High efficiency metalens design using wavefront error optimization

Narak Choi*, Keng Heng Lai, Yuan Hsing Fu#

Institute of Microelectronics, A*STAR (Agency for Science, Technology and Research), 2 Fusionopolis Way, #08-02, Innovis Tower, Singapore 138634, Singapore

ABSTRACT

Conventional metalens design is based on the library where phases and transmissions of the meta-atoms are calculated with the periodic boundary condition. And the most suitable meta-atom is picked up from the library ignoring its environment. However, the coupling between adjacent meta-atoms produces the phase error, leading to low efficiency and scattering of the metalens. We proposed a method of numerical optimization of the wavefront error by adjusting the meta-atoms size, which reduces phase errors leading to higher efficiency compared to the conventional metalens design. This method is scalable for a large size metalens and for metalens with an arbitrary phase profile.

Keywords: flat optics, metasurfaces, design, optimization, wavefront error

1. INTRODUCTION

Flat optics components, such as metalens, can potentially substitute conventional bulky optical components due to their lightweight and small form factor. Instead of using the geometrical shape of conventional optical components, metalens utilizes the variation of the effective index of refraction to manipulate the wavefront (phase) of the incoming light. Most widely used method to manipulate the variation is changing the meta-atoms size as holding its height. There is a relationship between the meta-atoms size and the phase shift, and it provides intuitive method how to design a metalens.

In the conventional metalens design, the meta-atom size and its phase shift are paired in the library based on the pitch arrays. When designing a meta-surface, the meta-atom size is chosen from the library where its corresponding phase shift is required. This method has successfully shown its usefulness in many applications, and it provides intuitive and efficient way of designing large size meta-surface without demanding large scale computing power. However, the different geometry of neighboring meta-atoms causes phase error leading lower efficiency of the device. And the discrepancy is not only lowering the efficiency but can be a hurdle to design other applications such as achromats[1].

To mitigate this phase error, some researchers choose meta-atom geometry paired with not the closest phase but the one located nearest position in the complex plane to the desired electric field[2], and this simple alteration could improve the efficiency. Some other researchers have approached to this problem more actively with topology optimization[3] with and without gradient calculations. The adjoint optimization method is the most popular gradient method due to its efficiency in calculating gradients of large number of variables[4-6]. They iteratively optimized the permittivity distribution in the design space by calculating gradient of the figure of merit function with respect to the permittivity at the sampled points. Each iteration requires two simulations from the design space to the target space and vice versa. However, it costs lots of computation time and memory, limiting its application. To overcome this limitation, some other researchers compromised between optimization accuracy and the computation time by proposing local approximation where small sections are rigorously optimized and the whole design is constructed by stitching the sections. The area to be optimized stays small so that it is computationally less intensive. And the whole system would be constructed by stitching the small fragments, large size device can be designed without worrying about the computation time[7]. Also, other researchers designed their meta-surface devices by positioning meta-atoms randomly and refined their library to be more suitable for this random distribution[8]. They built their library by averaging the ensemble of the surrounding geometry variations so that the phase error in the design can be mitigated.

*narak_choi@ime.a-star.edu.sg; phone 65 6770 5358; fax 65 6465 9136; www.a-star.edu.sg

#fu_yuan_hsing@ime.a-star.edu.sg; phone 65 6770 5461; fax 65 6465 9136; www.a-star.edu.sg

In this paper, we propose another method to alleviate the error by the discrepancy between the desired and the realized phase distribution based on the numerical iterative modification of the design. By adjusting pillar diameter of each unit cell, our approach gives simple way to consider all these effects into the design without complicate optimization formulations. Since it relies on the rigorous simulations, it takes non-negligible computation time, but the domain of computation is significantly reduced, and it can be applicable to larger device if proper parallel processing is implemented.

In the following sections, we introduce the idea of the wavefront error optimization and the performance comparisons between the conventional design and the proposed design in terms of wavefront error and power efficiency are presented.

