Contents

Metalens - Fresnel

Metalenses, a direct application of metasurfaces, represent a significant advancement in photonics. Where conventional lenses rely on curvature to focus light, metalenses are arrays of sub-wavelength elements to achieve the same optical performance while maintaining a thin and lightweight profile. These high index contrast sub-wavelength elements provide a cumulative bending effect on the optical source [1].

This particular example uses the traditional Fresnel lens design to demonstrate the effectiveness of a metalens.

Labels

Fresnel; Lens; Metalens; Metasurface; FDTD; Consumer Electronics; Medical Devices; Telecommunications

Theory

The general approach to a metalens design is to examine the phase modification required for the the desired lensing and divide the domain into sub-wavelength elements. The design is then developed to provide the correct effective index or phase modification for each element.

The traditional Fresnel lens, shown in Figure 1, consists of concentric zones of high (white) and low (black) transmission [2]. The zones are determined by the expression

$$F(x,y) = U\left[cos\left(\pi\frac{x^2+y^2}{\lambda f}\right)\right] \quad (1)$$

$$U(v) = \begin{cases} 1 & v \geq 0 \\ 0 & v < 0 \end{cases} \quad (2)$$

where U is the unit step function and f is the desired focal length for the given wavelength λ.

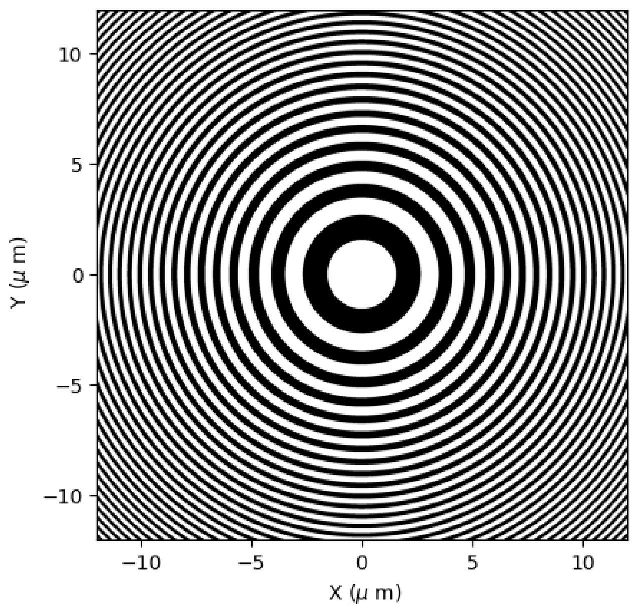

Figure 1: Figure 1: Demonstration of a Fresnel zone plate using equation (1) with $\lambda = 0.6$ μm and a focal length of $f = 8$ μm.

The metalens design will be achieved through an array of subwavelength air holes introduced into a dielectric (Si) slab within the desired regions of high transmission. This will reduce the effective index of these areas and improve transmission.

Design

There will be three simulation designs explored in this demonstration: Dielectric slab, thick Fresnel lens; Fresnel metalens. The freespace and thick Fresnel lens examples will provide reference and context for the metalens design.

Each simulation will maintain the same general wafer, source, and discretization parameters which are outlined below. The details for each of the lens examples will be found in their relevant section.

General simulation parameters

Table 1: Wafer specifications and boundary conditions

Wafer properties	Value
Length along x	10 μm
Length along y	10 μm
Length along z	12 μm
Boundary conditions	Anisotropic perfectly matched layer (APML)

The input plane was configured using a rectangular distribution as the optical source

Table 2: Details of the optical source employed in the simulation

Optical source features	Value
Position	0.25 μm
Wavelength	0.85 μm
Half Width	0.5 μm
Direction of propagation	$\hat{z}$
Time domain shape	Continuous Wave (CW)

In order to ensure simulation result consistency across all three simulations the discretization mesh for all three designs was based on the most constrained simulation (metalens).

Table 3: Details of the mesh discretization. Any properties not specified are set to Auto.

Mesh properties	Value
Δ x and Δ y	0.01 μm

Mesh properties	Value
Δ z	Non-uniform with maximum Δ of 0.07 μm and minimum of 0.02 μm. The minimum mesh was set to cover from $z = 0.5$ μm to 2.05 μm.

Dielectric Slab

The first design consisted of a dielectric (Si) slab. This example will demonstrate the lack of field focusing and serve as reference for the two lens designs. The slab will also form the basis of the subsequent designs as each will be etched into the slab.

Table 4: General properties for the base example of a XY dielectric slab.

