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Metalens wide-angle receiver for free space optical communications

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ABSTRACT

Receiver field of regard is one of the major problems for free space optical (FSO) communications. Drift or vibrations in transceiver orientations reduces effective communication time. The methods implemented to overcome this limitation, often require bulky optical and complex mechanical assemblies with feedback control, that are not suitable for long run operation in an airborne system. In this paper, we propose a novel receiver system that can effectively reduce the impact of pointing errors. The system is composed of two metalenses and one off-the-shelf conventional lens. The first metalens focuses optical beam incident at different angles on the aperture, at different locations on focal plane. The second metalens is placed on the focal plane of first metalens. After passing through the second metalens, the beams become parallel to optical axis of the receiver optical system. The parallel beams are collected by a suitable off-the-shelf aspheric lens and focused back on single detector that sits on a point on the optical axis. The system is designed and analyzed by physical optics theory. With 0.5 mm receiver aperture and 50 mm diameter aspheric lens, Zemax simulation shows that the system can collect +/-5-degree incident angle with detector diameter of 273μm. COMSOL frequency domain simulation with smaller diameter beam shows that the efficiency of the 2 metalens system is about 80%. Efficient metalens design and beam compression at detector plane are two key features of the proposed system. The system relaxes the strict requirement of aligning the transmitter and receiver unit in FSO communication.

Keywords: Metalens, free space optical communication, wide angle receiver

1. INTRODUCTION

Metalenses have emerged as a new technology to realize conventional lens function in small compact scale. In conventional lenses, glass surface is curved to change wavefront of incoming beam to realize focusing function. Instead, metalenses work on the principle of applying spatial phase on input beam using subwavelength scale scatterers, known as meta unit cell. Metalenses already have found application in imaging [1], spectroscopic [2] and AR/VR [3] system. But space application of metalenses has not been explored much in literature. In this paper, we showed an application of metalens in free space optical (FSO) communication. In FSO communication, the transmitter is far away from receiver and the transmitted optical beam suffers from diffraction power loss. To increase efficiency, receiver system implements lenses to compress and focus the received beam on detector. This system works perfectly when transmitter and receiver system are in line of sight (LOS). Even with a slight deviation from LOS, the beam hit receiver aperture at oblique incident angle and the focus gets shifted along the focal plane in transverse direction. As the detector size is typically in micrometer range, the receiver can only work for very small angle. This decreases effective communication time between transmitter and receiver. To overcome this problem, complex tracking algorithm is needed to keep the receiver always aligned with transmitter. Still, some short time vibration in receiver/ transmitter system can introduce jitter in the system [4]. Any system that can accept broad incident angle can eliminate partially or totally such problem. One such system is proposed in [5] that can work for broader range of incident angle. The system uses fluorescence that makes the system slow. Here we propose a receiver system that can capture broad incident angle while not compromising beam compressibility. Our system is simpler than the system presented in [5]. The system consists of two metalenses and one off the shelf aspheric lens. As a proof of concept, we presented a design that has an input aperture of 0.5 mm and can capture incident angle up to 5° with a detector area of 0.275 mm. Our proposed system is static and has no moving part, so free from mechanical wear. As the system can accept broad incident angle, it reduces burden on tracking algorithm. Once implemented, the system can reduce the strict alignment requirement in FSO communication.

The paper is organized as follows. In section II, we discuss the working principle of the proposed receiver system. In section III, the example design is presented with ray optics and physical optics propagation analysis. We discuss about the physical realization of the metalens in section IV. In section V, a full wave simulation is presented to show the efficiency of metalens in a much-simplified system.
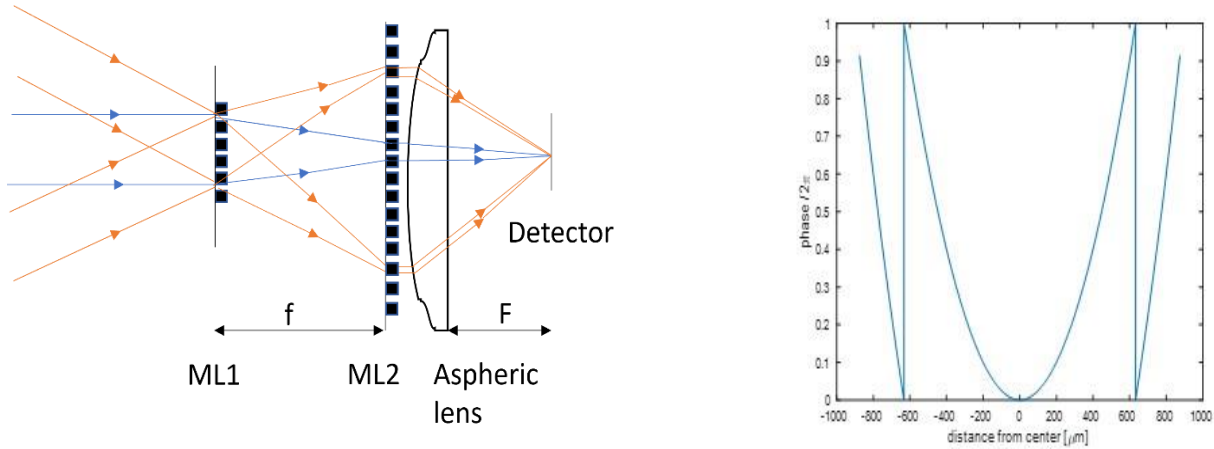
2. WORKING PRINCIPLE