2. WAVEFRONT ERROR OPTIMIZATION

In this section, we illustrate the optimization for a metalens as an example. The metalens is formed with various diameters of pillar with hexagonal periodic cell, and the height of the pillar and the period of the cell are pre-chosen. Hence, we can have the meta-atom library of the phase shift as the function of diameter of pillar. To focus the light, it is needed to generate the parabolic phase profile along the radius of the metalens for a given wavelength of light and the numerical aperture value. We construct initial metalens design using the conventional design method and calculate the phase error between the target and the generated wavefront by this design. For this calculation, we put an evaluation plane right after the pillars where evaluation points are located at the center of each paired pillar as shown in Figure 1. The phase of the electric field is calculated and compared to the required phase at each evaluation point. To calculate the electric field, a commercial FDTD simulation software is used, therefore it might be computationally demanding. However, the evaluation plane is located right after the pillar, the domain size in z-direction is quite small compared to the conventional forward simulation.

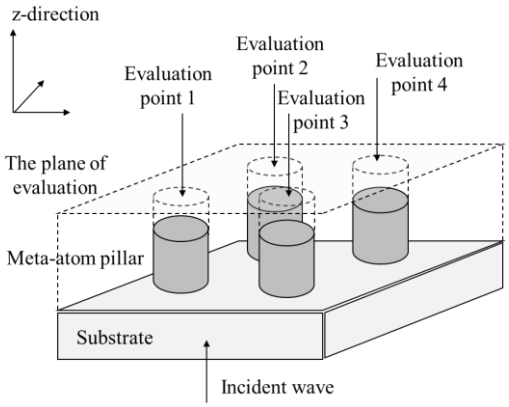


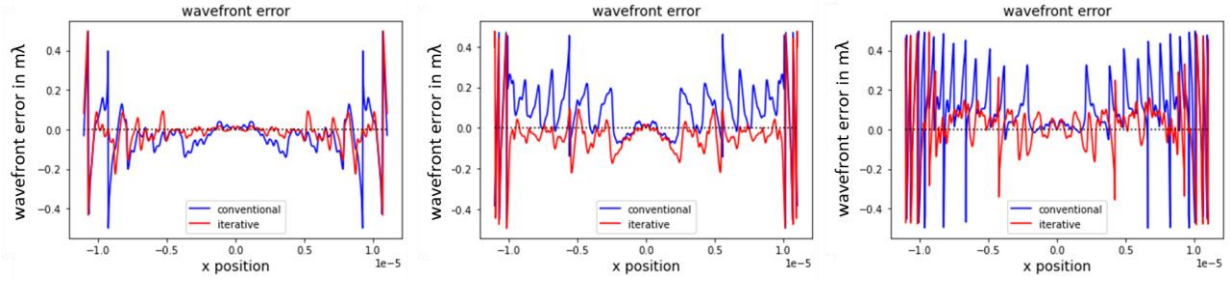
Figure1: The evaluation plane is located right above the pillars and each evaluation point is paired with a meta-atom pillar. The phase is extracted from the electric field at these evaluation points.

3. RESULTS AND DISCUSSIONS

To validate the effectiveness of the proposed method, we considered three metalens designs with three different pitch of 0.465 μm, 0.300 μm, and 0.160 μm for the wavelength of 0.94 μm, 0.60 μm and 0.46 μm respectively. All the three metalenses are designed to have the same numerical aperture value of 0.7 and the focal length of 10 μm. The diameter of the metalens is 20 μm.

We firstly designed the metalens using the conventional method as the initial design and optimized it using the proposed wavefront error optimization. Figure 2 shows the wavefront error in mλ along the x-axis of the metalens, the blue lines

and red lines represent the wavefront errors of the conventional designs and the optimized designs, respectively. The wavefront error is calculated from the phase of the x-component of the electric field in the evaluation plane. In all the three cases, it can be observed that the wavefront errors are significantly reduced in the optimized cases compared to the conventional one.



(a) (b) (c)

Figure 2: Wavefront error along the x-axis of metalens of the conventional design (blue lines) and the proposed optimized designs (red lines) for (a) the case of λ = 0.94 μm, (b) the case of λ = 0.60 μm, and (c) the case of λ = 0.46 μm.

