

Introduction on Freeware Metalens Design Tools and Methods

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ABSTRACT

Recently, metalenses have been widely spotlighted in miniaturized optics, and have shown potential capabilities of high numerical aperture (NA), leading to short focal lengths, and high focusing intensity efficiencies. Each metamaterial composing of the designed metalens is tightly controlled in its design for high transmission and phase distribution of scattered lights at each location required for the lens equation. This work covers design methods on how to find optimized individual metamaterials, and how to acquire metalens simulation results at 633 nm of an operating wavelength on freeware simulators, the MAXIM and SMD tools.

KEYWORDS : Metamaterials, Metalens, Subwavelength, Freeware, MAXIM, RCWA, SMD

1. INTRODUCTION

Conventional focusing lenses manipulate light deflection using the intrinsic refractive index of their crystal materials, combined with thickness curvature processing. This approach, characterized by equal thickness across concentric circles, is essential for achieving the required phase distribution in the lens equation. However, this approach frequently leads to geometrical constraints, resulting in bulky and heavy designs, typically spanning over several centimeters in size. In contrast, metalenses represent a significant departure from traditional lens designs. The metalens is one of ultrathin-flat optics based on the arrangement of individual metamaterials at subwavelength scales. They utilize flat surfaces embedded with individual resonators of subwavelength features to fine-tune optical properties. This innovative structure enables incident light to be localized and manipulated at the subwavelength scale through optical resonance.^[1] The light is scattered with a precisely tailored optical phase, which is particularly effective in achieving a high numerical aperture (NA).^[2] Also, one of the key advantages of metalenses is their abilities to alleviate limitations inherent in traditional lenses, such as spherical aberration.^[3] This aberration occurs when light rays passing through different parts of a lens focus at varying points, leading to blurred and distorted images. Metalenses, through the use of meticulously engineered nanostructures, offer enhanced control over the light path. By adjusting these nanostructures on the metalens surface, designers can influence how different light wavelengths interact with the lens, significantly reducing aberrations. Despite these advancements, it is important to recognize that metalens technology is still in a developmental phase. It has not yet sufficiently reached the maturity or widespread

adoption of traditional lenses in industrial fields. Current challenges, including efficiency, bandwidth limitations, and manufacturing complexities, need to be overcome before metalenses can comprehensively replace traditional lenses in various applications.

He-Ne gas lasers, emitting a wavelength of 633 nm, have been widely applied in various fields such as medical treatments,^[4-5] primary standard of length measurement,^[6] and holographic imaging.^[7] In particular, He-Ne gas lasers serve as a universal light source for single-wavelength ellipsometry (SWE) technologies,^[8] and are used in the semiconductor and thin-film industries,^[9] as well as laboratories. Here, the author aims to design the metalens at 633 nm.

The design of metalenses has necessitated extensive data and high-performance workstations capable of supporting ultrafast computational calculations for solving electromagnetic (EM) wave simulations on the expensive commercial simulators. Especially, the Finite-Difference Time-Domain (FDTD) method, which is based on the principles of solving Maxwell's equations, offers the significant advantage of enabling the calculation of S-parameters across multiple wavelengths in a single simulation. However, this method is characterized by its computationally intensive nature and the generation of substantial volumes of data. In this context, our objective is to introduce freeware simulators and guide users on how to design individual metamaterials covering high transmission and 360 degrees of phase difference for a metalens configuration. The author offers simulation methods using two freeware simulation tools at 633 nm of an operating wavelength under the EM plane waves on the MAXIM, and SMD (Simple Metalens Design) tools,^[10-11] respectively. Both

tools are attractive options due to their easy-to-understand user interfaces and support for lightweight computation on personal computers.