Design properties	Value
Slab material	Si (n = 3.48)
Slab thickness	1.55 μm
Slab start position	0.5 μm
Observation point position	11 μm
YZ Observation Area position (x, y, z)	(0, 6, 0) μm
YZ Observation Area dimensions (Z length, Y length)	(12, 10) μm

Thick Fresnel Lens

The first lens example is that of a Fresnel lens wtih a thickness matching the dielectric slab (1.05 μm). The starting radii for each ring was analytically calculated from (1) and shown in Table 5. A series of decreasingly smaller fiber waveguides were created using these radii with the assigned material alternating from Si to air such that the center region was air. The creation of the fiber waveguides was accomplished using VBScripting available within OptiFDTD and included in the attached design file.

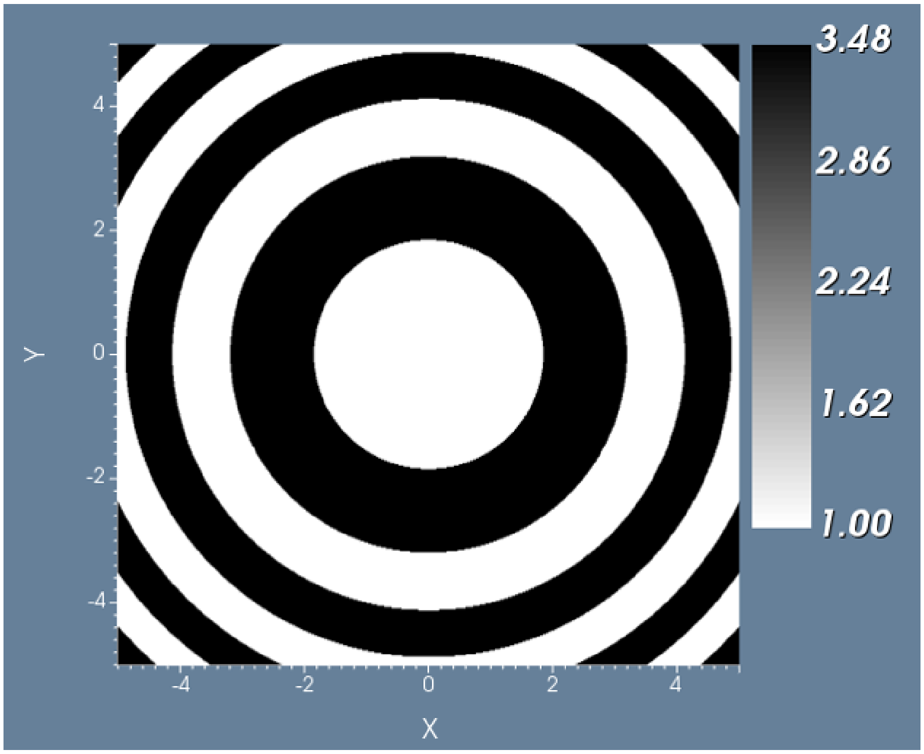

Figure 2: Figure 2: Frensel lens design in OptiFDTD

Table 5: Radii used for concentric fibers in order of creation for the Fresnel lens. Note, the smaller the radius for the fiber, the higher in the project browser to ensure that the refractive index of the fiber takes precedence over the previous fibers.

Ring	Outer Radius (μm)
1	7.602631
2	7.141428
3	6.648308
4	6.115554
5	5.531727
6	4.878240
7	4.123106
8	3.193744
9	1.843909

Effective Index Fresnel Lens

The metalens was created through the creation of a square lattice over the simulation domain. At each node it was determined whether the location of the node was within a region of high or low transmission using equation (1). If high transmission was required an air hole would be created using a fiber waveguide with air assigned. If the region was low transmission the creation of the air hole was bypassed.