The wavefront error distributions over the entire metalens pupil are depicted in Figure 3. The errors are high in the vicinity of the boundaries between the 2π-folded regions because the neighboring pillars' diameters are changing abruptly in those boundaries. This sudden change makes larger geometry discrepancy between in real design and in the library and causes the larger phase errors. And we could expect that if the metalens NA gets larger, the phase error would also get larger because it will contain more boundaries. With the proposed optimization, this phase errors are significantly reduced throughout the whole pupil area, and we could expect that the proposed optimization would be more useful for higher NA metalens.

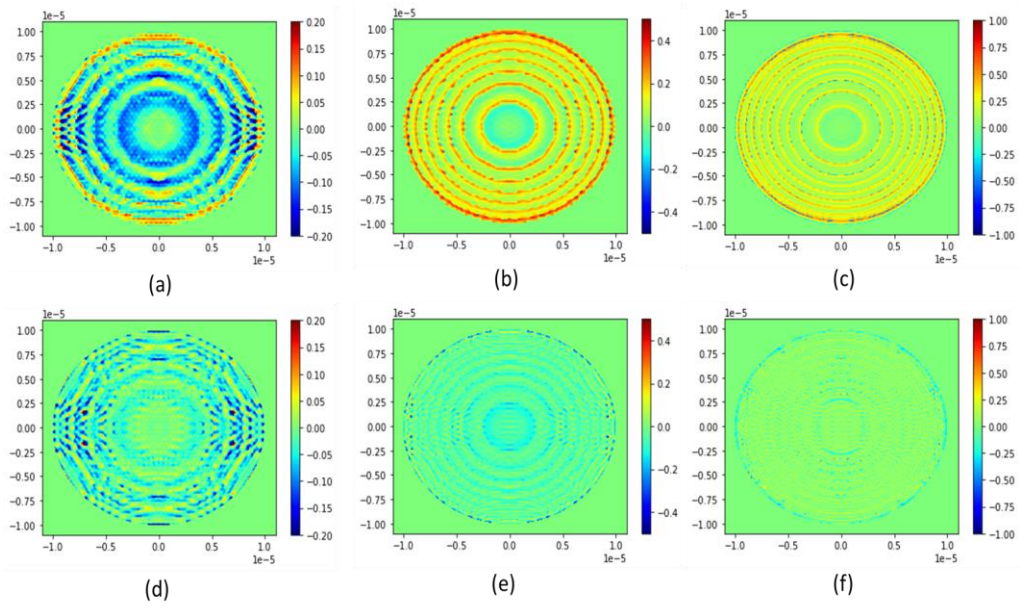


Figure 3: The wavefront error distributions over the entire pupil of the metalens designed with the conventional method (a, b, c) and the proposed method (d, e, f) for the cases of (a, d) λ = 0.94 μm, (b, e) λ = 0.60 μm, and (c, f) λ = 0.46 μm.

To describe the performance improvement qualitatively, we characterized the performances of the optimized metalens and compared them to the performances of the metalens designed by the conventional method using the numerical FDTD simulations. To characterize the metalens performance, we calculated the focal length, the efficiency, and the transmittance. The focal position is determined where the maximum intensity is located, and the efficiency is the ratio of the encircled energy within the circle twice larger than the Airy disk to the total transmitted energy. The transmittance is given by the ratio of the transmitted energy to the total incident energy.