Figure 1. (a) Proposed system architecture with normal (blue) and oblique (orange) incident beam (b) quadratic phase profile

A schematic of the proposed receiver system is presented in Fig. 1(a). Metalens 1 (ML1) and 2 (ML2) both implement quadratic phase profile (shown in Fig. 1(b)) with same focal length f. Metalens 1 acts as focusing lens. When there is oblique incident beam, quadratic phase profile ensures that the focused beam only have displacement in transverse plane [6]. So, a metalens with quadratic phase profile is expected to have zero field curvature error. It can also be shown by physical optics propagation. Electromagnetic beam propagation in free space is governed by Helmholtz equation.

$$\nabla^2 \vec{E} + n^2 k_0^2 \vec{E} = 0 \qquad [1]$$

With $\vec{E} \propto E_0 (x, y, z) e^{-jk_z z}$, under slow varying envelop approximation, the envelope E_0 satisfies paraxial wave equation

$$\left(\frac{\partial^2}{\partial x^2} + \frac{\partial^2}{\partial y^2}\right) E_0 (x, y, z) - 2i\, k_z \frac{\partial\ E_0(x,y,z)}{\partial z} + (n^2\, k_0^2 - k_z^2) E_0 (x, y, z) = 0 \qquad [2]$$

The solution of the paraxial wave equation can be written for small incident angle as

$$E_0 (x, y, z) \propto e^{-\frac{i\,k_0\,(x^2+\,y^2)}{2z}} \iint_{-\infty}^{\infty} E_0(x', y', z = 0)\ e^{-\frac{i\,k_0\,(x'^2+\,y'^2)}{2z}}\ e^{+\frac{2i\,k_0\,(xx'\ +yy'\ )}{2z}}\ dx'dy' \qquad [3]$$

When metalens introduces quadratic phase profile of the form $e^{\frac{ik_0(x^2+y^2)}{2f}}$, we get the output beam at focal plane z=f using equation (3).

$$E_0 (x, y, f) \propto e^{-\frac{i\,k_0\,(x^2+\,y^2)}{2f}}\ \widehat{E_0} \left(k_x = \frac{k_0\,x}{f}, k_y = \frac{k_0\,y}{f}\right) \qquad [4]$$

Where, $\widehat{E_0}\,(k_x, k_y)$ is the 2D fourier transform of beam at z=0 plane. When incident angle is small, similar calculation shows that the output beam at the focus of first metalens will be fourier transform of input beam, shifted along the transverse plane depending on incident angle.

$$E_0 (x, y, f) \propto\ e^{-\frac{i\,k_0\,(x^2+\,y^2)}{2f}}\ e^{-ik_0 f}\ \widehat{E_0} \left(k_x = \frac{k_0\,(x - f\sin(\theta_x))}{f}, k_y = \frac{k_0\,(x - f\sin(\theta_y))}{f}\right) \qquad [5]$$

Where, $\theta_{x,y}$ depends on the incident angle. The analysis shows that the focused beam has a quadratic spatial phase shift on the focal plane, which is the signature of a spherical wavefront. The phase shift is independent of the incident angle. Second metalens cancels this phase shift, and so the ouput beam leaving the second metalens will be parallel to optical axis. All the parallel beams hit the aspheric lens at different location on the surface. A well-designed aspheric lens would be able to focus back all the beam on same point on the system's optical axis. Due to imperfection in aspheric lens design, and improper realization of quadratic phase in metalens, the intercept of final focused beam on detector plane may deviate from optical axis. The system needs to be optimized to obtain the minimum beam size and minimum transverse displacement from optical axis at the detector.

