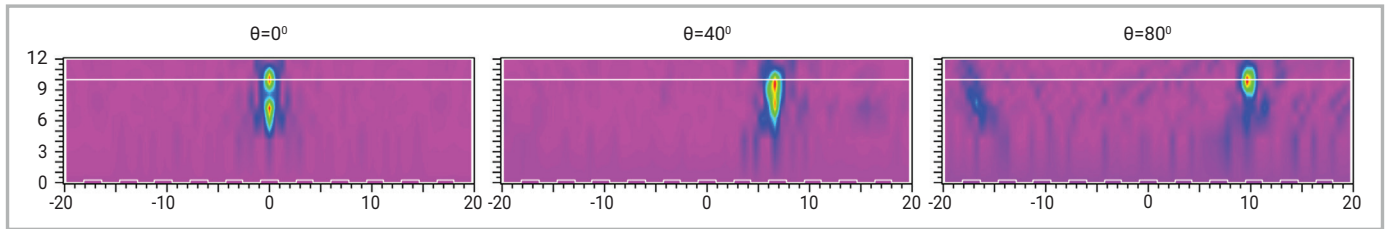

Figure 6: Optimized results from MetaOptic Designer

We used a small metalens of 40μm x 40μm to validate the results with FDTD, which takes ~250G RAM and ~13 hours on a 16-core computer for each simulation. The optimized metalens was simulated for all 9 incident angles and the results, shown in Figure 7, are very close to those of MetaOptic Designer shown in Figure 6.
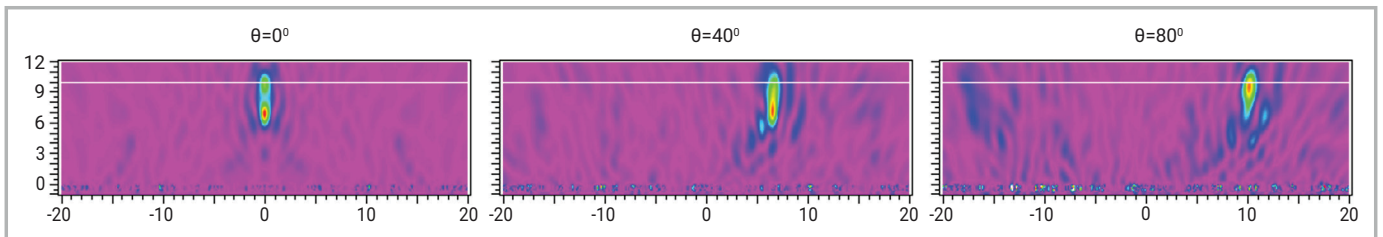

Figure 7: Validation results from FDTD simulation

For imaging lenses, large FOV and achromaticity are important characteristics. It is very difficult to achieve both with a single metalens using the meta-atom shown in Figure 5(a). However, a metalens with two metasurfaces can achieve both large FOV and achromaticity [11].

Designing a multi-layer metalens is technically challenging. MetaOptic Designer makes this process much easier. To demonstrate the tool's capability for multi-metasurface applications, we chose a small metalens with a 40μm diameter, as shown in Figure 8(b). FDTD simulation is feasible in this case with commonly available computer resources. Both metasurfaces consist of Si_3N_4 meta-atoms which are placed on both sides of a 5μm-thick SiO_2 substrate.
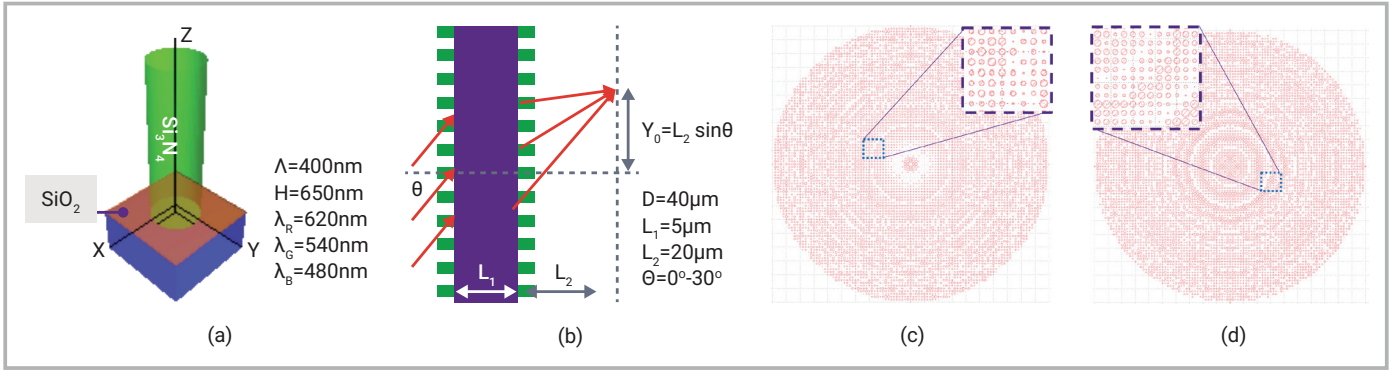