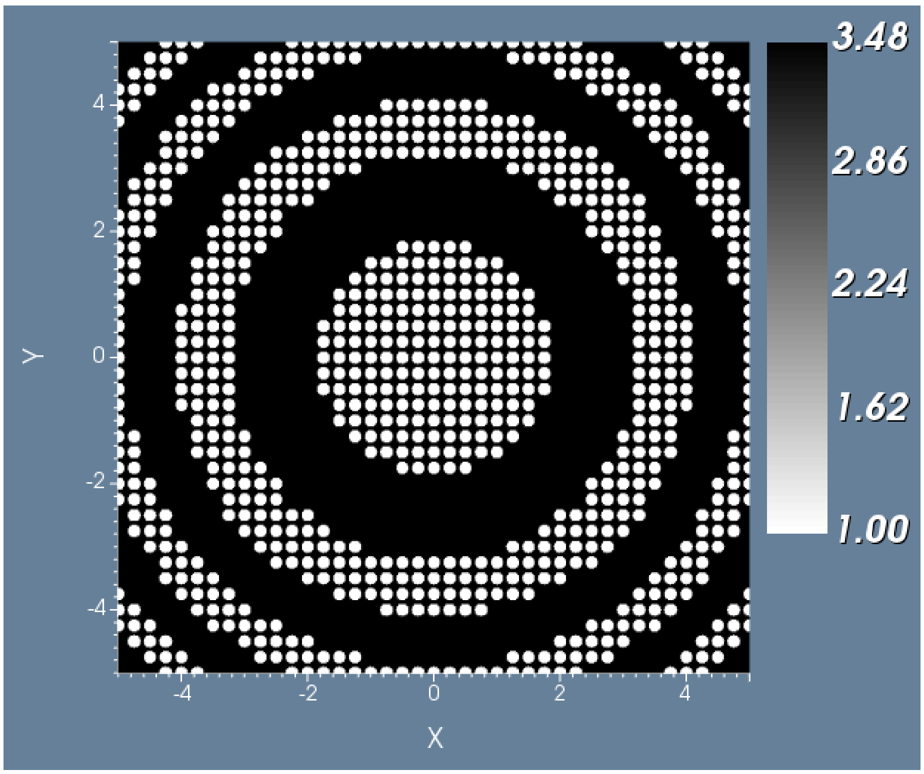

Figure 3: Figure 3: Metalens design in OptiFDTD

The properties for the lattice and the air hole atoms are outlined in the table below.

Table 6: General properties for air holes.

Design properties	Value
Material	Air
Rod radius	0.2 μm

Design properties	Value
Lattice	Square with 0.25 μm lattice spacing

Results

As a baseline, the dielectric slab demonstrates the lack of field focusing as well as the anticipated Fabry-Perot resonance within the slab.

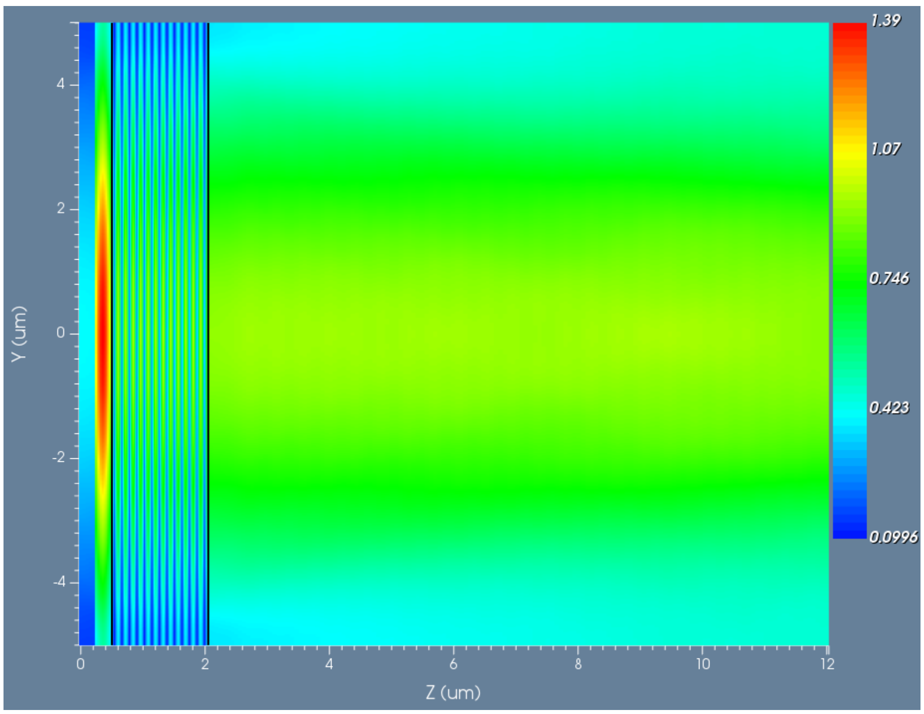

Figure 4: Figure 4: YZ slice of the Ey field for the dielectric slab.

Introduction of the Fresnel lens design result in the field being focused, Figure 5. Taking a slice along the z-axis, Figure 6, shows the peak of the focal point is at 8. 2319 μm.