3. DESIGN EXAMPLE

In our example design. The receiver optical axis is aligned along z axis. An input gaussian beam of width 500 μm is incident on metalens 1. Metalens 1 implements quadratic phase profile $e^{\frac{ik_0(x^2+y^2)}{2f}}$, with f=200mm. This metalens behaves like a hypothetical spherical lens with $r \to \infty$ and $n \to \infty$ [6]. As shown before on the z=f focal plane we will get the fourier transform of the input beam, in this case which is also a gaussian beam with beam width of 0.127 mm. For incident angle variation of $\pm 5^0$, the beam width at the focal plane is nearly remain same. But the focus will be displaced along the transverse of propagation direction. Based on the discussion presented before, the displacement along x and y axis can be calculated as $f\sin\theta_{x,y}$ where $\theta_{x,y}$ is direction angle of the incident beam along the respective transverse x and y axis. For a focal length of 200 mm, the deviation of the input beam along the focal plane will be large, about 17 mm. So, it is obvious that a detector typically of micron size on optical axis, would not be able to capture all the incident signals. Second metalens with same quadratic phase profile has been placed on the focal plane of first metalens. Transmitted beam from the second metalens became parallel to the optical axis. At very close proximity of second metalens an aspheric lens is placed to collect all the parallel beams and focus them back to optical axis. The curvature on aspheric lens surface determines the size of final focused beam.

The ray diagram of the system for 1^0 to 5^0 incident angles along y axis are obtained in Zemax and presented in Fig. [2]. The metalenses have been realized by Binary 2 surface feature of Zemax. Binary 2 surface with 0 thickness could introduce phase expressed as the coefficient of even order polynomial. We use a commercial off-the-shelf aspheric lens from Edmund Optics [7] to finally focus the beam on optical axis. The ray diagram shows that all the beams of different incident angles are focused back near the same point on optical axis. To calculate the detector size needed, we obtained the footprint diagram which is presented at fig. 3. Here we vary incident angle $\pm 5^0$ along both x and y direction. The footprint diagram shows that the detector diameter should be 0.271 mm to capture all the incident angles.

To calculate the beam size at the detector, we did further analysis on Zemax Physical Optics Propagation (POP). Fig.4 shows optical beam on the detector plane for 0° and 5° incident angles. The 2 key parameters we are looking here is the beam size and the chief ray intercept on the detector plane. Both data are available after the Zemax POP analysis. Table 1 summarizes these 2 results for different incident angles. From the analysis, to capture $\pm5°$ incident angle we need a detector of diameter (93.81+87/2) *2 μm = 273.4 μm, which is close what we get from footprint diagram.
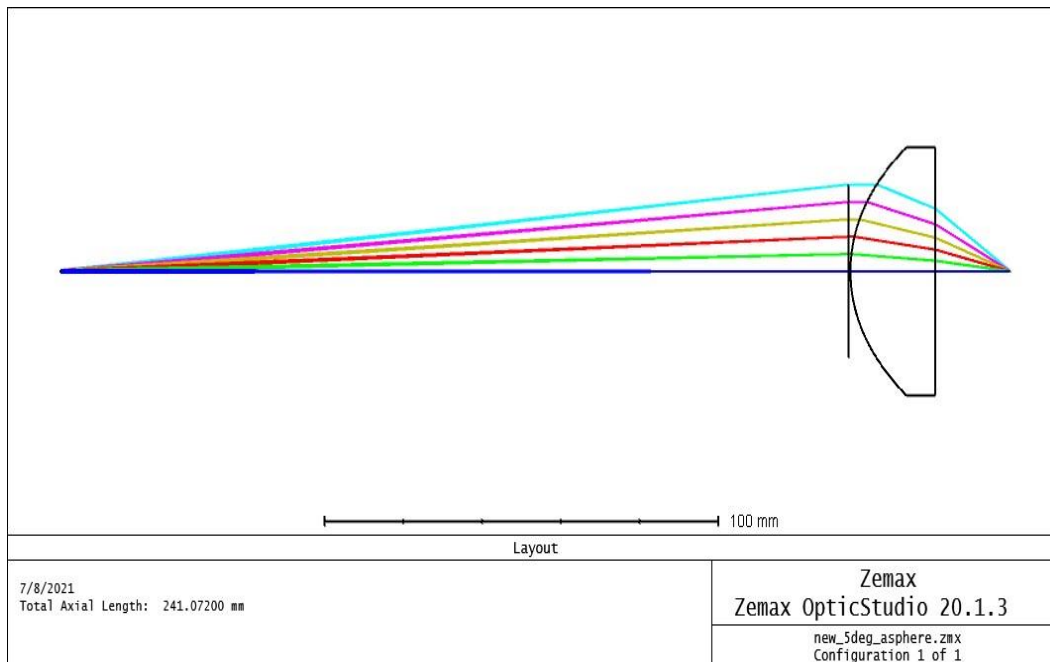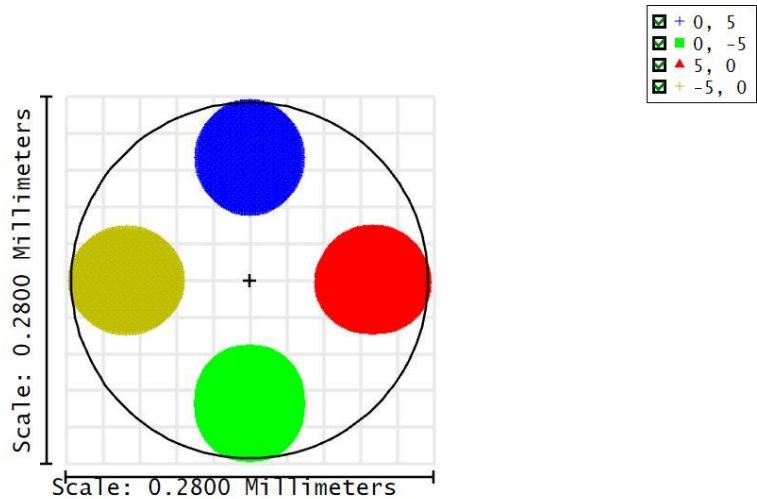

