A Broadband Polarization-Insensitive Diffractive Lens Design for Subwavelength Focusing of Light

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ABSTRACT
In this study, we propose the metaheuristic design of a polarization-insensitive diffractive lens. The designed lens structure consists of concentric dielectric rings with optimally modulated widths and heights. Here, the evolutionary optimization approach is conducted to find the optimum values of concentric rings' widths and heights to obtain polarization-insensitive subwavelength focusing effect of the incident light. Three-dimensional finite-difference time-domain (3D FDTD) method is incorporated with the optimization algorithm to evaluate the focusing ability of instantly designed lens structures throughout the optimization process. The presented lens structure is designed at operating frequency of 10 GHz, and has a diameter of 18.45 cm with thickness of 2.4 cm. The detailed analysis of the polarization-insensitive focusing effect of designed diffractive flat lens is numerically investigated at microwave frequency regime considering the scenario of experimental verification to be conducted at the same spectral region. Possible experimental verifications are discussed along with the 3D-printing of the designed lens structure. As a further step, the presented design concept may be applied to design metasurfaces operating at visible wavelengths.
Keywords: diffractive lens, polarization-insensitive, subwavelength focusing, optimization, microwaves.

1. INTRODUCTION

Optical lenses are playing an important role in light-enabled technologies. The focusing effect of the bulky refractive lenses has been perfected by introducing diffractive flat lenses where the main concept is using diffraction phenomena of light [1]. In such diffractive flat lenses incident light focused by spatially tuning of the concentric rings called "zones". By adjusting those zones incident light undergoes sequential phase change (phase correction) which enables focusing effect by means of constructive interference at the back focal plane of the lens. To improve focusing effect of diffractive lenses the concepts of multilevel gratings and step-like cross sections were developed [2]. Moreover, to obtain efficient and strong focusing effect physical dimensions of each zones can be adjusted by tuning their heights [3] or both different heights and widths [4]. Further, in order to increase the efficiency and to reduce the intrinsic losses, dielectric materials are utilized in the fabrication process of a diffractive lens instead of plasmonic metasurfaces [5].

Due to the light matter interaction, transverse-electric (TE) and transverse magnetic (TM) polarizations are affected differently which makes polarization-insensitive lenses valuable. There exist several approaches to design an all-dielectric polarization-insensitive which involve annular photonic crystal (PC) flat lens [6] and metalens composed of cylindrical nanopillars [7]. Also, it is possible to observe polarization insensitivity in broadband applications via nanostructures [8]. In addition, metasurfaces provide polarization insensitive focusing in visible wavelengths [9].

Moreover, optimization algorithms lead to the design of PCs and metasurfaces for focusing applications [10-11]. In recent years, the so-called inverse design techniques have gathered great amount of interest due to enabling highly efficient photonic devices [12, 13]. Lately, machine learning and artificial neural networks find a place for themselves as design approaches in photonics. A reinforcement learning algorithm is introduced to obtain strong light confinement [14]. In addition, artificial neural networks are applied to inversely design metasurfaces [15].

In this study, we introduce a polarization insensitive diffractive lens which is capable of focusing TE and TM polarizations with equal focal distance. The heights and widths of zones are determined via optimization algorithm to obtain focusing effect. The designed lens has diameter of 18.45 cm and height of 2.4 cm, and made of dielectric polylactic acid (PLA) material with refractive index value of 1.555. The selected thermoplastic PLA material is commercially available for 3D-printing fabrication of structures which enables the possible experimental verification of the designed lens at microwave wavelengths in the future [16]. Corresponding microwave experiments will be shared in the conference.

2. DESIGN APPROACH AND NUMERICAL RESULTS

The conventional bulky refractive lenses are expensive and have large dimensions and curved surfaces. In recent years, diffractive planar components including metasurfaces lead to small sizes with enhanced performance for optical systems. The geometrical arrangement of diffractive components provides us to obtain desired intensity or phase distributions [17]. To take it one step further, we applied the DE algorithm to design an all-dielectric polarization-insensitive diffractive lens which composed of PLA material (thermoplastic PLA material is considered in order to realize microwave experiments) [18]. For this purpose, we integrated the FDTD method [19] into the optimization algorithm and optimized the structural parameters of a diffractive lens to focus both TE and TM polarized light into same focal point with decreased full width at half maximum (FWHM) and suppressed maximum sidelobe levels (MSL) values.