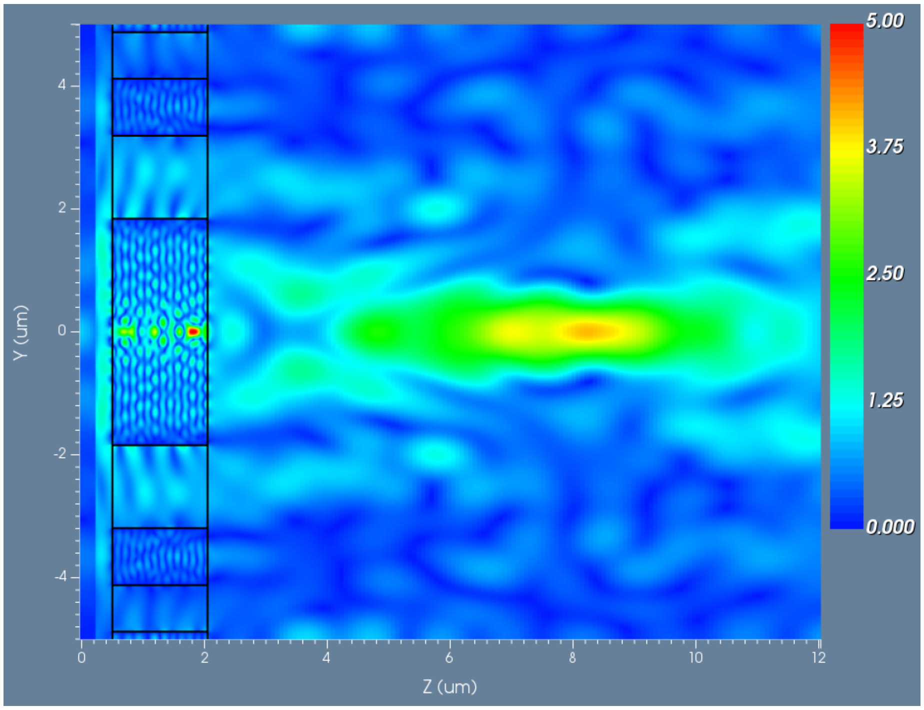

Figure 5: Figure 5: YZ slice of the Ey field for the Fresnel lens.

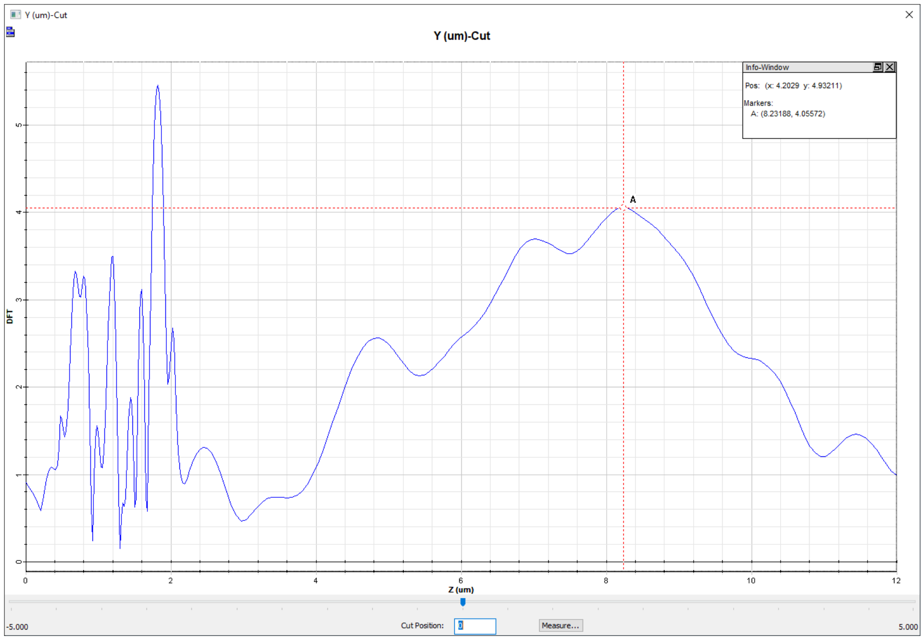

Figure 6: Figure 6: Z slice along the YZ observer of the Ey field for the dielectric slab.

Changing the lens design to the metalens provides qualitatively similar results. While the peak of the focal point is located at 8.0475 μm, the spot size is larger. The deviation between the results is a function of the differing index contrast and lower transmission for the high transmission zones in the meta lens.