Figure 2. Ray diagram of the proposed system

Footprint Diagram

7/8/2021	Zemax
Surface 7:	Zemax OpticStudio 20.1.3
Ray X Min = −0.1357 Ray X Max = 0.1357	
Ray Y Min = −0.1357 Ray Y Max = 0.1357	new_5deg_asphere.zmx
Max Radius= 0.1357 Wavelength= 1.0000	Configuration 1 of 1
Legend items refer to Field positions	

Aperture Diameter: 0.2714   % rays through = 100.00%

Figure 3. Footprint diagram at the detector plane

4. METALENS DESIGN

A metalens is created by quasi-periodic arrangement of meta-unit cells. One or more parameters are varied from one meta-unit cell to other to realize the desired phase in the transmitted light. In this work, we designed a meta unit cell consists of a-Si cylindrical nanopillar with 450 nm height on glass (SiO$_2$) substrate of 200nm thickness (shown in Fig. 3(a)). Both the material has low losses at our target wavelength 1µm. Unit cell simulation is done in COMSOL with periodic boundary
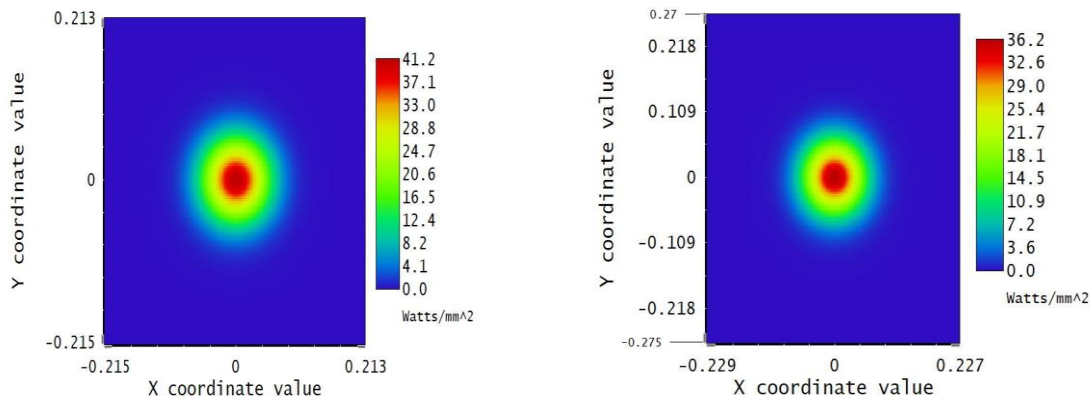
Total Irradiance surface 7	Total Irradiance surface 7
7/13/2021	7/13/2021
Beam wavelength is 1.00000 µm in the media with index 1.00000 at 0.0000 (deg)	Beam wavelength is 1.00000 µm in the media with index 1.00000 at 5.0000 (deg)
Display X Width = 4.2920E-01, Y Height = 4.2920E-01 Millimeters	Display X Width = 4.5791E-01, Y Height = 5.4534E-01 Millimeters
Peak Irradiance = 4.1206E+01 Watts/Millimeters^2, Total Power = 3.9270E-01 Watts	Peak Irradiance = 3.6240E+01 Watts/Millimeters^2, Total Power = 3.9270E-01 Watts
X Pilot: Size= 7.7890E-02, Waist= 6.6747E-02, Pos= +8.4184E+00, Rayleigh= 1.3996E+01	X Pilot: Size= 7.8809E-02, Waist= 7.1779E-02, Pos= +7.3370E+00, Rayleigh= 1.6186E+01
Y Pilot: Size= 7.7890E-02, Waist= 6.6747E-02, Pos= +8.4184E+00, Rayleigh= 1.3996E+01	Y Pilot: Size= 7.0322E-02, Waist= 6.7363E-02, Pos= +4.2717E+00, Rayleigh= 1.4256E+01
Beam Width X = 7.78909E-02, Y = 7.78909E-02 Millimeters	Beam Width X = 7.88093E-02, Y = 8.75317E-02 Millimeters