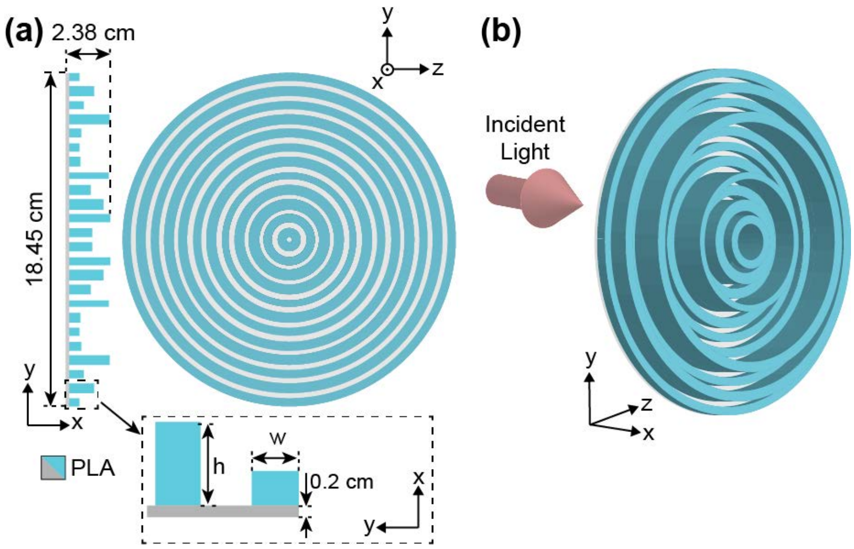

Figure 1: (a) Top and (b) perspective views of diffractive lens with structural parameters, respectively. The important dimensions are included ass inset in (a).

The designed lens structure consisting dielectric rings/zones is constructed on a thin PLA substrate as shown in in Fig. 1(a). The refractive index of PLA material is fixed to 1.555 in FDTD simulations. DE algorithm determined the heights (*h*) and widths (*w*) of concentric rings where the thickness of substrate is fixed to 0.2 cm. As a result of optimization process, the lateral and longitudinal sizes of diffractive lens are emerged as 18.45 cm and 2.38 cm, respectively. In Fig. 1(b), perspective view of the lens is depicted with the light excitation schematic. We should emphasize that the proposed lens structure is designed at the microwave frequency of 10 GHz for both TE and TM polarization modes.

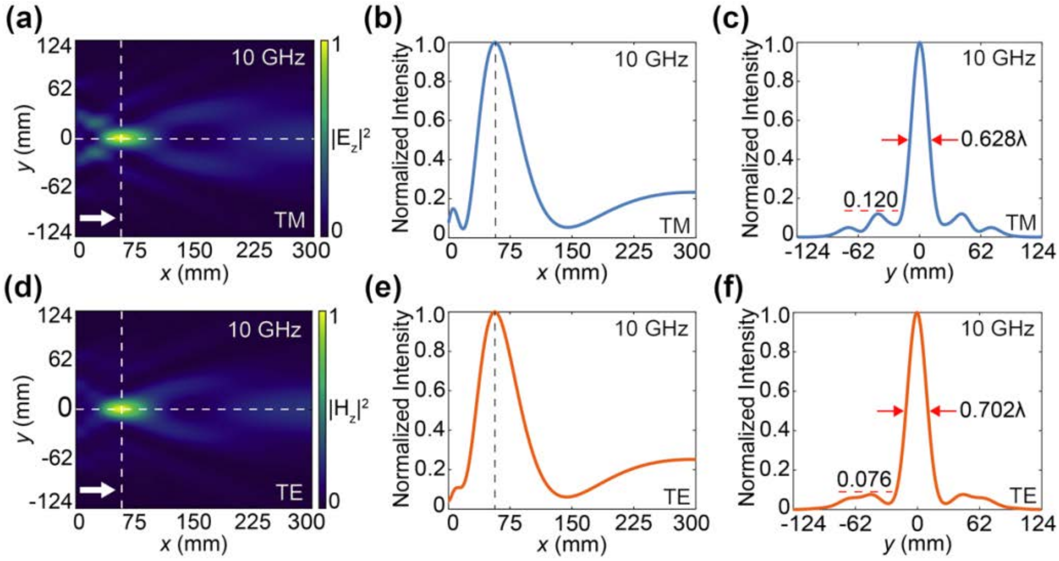

Figure 2: (a) The calculated electric field intensity ($|E_z|^2$) distribution at frequency of 10 GHz with its corresponding (b) normalized longitudinal cross-sectional profile on optical axis and (c) normalized lateral cross-sectional profile at focal point; (d) The calculated magnetic field intensity ($|H_z|^2$) distribution at frequency of 10 GHz with its corresponding (e) normalized longitudinal cross-sectional profile on optical axis and (f) normalized lateral cross-sectional profile at focal point. The horizontal and vertical dashed lines in (a) and (b) indicates the positions of longitudinal and lateral cross-sections, respectively, and intersect at the focal points. The arrows show the propagation direction of incident light. The vertical dashed lines in (b) and (e) denote the focal distances. The calculated FWHM and MSL values are superimposed in (c) and (f).