2. DESIGN OF METAMATERIALS

The author proposes individual metamaterial structures in the simple isotropic form of the silicon pillar in in-plane geometries to alleviate polarization selectivity at normal incident lights. The MAXIM tool provides the simulation results of the transmission coefficients for not only the x-polarized light but also y- and z-polarized lights under x-polarized incident lights. However, the components for both y- and z-polarized lights have almost zero values due to symmetric pillar structures at normal incidence. Of course, both transmission and phase are calculated to be same values even under y-polarized lights due to their symmetric geometries. Users

can also try to introduce anisotropic rectangular structures that support polarization-selective metalenses. The schematic and geometrical parameters for a unit structure of metamaterials are provided in the caption of Figure 1(a). The parameter sweep function of MAXIM provides transmission coefficients and phase distribution of metamaterials over a range of geometrical parameters as shown in Figure 1(b-c). In the range of radius 20 nm to 90 nm at height 360 nm, the simulation results cover 360 degrees of phase difference and 0.72-0.98 of transmission intensities. The simulations were set to silica substrate as the input medium (n_i) and free-space as the output medium (n_f) at normal incidence ($\theta = 0$) on the MAXIM tool. Here, we can ignore the substrate effects since the phase delay is identical for all unit cells due to the same substrate thickness at all locations. The phase distribution was separately calculated from the complex numbers of the transmission coefficients.

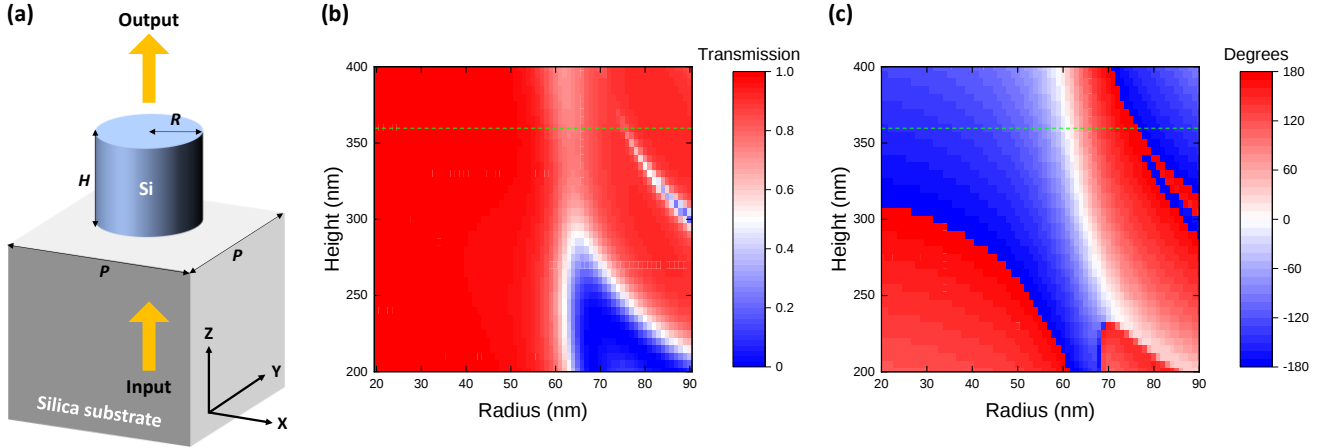


Figure 1. Designs and MAXIM simulation results of a unit structure of metamaterials. (a) A schematic of a unit structure. The parameter sweep was performed under geometrical dimension ranges : P (period) = 300 nm, H (height) = 200 nm to 400 nm with a 5 nm step, and R (radius) = 20 nm to 90 nm with a 1 nm step. (b) The simulated transmission, and (c) estimated phase distribution for x-polarized lights at 633 nm of an operating wavelength, respectively.