(a)   (b)

Figure 4. Output beam magnitude plot for 1^0 (a) and 5^0 (b) incident angle

Table 1. Physical Optics Propagation Analysis for different incident angles

Incident Angle	Beam Width at Detector [mm]	Chief Ray Intercept [μm]
0°	0.078	0
1°	0.078	0.39
2°	0.077	3.84
3°	0.076	11.84
4°	0.082	34.08
5°	0.087	93.81

condition in transverse plane. Due to high index contrast, the field is primarily concentrated inside the nanopillar, and it is assumed that the phase obtained with periodic simulation would not change much when nanopillar with different diameter is present nearby. The period of unit cell is fixed as 400nm. The diameter of the nanopillar is varied from 100 nm to 305 nm to realize full 2π phase shift. The magnitude and phase of the transmitted beam through the unit cell for different nano-pillar diameter is shown in Fig. 3(b). It shows that the transmission remains very high in this range of diameter, and we can realize full 2π phase shift. Also due to axial symmetry, the unit cell is polarization insensitive.
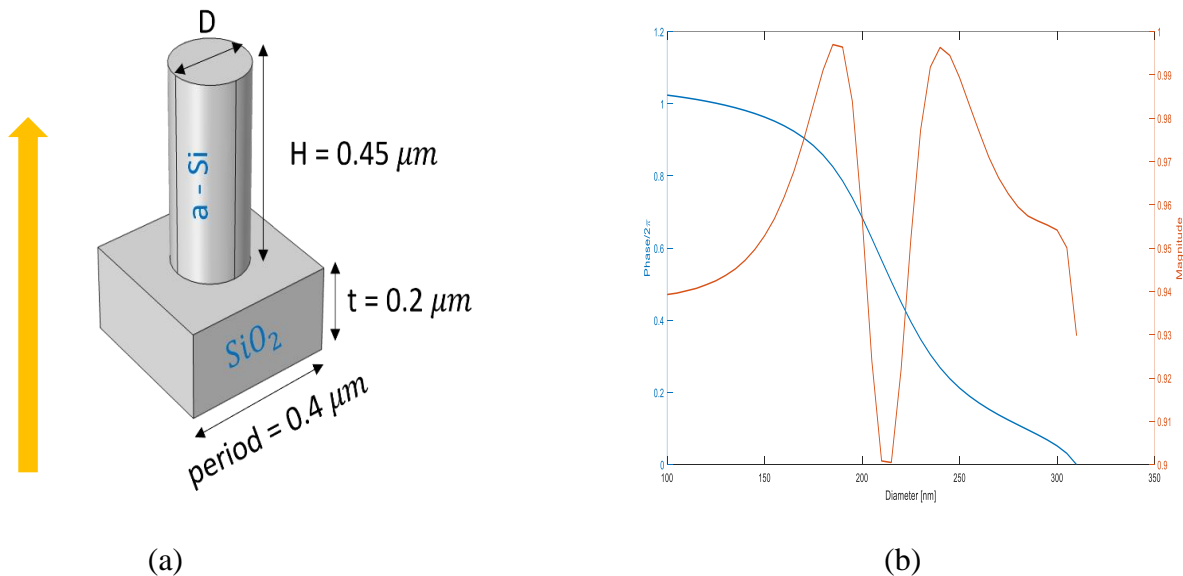