The calculated electric field intensity distribution at frequency of 10 GHz is presented in Fig. 2(a) for TM polarization. The longitudinal cross-sectional electric field intensity profile on optical axis is plotted in Fig. 2(b) where the focal point is emerged at a distance of 57.12 mm away from the lens structure. In Fig. 2(c), the lateral cross-sectional electric field profile is given in which the FWHM and MSL values are calculated as 0.628λ and 0.120, respectively, where the λ denotes the wavelength of incident light. Similarly, for the TE polarization, Fig. 2(d) shows the calculated magnetic field intensity distribution at the same frequency of 10 GHz. The distance between the focal point and the lens structure is appeared as 57.12 mm which can be seen from the longitudinal cross-sectional magnetic field intensity profile given in Fig. 2(e). In Fig. 2(f), lateral cross-sectional magnetic field profile at the focal point is plotted. The FWHM value is calculated as 0.702λ where the suppressed MSL value is equal to 0.076. It should be noted that the focal distances emerged as the same for both polarizations.

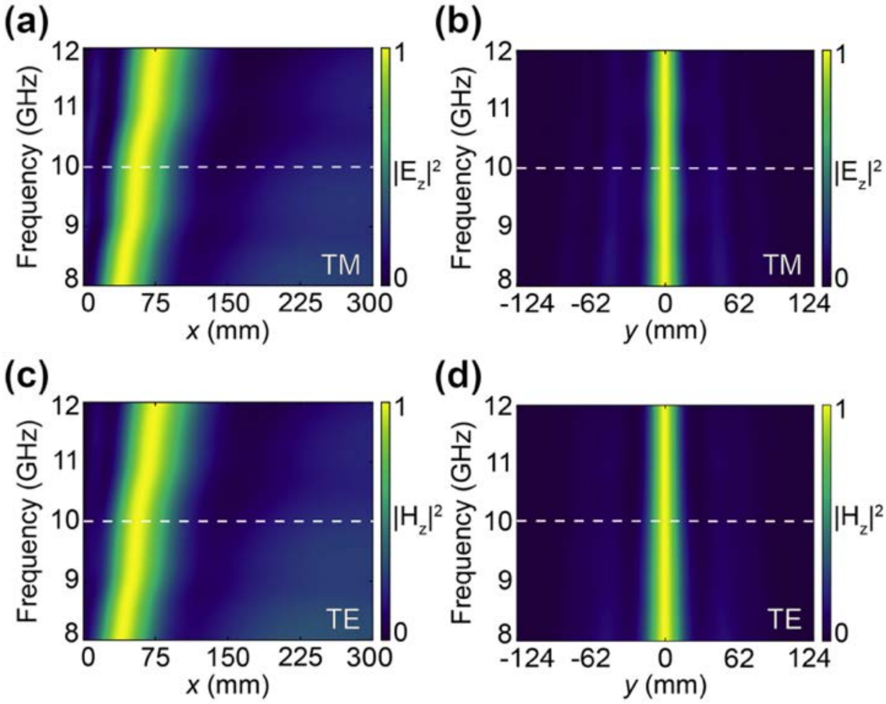

Figure 3. The maps of cross-sectional intensity profile in longitudinal direction on optical axis for (a) TM and (c) TE polarizations at the selected frequency regime. The maps lateral cross-sectional intensity profiles at focal points for (b) TM and (d) TE polarizations of frequencies from the interval. The dashed lines indicate the design frequency of 10 GHz.

To evaluate the polarization-insensitive focusing of the proposed diffractive lens, we performed FDTD simulations for both polarizations in a frequency regime between 8 GHz – 12 GHz. The cross-sectional electric field intensity profiles in longitudinal direction on optical axis and lateral direction at focal point are given as maps in Figs. 3(a) and 3(b), respectively. In addition, the similar maps of cross-sectional magnetic field intensity profiles are extracted for the TE polarization and are given in Figs. 3(c) and 3(d) for longitudinal on-axis and lateral focal point directions, respectively. As can be seen from the maps of longitudinal cross-sectional intensity profiles, the focal distances slightly, but in the same manner, vary in the frequency interval of interest for both polarizations. The maps of calculated cross-sectional intensity profiles at focal points indicate that the designed diffractive lens has the broadband focusing ability.

3. CONCLUSION

Concluding, we present a diffractive lens with the ability of polarization-insensitive focusing at microwave frequencies. For this purpose, we applied DE algorithm to adjust the geometrical parameters of the lens structure and performed 3D FDTD simulations. The designed lens structure consists of dielectric PLA zone plates on a thin substrate, and can be fabricated by 3D-printing technology. Thus, microwave experiments can be performed to demonstrate the polarization-insensitivity focusing ability of the lens structure in the future. The detailed numerical investigation of polarization-insensitive focusing effect is presented for the microwave frequency regime of 8 GHz – 12 GHz. We believe that the proposed optimization assisted design approach can also be useful to design metalenses for applications at visible wavelengths.

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