Table 1: Performance characterization, estimated by using the FDTD simulation, of the metalens of the design with the conventional method and of the design with the proposed optimization method for the three test cases.

	pitch=0.465μm, λ=0.94μm		pitch=0.300μm, λ=0.60μm		pitch=0.160μm, λ=0.46μm	
	initial design	optimized	initial design	optimized	initial design	optimized
focal length [μm]	9.6	9.9	9.6	9.8	9.5	9.9
efficiency [%]	80.2	83.7	63.6	79.5	52.9	72.3
transmittance [%]	79.1	81.1	88.8	84.4	85.9	80.3
wavefront error rms [mλ]	63.5	42.4	96.1	49.4	148.0	75.0

Table 1 summarizes the predicted metalens performances. For the case of $\lambda = 0.94$ μm where the pitch of meta-atom is selected to be 0.465 μm, the wavefront error RMS value is improved from 63.2 mλ in the conventional method to 39.5 mλ in the proposed method, leading the efficiency improvement from 79.9 % to 82.8 %. And the focal length of the metalens is closer to the desired one in the optimized design by 0.3 μm. Next, for the case of $\lambda = 0.60$ μm where pitch of meta-atom is selected to be 0.300 μm, the wavefront error RMS value is improved from 96.1 mλ to 49.4 mλ, resulting in the efficiency improvement from 63.6 % to 79.5 %. And also, the focal length of the metalens becomes closer to the target focal length in the optimized design by 0.2 μm. Lastly, for the case of $\lambda = 0.46$ μm where the pitch of meta-atom is selected to be 0.160 μm, the wavefront error RMS value is improved from 148.0 mλ to 76.3 mλ, leading the efficiency improvement from 52.9 % to 71.0 %. And the focal length of the optimized design exhibits 9.9 μm while the conventional one does 9.5 μm.

Comparing the three cases, as the pitch of meta-atom gets smaller, the coupling effect gets stronger and the metalens efficiency gets lower. Since the proposed optimization method compensates the wavefront error caused by the coupling effects, the proposed method contributes more to the cases where the pitch of meta-atom are smaller.

4. APPLICATION TO LARGE SIZE DEVICE

Since the proposed method is directly wavefront error optimization from the evaluation plane that is very close to the pillar. To apply on the large size device, we can divide the device in several pieces, optimize the wavefront error individually and parallelly, and stitch the results. To illustrate this method, we choose a metalens for wavelength of 0.94 μm with the pitch of meta-atom of 0.465 μm, focal length of 10 μm and diameter of 50 μm as an example and it is shown in Figure 4(a).

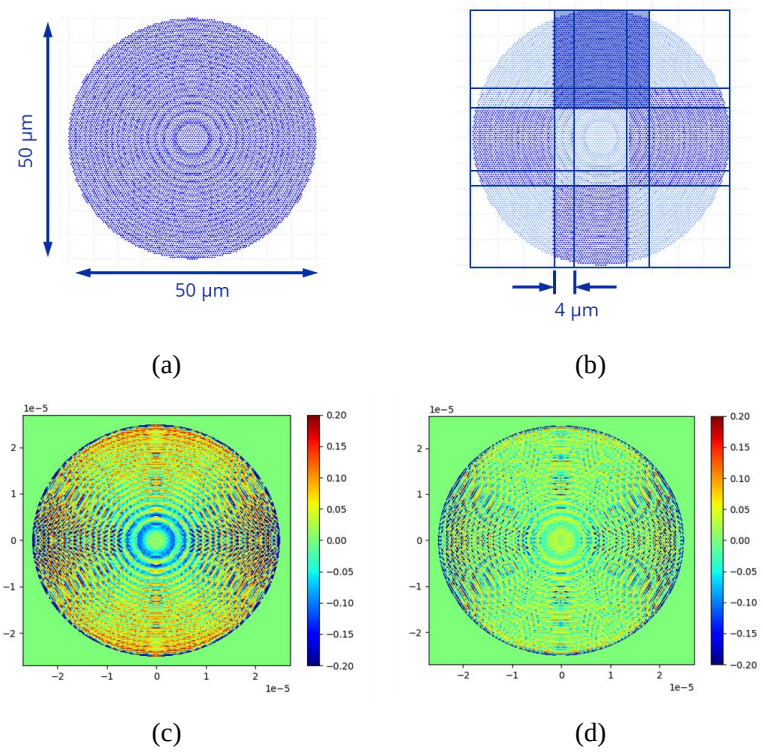


Figure 4: (a) conventional design of a metalens with diameter of 50 µm and NA of 0.88 (b) metalens of (a) is divided into 9 small pieces (c) the wavefront error of the conventional design over the metalens pupil (d) the wavefront error of the optimized metalens over the metalens pupil.