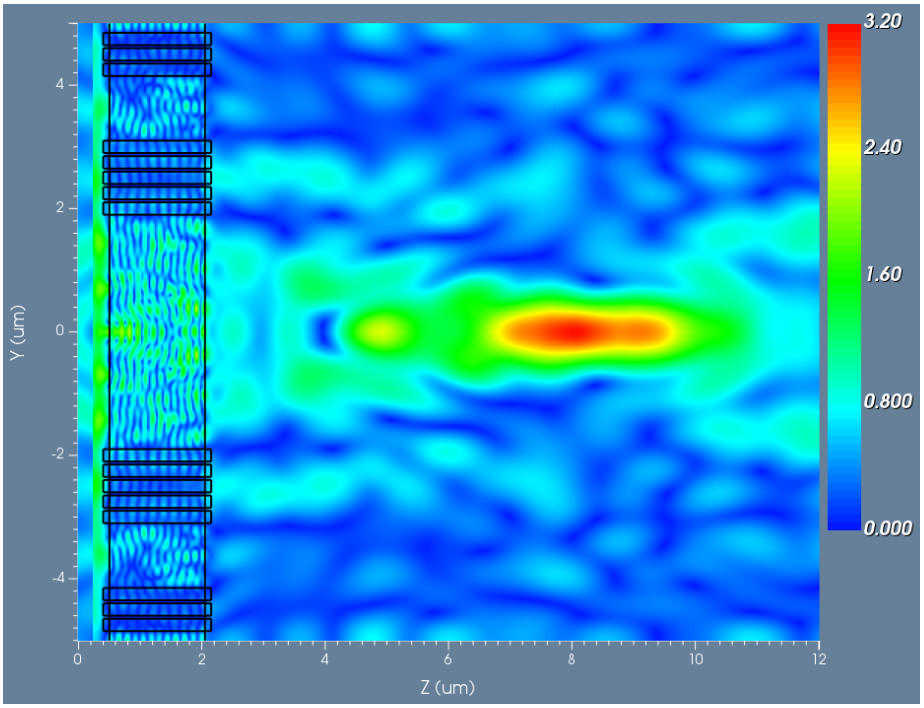

Figure 7: Figure 7: YZ slice of the Ey field for the Fresnel lens.

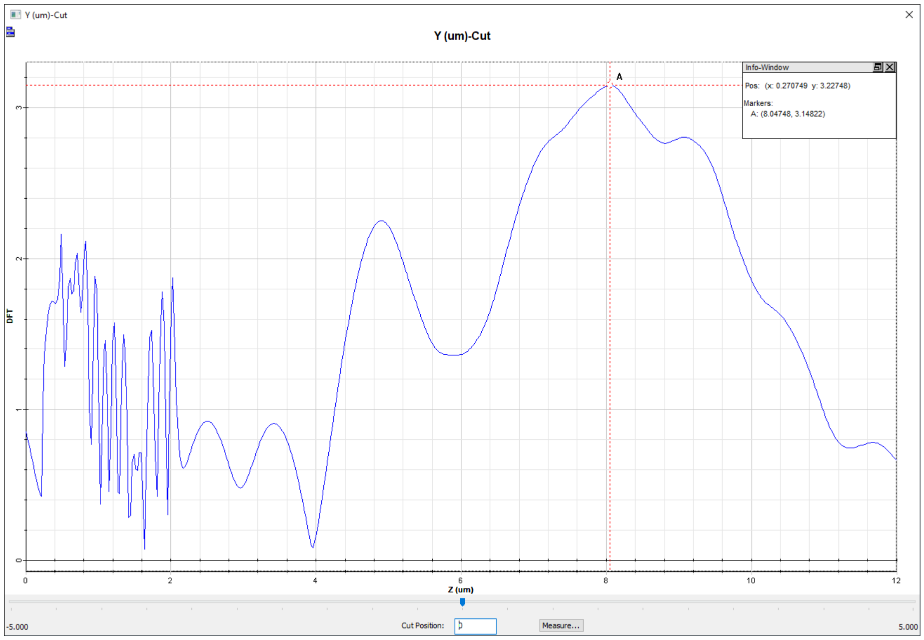

Figure 8: Figure 8: Z slice along the YZ observer of the Ey field for the dielectric slab.

References

1. M. Khorasaninejad, et. al. “Polarization-Insensitive Metalenses at Visible Wavelengths”. Nano Letters, 16 (11), 7229-34. (2016).
2. B. E. A. Saleh, M. C. Teich, “Propagation of Light in Free Space,” Fundamentals of Photonics, 2nd ed. Hoiboken, NJ, USA: Wiley-Interscience, 2007, pp. 110.