Figure 8: (a) Meta-atom & parameters; (b) lens configuration & parameters; (c) first optimized metasurface; (d) second optimized metasurface

For a total of 12 cases (3 wavelengths X 4 incident angles: 0°, 10°, 20°, 30°), it takes MetaOptic Designer ~12 minutes on a 6-core laptop to achieve the optimum designs and layouts for both metasurfaces shown in Figure 8(c) and (d), respectively. The optimized results at 0° and 30°, zoomed in around the desired focal positions, are shown in Figure 9, and clearly indicate the RGB inputs focus on the desired positions for both normal and tilted cases.
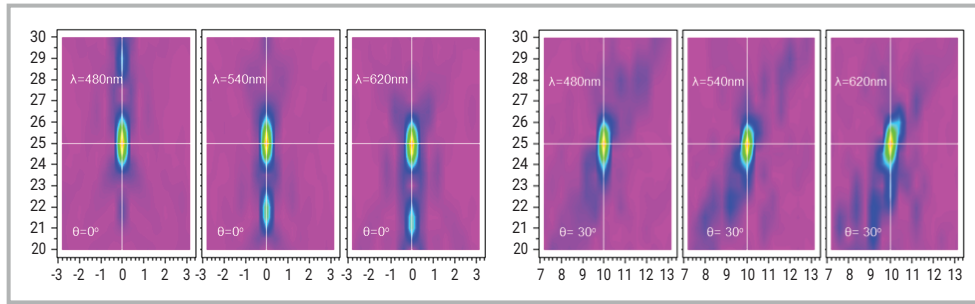

Figure 9: Optimized results for incident light at 0° and 30°

To validate MetaOptic Designer's results for multiple cascaded metasurfaces, we performed FDTD simulations on the optimized metalenses for the above six cases. The simulation results, shown in Figure 10, clearly indicate that the FDTD simulation results are very close to the MetaOptic Designer results. This shows that MetaOptic Designer can produce reliable results for multi-layer metalenses.

The metalens examples presented so far are very small to enable validation by FDTD, which requires a lot of computer resources. For the above multi-layer example, it takes ~500G RAM and ~33 hours on a 16-core computer for one case only, so the above six cases could take about two weeks to complete on a cloud-based network.
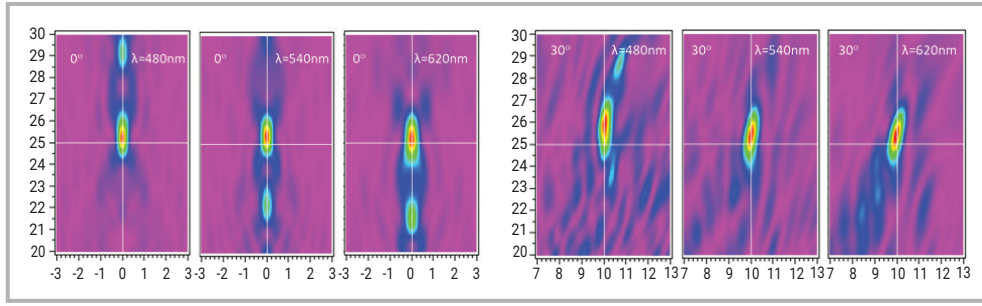
Figure 10: FDTD simulation results of the optimized metalenses for incident light at 0° and 30°