(a)

(b)

Figure 5. (a) Structure of meta unit cell with thick arrow showing input beam direction (b) Phase and magnitude of transmitted signal through metalens

5. FULL WAVE SIMULATION OF METALENSES

Simulation of metalens with mm size aperture and focal length is very difficult. To get an idea about the efficiency of our metalens system, here we tried to do full wave simulation of a simplified system. For simplification, we reduced the beam size to 25μm and the focal length to 1.5 mm. We only considered TE polarization. We simulated a cylindrical system, where the source and lens system were periodic in y direction with floquet wavenumber 0. We changed the incident angle

with the x direction, where 0^0 incident angle means 0^0 with z axis and 90^0 with positive x axis. We separated the simulation in three parts. First, we simulated a small region surrounding the metalens 1 (ML1) with the input gaussian source using COMSOL frequency domain simulation. By tilting the input source plane, we can change the incident angle of the beam on metalens 1. We chose a cut plane in front of ML1 and used the field on that plane as a source to propagate it to the focal length of the lens. We used here Beam Envelop Method for free space propagation, which is fast and well suitable here as we do not expect any reflection in this part of simulation. Finally, we excited the field in a small region around the focal plane of first metalens, placed the second metalens (ML2) and did full wave simulation to obtain the output beam. The output beam got nearly parallel to optical axis of the system, z axis in our simulation. The granularity in final beam is because of discretization of continuous phase and effect of finite size simulation region. Finally, we calculated the efficiency of our system just before the aspheric lens. The calculated efficiency is 80% for 5° incident angle.
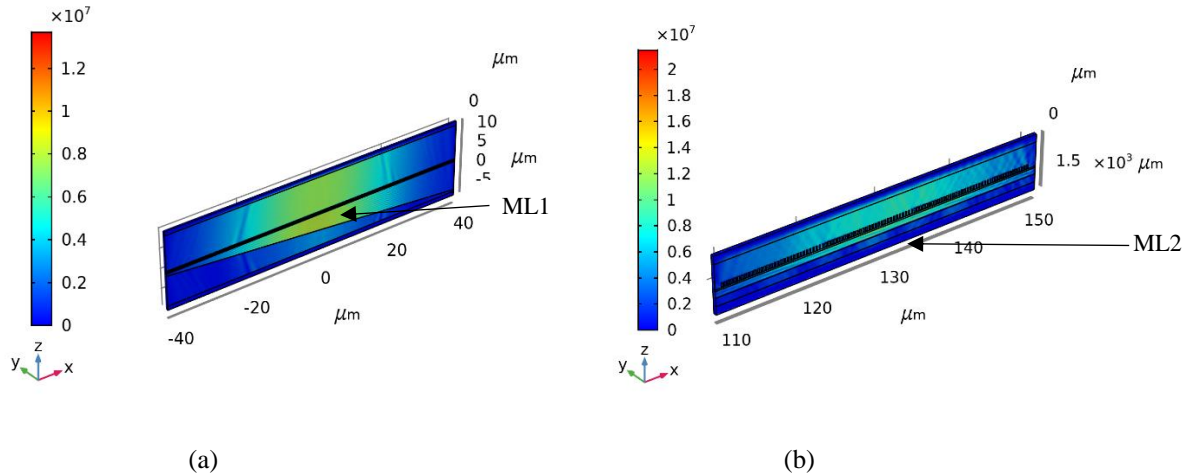

(a)   (b)

Figure 6. Magnitude of electric field near metalens 1 (a) and near metalens 2 (b) for 5° incident angle

6. CONCLUSION

In the paper, we reported a receiver system that can capture broad incident angle while maintaining good beam compressibility. We presented both system level and full wave simulation to show the function and efficiency of the system. Although, presented with gaussian beam input, the system can be easily extended to include rectangular plane wave incidence. By optimizing the phase profile of metalenses and surface profile for aspheric lens, one can determine the best operating condition of the system. Optimization is needed specially for increasing the incident angle and reducing the receiver longitudinal size. Another possible direction for future research is to adapt the system to use with conventional telescope system (Galilean / Keplarian) of FSO communication.

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