The metalens is divided into 9 pieces with 4 µm-width overlapping area as shown in the figure 4(b) and each piece is optimized individually. The final optimized designs are recombined and the wavefront error distribution by the whole recombined design is calculated using FDTD simulation and the result is shown in Figure 4(d). The wavefront error RMS of the conventional method is given by 94 mλ while the error RMS of the optimized one is given by 73 mλ exhibiting 22 % wavefront error reduction. Also, compared to the wavefront error distribution by the conventionally designed metalens shown in the Figure 4(c), it can be observed that there is no significant error between stitching boundaries. This example exhibits that the proposed method is parallel-computing friendly, and it can be applied to large size metalens.

5. CONCLUSION

In this paper, we proposed a method to improve the efficiency of the metalens by iteratively adjusting the diameters of the meta-atoms to optimize the wavefront error. The results show that it reduces the difference between the desired and the realized phase at the plane right after the meta-atom pillars. Our simulation shows that the method improves the efficiency up to 36 % compared to the conventional method and it is particularly useful when the coupling between neighboring pillars is strong. Compared to the usual forward/ adjoint simulation to optimize metalens performance, the domain of the computation in this method is small. Also, the method is parallel-compute friendly and, if stitched properly, it can be applied to larger size devices. Furthermore, the optical proximity correction (OPC)[9] can be well implemented for the metalens design with this optimization method.

ACKNOWLEDGEMENTS

This research is supported by Agency for Science, Technology and Research (A*STAR), Singapore under RIE2020 Advanced Manufacturing and Engineering (AME) Programmatic Grant (A18A7b0058) and Agency for Science, Technology and Research (A*STAR), Singapore under Advanced Manufacturing and Engineering (AME) Individual Research Grant (IRG) (A2083c0060).

REFERENCES

[1] Shrestha, S., Overvig, A. C., Lu, M., Stein, A. and Yu, N., "Broadband achromatic dielectric metalenses," Light Sci Appl **7**(1), 85 (2018).

[2] Khorasaninejad, M., Zhu, A. Y., Roques-Carmes, C., Chen, W. T., Oh, J., Mishra, I., Devlin, R. C. and Capasso, F., "Polarization-Insensitive Metalenses at Visible Wavelengths," Nano Lett. **16**(11), 7229–7234 (2016).

[3] Molesky, S., Lin, Z., Piggott, A. Y., Jin, W., Vucković, J. and Rodriguez, A. W., "Inverse design in nanophotonics," Nature Photon **12**(11), 659–670 (2018).

[4] Christiansen, R. E. and Sigmund, O., "Compact 200 line MATLAB code for inverse design in photonics by topology optimization: tutorial," J. Opt. Soc. Am. B **38**(2), 510 (2021).

[5] Christiansen, R. E. and Sigmund, O., "Inverse design in photonics by topology optimization: tutorial," J. Opt. Soc. Am. B **38**(2), 496 (2021).

[6] Lalau-Keraly, C. M., Bhargava, S., Miller, O. D. and Yablonovitch, E., "Adjoint shape optimization applied to electromagnetic design," Opt. Express **21**(18), 21693 (2013).

[7] Phan, T., Sell, D., Wang, E. W., Doshay, S., Edee, K., Yang, J. and Fan, J. A., "High-efficiency, large-area, topology-optimized metasurfaces," Light Sci Appl **8**(1), 48 (2019).

[8] Nasari, H., Dupré, M. and Kanté, B., "Efficient design of random metasurfaces," Opt. Lett. **43**(23), 5829 (2018).

[9] Choi, N., Lai, K. H., Sundaram, A., Singh, N., Fu, Y. H. and Lee, L. Y. T., "Model-based optical proximity correction for immersion lithography-based flat optics platform," High Contrast Metastructures XII **12432**, 19–23, SPIE (2023).