Recent research has shown that a single metasurface with two design variables, nano-fin width and length, can achieve a large FOV and achromatic performance [12]. To demonstrate MetaOptic Designer's ability to handle multiple design variables, a metalens using the meta-atom in reference [12] was created and shown in Figure 11(a). Using the same design specifications as the reference, the optimized layout shown in Figure 11(b) was obtained. The optimized results are shown in Figure 11(c)-(f). For metalenses that are 240µm in diameter, it takes about four hours on a 6-core laptop using 10 design cases for two wavelengths and five incident angles ranging from 0° to 40° at 10° intervals.
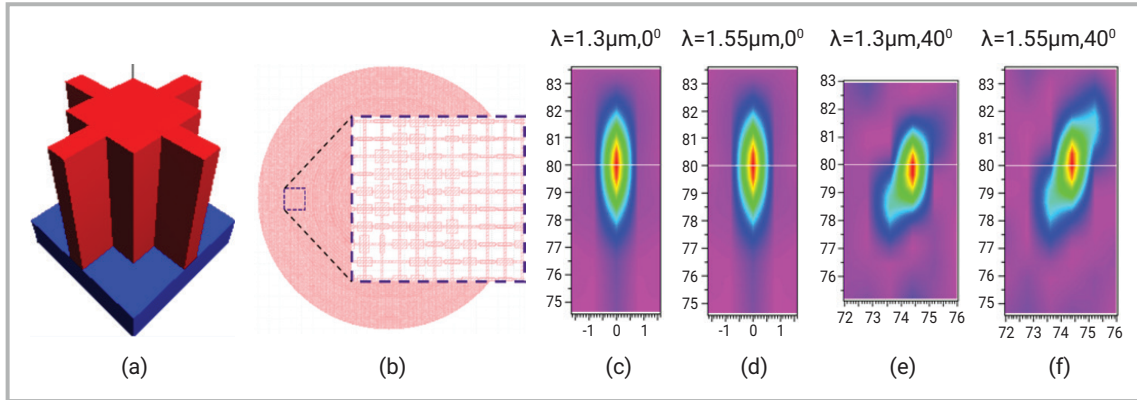

Figure 11: (a) Meta-atom with wings; (b) optimized layout; (c)-(f) zoomed focal spots at different wavelengths and incident angles

Similar to what was observed in the referenced research, the designed metalens focuses light at two different wavelengths on the same spot, even at different incident angles. This shows that MetaOptic Designer can also be used for metalenses based on multiple design variables.

Design Example: Polarization Beam Splitter

As demonstrated in the previous example, multiple design variables provide extra degrees of freedom to achieve the desired performance. By varying both width and length of the nano-fin, the meta-atom also creates birefringence in addition to phase delay. By optimizing width and length of the nano-fin over the entire metasurface, the metalens can split two orthogonal polarizations and focus them at different positions, as shown in Figure 12. The arrows' size and direction indicate field intensity and polarization direction at that position, respectively.
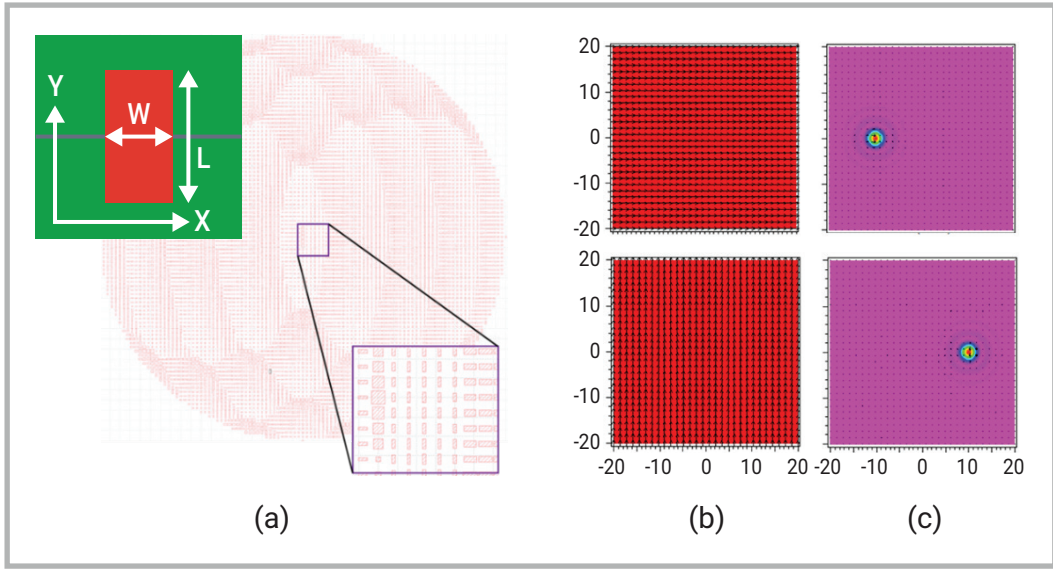
Figure 12: (a) Optimized metalens with nano-fin type meta-atoms; (b) input with different polarizations; (c) different focal positions