3. DESIGN OF METALENS

Metalens design and its simulation are performed on the SMD tool. Users can set the size, focal length, and focal position of the desired metalens on the **Target Phase Generator** module. Here, since the author designed the metamaterials based on the operating wavelength of 633 nm and configured free-space as the output medium, the wavelength should be set to 633 nm, and the refractive index (n) should be set to 1. A schematic of the designed metalens and its size (L), focal

length (F), and focal position for x- and y-coordinates (X_f and Y_f) are provided in the caption of Figure 2(a). The coordinates for the center position of metalens are $L/2$, $L/2$. The SMD tool provides a **Target Phase Data** sheet of the phase distribution for the tailored metalens as shown in Figure 2(b). The estimated phase distribution on the SMD tool is calculated from lens phase equation as follows :

$$\varphi(x, y) = \frac{2\pi}{\lambda} \left\{ F - \left(\sqrt{(X - X_f)^2 + (Y - Y_f)^2 + F^2} \right) \right\} \quad (1)$$

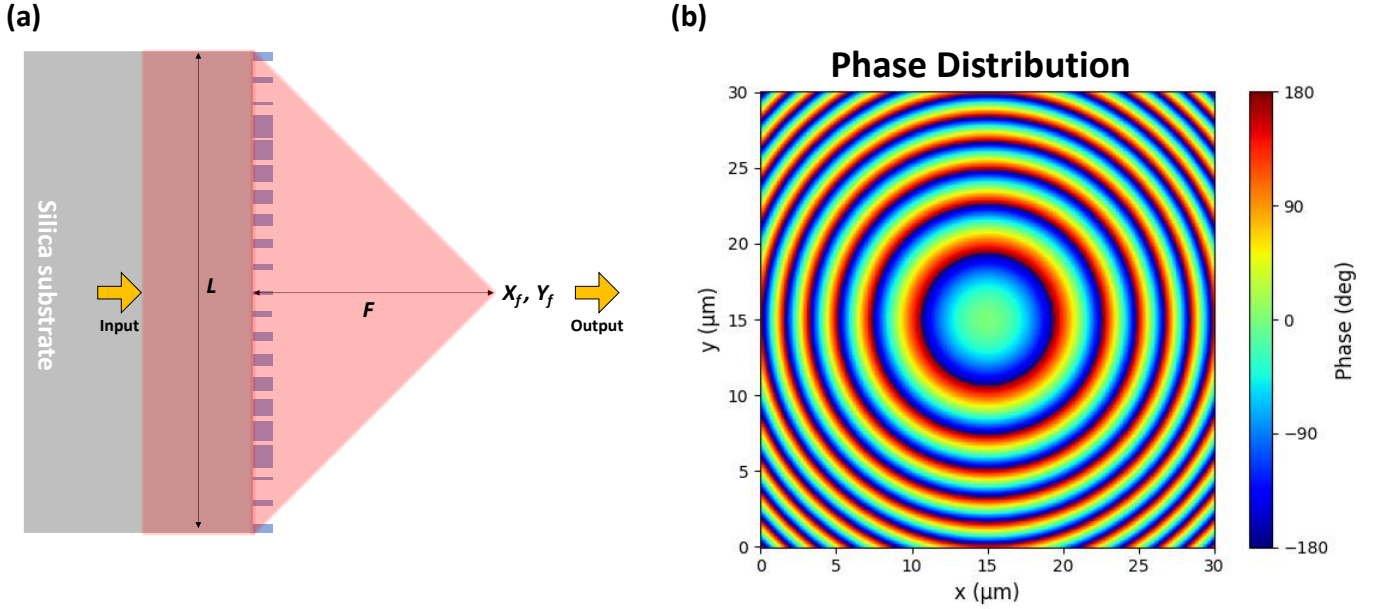


Figure 2. Metalens design. (a) A schematic of the designed metalens. Metalens was set as $L = 30 \mu\text{m}$, $F = 30 \mu\text{m}$ and $X_f = Y_f = 15 \mu\text{m}$, respectively. (b) The estimated metalens phase distribution was calculated from the lens phase equation (1).

Users can obtain a *Metalens (complete)* sheet of the radii distribution sheet for the designed metalens on the *Unitcell Arranger* module. This feature supports the creation of radii distribution of individual metamaterials corresponding to the phase distribution at each location. The condensed data in the compact phase difference offers narrow tolerances, thereby leading to enhancing performances and providing precise specifications. Here, the author set *Tmin* to 0.5, *Tmax* to 1.0, and *Phase Tolerance (deg)* to 15, in *Unitcell Arrangement Criteria*. The relatively high phase tolerance value was used due to the data not condensed in the positive phase range

shown in Figure 1(c).

The *Lens Simulator* module requires some inputs for *General Settings* and *Incident Beam Settings*, and the upload of the *Metalens (complete)* sheet. Users can choose one between the EM *Gaussian* and *Uniform* waves, but the author recommends users select the *Uniform* wave since the results of S-parameters of individual metamaterials were simulated under the EM plane waves on the MAXIM tool. The refractive index (n_i) of incident medium was set to 1. Here, the refractive index of the incident medium does not affect metalens simulation results at normal incidence.

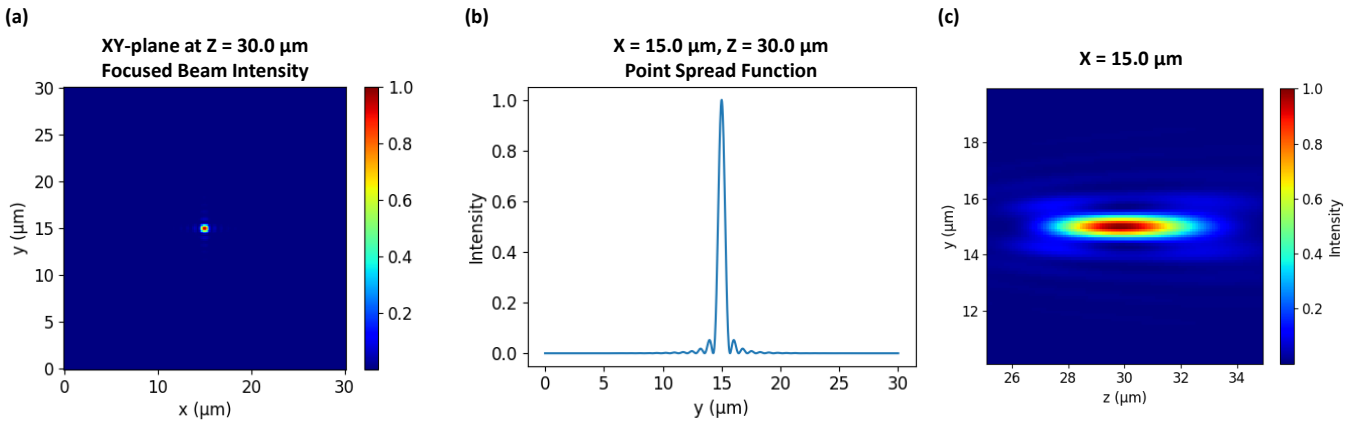


Figure 3. Metalens simulation results. (a) The focused beam intensity on the xy-plane at $Z = 30.0 \mu\text{m}$. (b) Point spread function along the y-direction at $x = 15.0 \mu\text{m}$ and $z = 30.0 \mu\text{m}$ (focal length). (c) The focused beam intensity on the yz-plane at $x = 15.0 \mu\text{m}$.

The simulation results of the designed metalens are presented in Figure 3. The beam intensity passing through the metalens is accurately focused at $z = 30.0 \mu\text{m}$ on the focal plane. The focusing intensity efficiency and full width at half maximum (FWHM) were estimated to be

0.769, $0.63 \mu\text{m}$, respectively, shown in Figure 3(a-b). The intensity distribution was normalized to 1 as maximum intensity of main lobe. Figure 3(c) shows the focused intensity on the yz-plane at $x = 15.0 \mu\text{m}$. The depth of focus (DOF), as assessed visually from the focal

length, is estimated to be approximately $\pm 2.5 \mu\text{m}$ under the EM plane wave. The depth of focus is simply expressed as follows :^[12]

$$\Delta F = 4\lambda \frac{F^2}{D^2} \quad (2)$$

Here, ΔF denotes the DOF, λ represents the operating wavelength, F signifies the focal length, and D corresponds to the diameter of the metalens. Taking D as the distance from the center of the metalens to its diagonal edges, the DOF is computed to be $5.064 \mu\text{m}$. This computed value shows close alignment with the depth of field (DOF) estimated visually, as presented in Figure 3(c).