Design Example: Holographic Display

A metalens can be used as a hologram to display images. To design a hologram in MetaOptic Designer, designers can change the default airy function to the desired image, as shown in Figure 13.
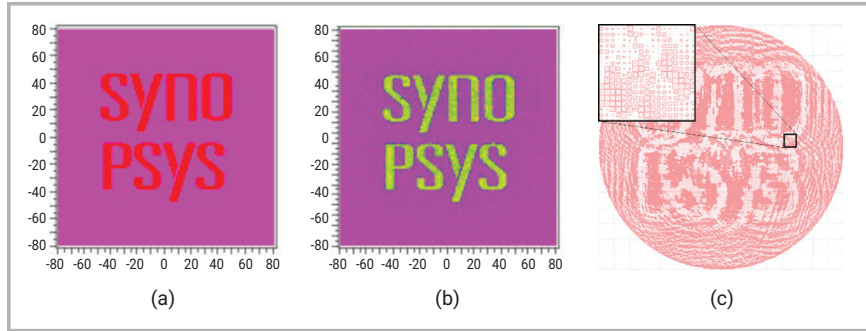

Figure 13: (a) Desired image (b) optimized result; (c) optimized layout

Unlike an imaging lens, which can have radial symmetry, a holographic metalens may not since the target image usually doesn't.

As previously described, the nano-fin type meta-atom is polarization dependent and the phase difference between the two linear polarizations is called the Pancharatnam-Berry phase, or geometric phase. If the phase difference is maintained at 180°, incident light with right-hand circular polarization (RCP) can turn into left-hand circular polarization (LCP), and vice versa. With a proper geometric phase profile over the metasurface, achieved by rotating the fin of each meta-atom, a metalens can display different images for incident light with different circular polarizations [13].

To determine the right geometric phase profile for such an application, extensive design knowledge and effort are typically required. With MetaOptic Designer, this complex design becomes more accessible to non-experts [14]. As shown in Figure 14, by optimizing the rotation angle of each nano-fin over the entire metasurface, left and right circularly polarized light can form different images as desired. The circles with arrows indicate the polarization state and direction. Furthermore, these images can be formed at different locations if needed.
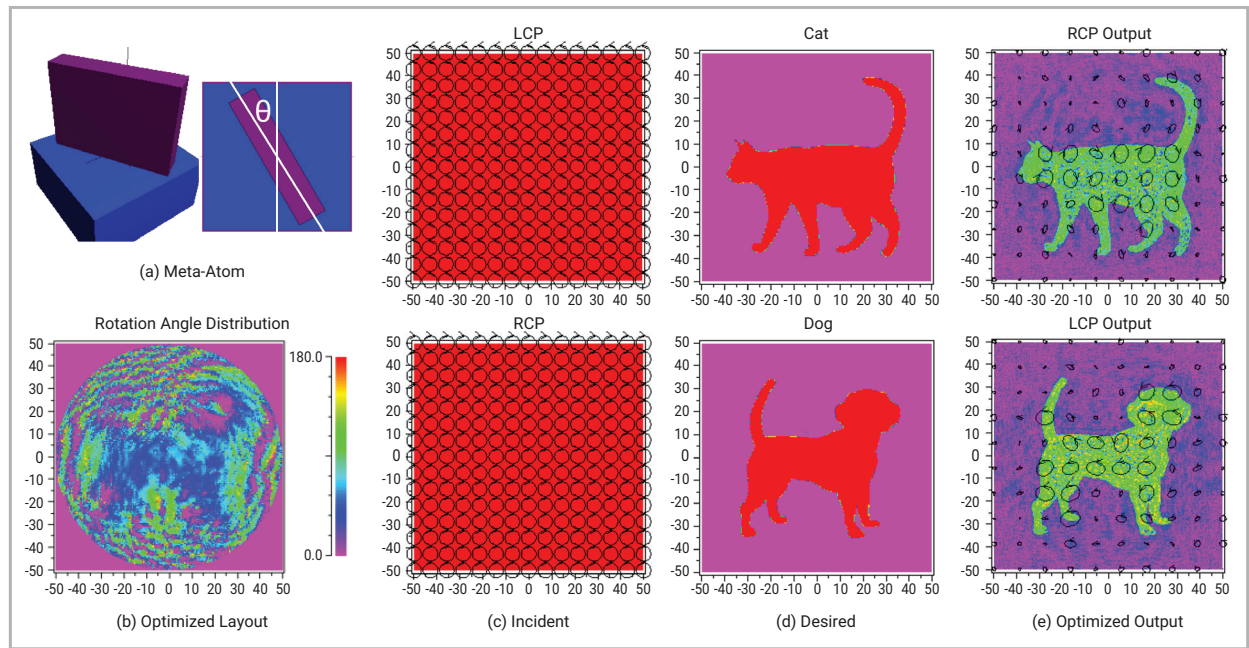
Figure 14: Chiral hologram to display different images for different circularly polarized light

Design Example: Metalens Combined with a Refractive Lens

Currently it is difficult to completely replace refractive lenses with metalenses in optical systems. Combining metalenses with refractive lenses is a useful solution, and this has been done in the cellphone camera lens announced by Samsung [15] and the self-driving car camera lens announced by LG [16]. Therefore, a design tool that can handle hybrid optical systems consisting of both metalenses and refractive lenses is necessary. To develop such a hybrid tool is very challenging, because bulky refractive lenses are designed by ray tracing, which is based on geometric optics, while nanoscale metalenses are modeled by rigorous electromagnetic solvers that are based on electromagnetic optics.

Synopsys provides leading design tools for both ray optics and wave optics, and has developed a unique and proprietary technology to interface between the two optical domains seamlessly to model optical system that combine metalenses and refractive lenses. Refractive lenses designed in CODE V [17] can be directly loaded into MetaOptic Designer, and metalenses can be optimized subsequentially within the hybrid lens system.

The ray tracing result in Figure 15(a) shows that a simple spherical lens cannot focus well over the entire visible spectrum. Physical-optics-based CODE V Beam Synthesis Propagation (BSP)[18] also indicates the defusing phenomena as shown in Figure 15(b). Loading the refractive lens into MetaOptic Designer and evaluating it confirms the aberration, as shown in Figure 15(c). A metasurface, called metacorrector, is added to the system and optimized in MetaOptic Designer. The optimized results show the light is now focused at the desired location, as shown in Figure 15(d).
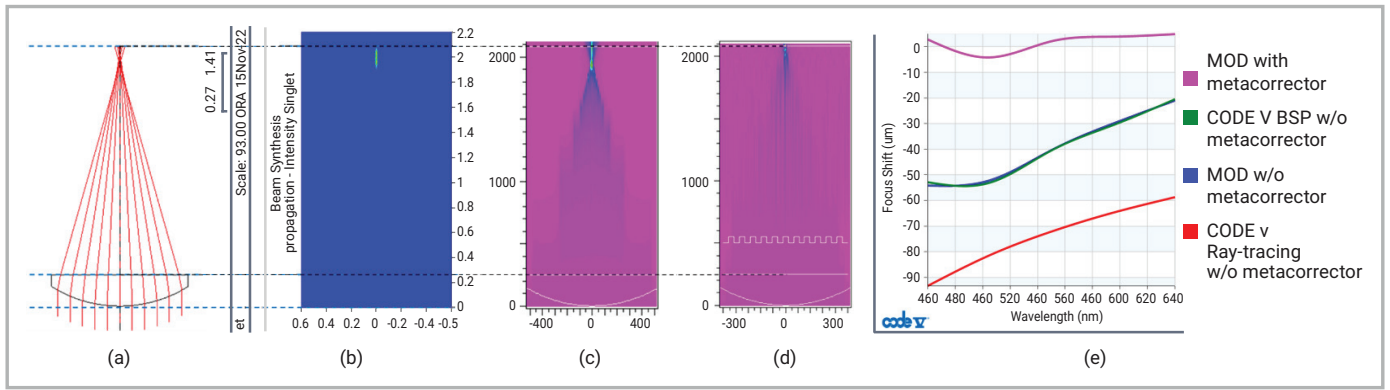
Figure 15: (a) Refractive lens designed in CODE V with ray tracing; (b) CODE V BSP simulation result of the refractive lens; (c) MetaOptic Designer simulation result of the refractive lens; (d) MetaOptic Designer simulation result of the combination of refractive lens and metacorrector; (e) comparison of the simulation results with and without metacorrector