4. METHODS

All the simulations in this work were conducted on a personal laptop computer, the Lenovo Yoga Slim 7 14ARE05, equipped with an AMD Ryzen 7 4800U processor. The MAXIM freeware tool, utilizing rigorous coupled-wave analysis (RCWA), facilitates the computation of diffraction characteristics for periodic structures with multiple layers. The MAXIM tool support calculations of EM fields by summing spatial harmonics of computational electromagnetics, and provides complex numbers of transmissive and reflective electric field components of S-parameters for individual metamaterials, so that users can calculate their phase information. Users have the flexibility to generate not only straightforward structures but also intricate polygonal structures using the convenient parameter sweep function. Additionally, they can simultaneously conduct multiple calculations for S-parameters under diverse conditions at once. The SMD tool facilitates the precise positioning of individual metamaterial elements, tailored to specific inputs such as the metalens size, focal positions, and the focal length. This functionality is crucial for optimizing the performance in various applications. Users can acquire the final simulation results of the tailored metalens through inserting the intensity and phase information for each metamaterial optimized from the MAXIM tool into the SMD tool.

All the data presented in this work were simulated under the EM plane waves. The designed metalens size ensures that the incident Gaussian beam is nearly apodized in real experiments, providing a close approximation to the uniform plane wave. The used dispersion models for silicon dioxide and silicon were provided as embedded materials on the MAXIM tool (version 1.0). The data presented in Figure 1(b-c) was

simulated at 7 of the truncation orders in x- and y-directions (f_x and f_y), and the run time was estimated to be approximately 225 minutes. Users can also try to investigate and refine the designs of metamaterials, aiming to improve the performance of metalenses at an identical operating wavelength. The author suggests that users opt for rectangular structures due to their capabilities to exhibit dual selectivity for x- and y-polarized lights, respectively. The SMD tool supports the rectangular phase distribution of designed metalenses. The data indicated in Figure 2(b) and Figure 3(a-c) were simulated on the SMD tool (version 1.25.24). Attention must be paid to the fact that the **Unitcell Data (circle)** sheet recognizes diameter values, not radii. The author used default setting on the **General Settings** of the **Lens Simulator** module. The author strongly recommends reading the tutorials and user manuals of each of the two tools before reading this work.^[10-11]

■ NOTES

This manuscript serves as an introductory guide to freeware tools for metalens design, tailored for use by small enterprises, research institutes, laboratories, and independent engineers and researchers. It does not cover professional development or advanced research. Additionally, the contents of this work are not planned for publication in an academic journal.

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Inyong Hwang received his B.S. degree in Electronic Engineering from Yeungnam University in 2015 and his Ph.D. degree in Electrical Engineering from Ulsan National Institute of Science and Technology (UNIST) in 2022, respectively, both in the Republic of Korea. His doctoral research activities were mainly focused on electrical phase modulations based on mid-infrared intersubband polaritonic metasurfaces, and surface-enhanced infrared absorption (SEIRA) spectroscopy based on metamaterial absorbers. He has served as a product development engineer at KLA Corporation since 2022.

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I.H. contributed to all aspects of this work, and wrote the manuscript totally.

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■ CONFLICT OF INTEREST

The author declares no conflict of interest.

■ DATA AVAILABLE STATEMENT

The data that support the findings of this work are available from the corresponding author upon reasonable request.

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