Shown in Figure 15(e) is the comparison of results with and without the metacorrector. The metacorrector can reduce chromatic focus shift and spherical aberration significantly. The improvement in imaging quality can also be viewed more visually from the zoomed-in plots of the field around the focal plane, as shown in Figure 16.
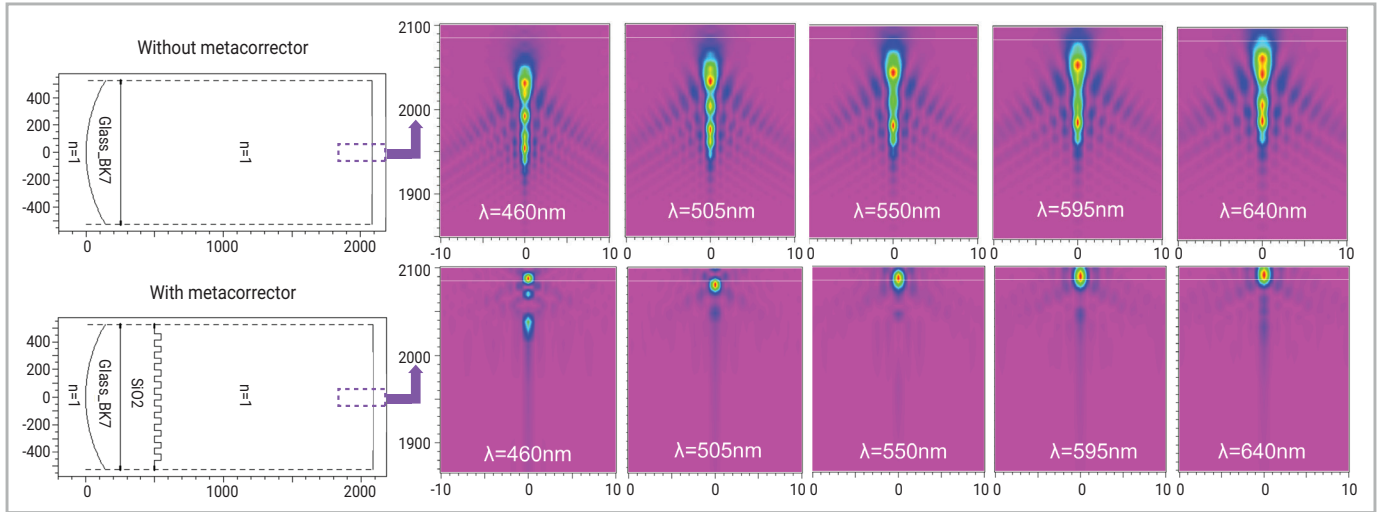

Figure 16: Comparison of the focusing with and without metacorrector

MetaOptic Designer's handling of refractive lenses has been validated using CODE V ray tracing and BSP techniques. BSP is a beamlet-based physical optical algorithm that is more accurate than ray tracing, especially for small lenses with diffraction and coherence effects. While all three methods agree on the focal length, both BSP and MetaOptic Designer also agree well on the shape of the intensity profile at the focal point.

Conclusion

MetaOptic Designer is the industry's first fully automated design tool for metaoptics with inverse design capabilities. When provided with a few basic inputs and the desired target patterns, MetaOptic Designer produces an optimized design. Validated by rigorous FDTD, MetaOptic Designer is a fast, accurate tool that can produce reliable GDS files for fabrication. With its built-in intelligence, MetaOptic Designer makes metalens design faster and easier, enhances productivity, reduces design costs, and accelerates time to market.

References

1. Chen, M. K., Wu, Y., Feng, L., Fan, Q., Lu, M., Xu, T., & Tsai, D. P. (2021). Principles, functions, and applications of optical meta-lens. *Advanced Optical Materials*, 9(4), 2001414.

2. Chen, Wei Ting, Alexander Y. Zhu, and Federico Capasso. "Flat optics with dispersion-engineered metasurfaces." *Nature Reviews Materials* 5.8 (2020): 604-620.

3. Novak, Matthew J., Bryan D. Stone, and Chenglin Xu. "Combined optimization, modeling and simulation techniques for non-traditional, next generation optics." *Computational Optics* 2021. Vol. 11875. SPIE, 2021.

4. Backer, Adam S. "Computational inverse design for cascaded systems of metasurface optics." *Optics Express* 27.21 (2019): 30308-30331.

5. Li, Z., Pestourie, R., Park, J. S., Huang, Y. W., Johnson, S. G., & Capasso, F. (2022). Inverse design enables large-scale high-performance meta-optics reshaping virtual reality. *Nature Communications*, 13(1), 1-11.

6. Bos, J., Scarmozzino, R., Bahl, M., Heller, E., Xu, C. A Design Automation and Simulation Flow for Lens Systems Containing Multiple Metasurfaces, META, July 2022, Torremolinos Spain.

7. Synopsys. (January 3, 2023). *FullWAVE Product Overview*. Synopsys, Inc. https://www.synopsys.com/photonic-solutions/rsoft-photonic-device-tools/passive-device-fullwave.html

8. Synopsys. (January 3, 2023). *DiffractMOD Product Overview*. Synopsys, Inc. https://www.synopsys.com/photonic-solutions/rsoft-photonic-device-tools/passive-device-diffractmod.html

9. Chen, Wei Ting, Alexander Y. Zhu, Jared Sisler, Yao-Wei Huang, Kerolos MA Yousef, Eric Lee, Cheng-Wei Qiu, and Federico Capasso. "Broadband achromatic metasurface-refractive optics." *Nano Letters* 18, no. 12 (2018): 7801-7808.

10. Liu, Yang, et al. "Silicon-based broadband metalens for wide-angle optical beam steering." *2021 IEEE 17th International Conference on Group IV Photonics* (GFP). IEEE, 2021.

11. Kim, C., Kim, S. J., and Lee, B. (2020), "Doublet metalens design for high numerical aperture and simultaneous correction of chromatic and monochromatic aberrations," *Optics Express*, 28(12), 18059-18076.

12. Liu, Y., Zhang, J., Le Roux, X., Cassan, E., Marris-Morini, D., Vivien, L., ... & Melati, D. (2022). Broadband behavior of quadratic metalenses with a wide field of view. *Optics Express*, 30(22), 39860-39867.

13. Mueller, J. B., Rubin, N. A., Devlin, R. C., Groever, B., & Capasso, F. (2017). Metasurface polarization optics: independent phase control of arbitrary orthogonal states of polarization. *Physical Review Letters*, 118(11), 113901.

14. Achuthan, N., Bahl, M., Scarmozzino, R., Heller, E., Bos, J., & Xu, C. (2022, October). Automated Design of Optical Systems with Metalenses. In *Frontiers in Optics* (pp. JW5A-51). Optica Publishing Group.

15. Villas-Boas, A. (August 12, 2019). *Samsung just unveiled the first smartphone camera that goes beyond 100 megapixels*. Business Insider. https://www.businessinsider.com/samsung-xiaomi-annonce-first-smartphone-camera-with-over-100-megapixels-2019-8?op=1

16. Zlatev, D. (July 6, 2022). *LG developing ultrathin camera metalens for compact and frugal electric vehicle self-driving kits*. NotebookCheck. https://www.notebookcheck.net/LG-developing-ultrathin-camera-metalens-for-compact-and-frugal-electric-vehicle-self-driving-kits.633472.0.html

17. Synopsys. (January 3, 2023). *CODE V Optical Design Software*. Synopsys, Inc. https://www.synopsys.com/optical-solutions/codev.html

18. Synopsys. (January 3, 2023). *CODE V Feature: Beam Synthesis Propagation*. Synopsys, Inc. https://www.synopsys.com/optical-solutions/codev/feature-closeup.html