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ABSTRACT
The refractive index of the immersion medium has a significant influence on the shape of the focal spot in the field of diffraction optics. For a refractive index of the immersion medium that varies from the designed one, the change in the focal properties of the diffractive optical elements needs to be verified. By combining the vectorial angular spectrum (VAS) theory with a genetic algorithm, multiannular nanostructured metasurfaces with super-resolution focusing abilities were designed with a linearly polarized beam in an oil immersion medium. The intensity distribution of the focusing field was calculated via the finite-difference time-domain, and the results agreed well with calculations using the VAS theory. The results of the theoretical calculations demonstrated an obvious shift of the focal spot and change in the spot size as the refractive index varied. The calculations showed that the refractive index had an impact on the focal properties of multiannular metasurfaces. This work provides theoretical guidance for super-resolution focusing and imaging.

I. INTRODUCTION

Breaking the Abbe diffraction limit is an important topic of research, and various methods and devices, such as near-field scanning optical microscopy,1 superlenses,2 plasmonic lenses,3 negative refractive index materials,4 nanoscale microspheres,5 and diffractive optical elements,6–11 have been used to realize this goal. The multiannular metasurface (MAM) is a new type of diffractive optical element. It was first proposed in 201210 and has been used to realize super-resolution focusing.11–17 To date, super-resolution optical needles15–17 and multifocus18 and single-focus optics19 have been reported. The focal principle of MAMs is based on destructive and constructive interference, which differs from traditional optical lenses.

Previous work has studied the influence of deviation of the illumination wavelength on the properties of the on-axis intensity distributions.7 The refractive index of the immersion medium has a significant influence on the focusing properties of the diffractive optical elements. However, the relationship between the two deviations of the refractive index from the designed value is not clear, which restricts the practical application of MAMs. In this work, by combining the vectorial angular spectrum (VAS) theory and a genetic algorithm (GA), a vectorial design theory for MAMs with super-resolution is introduced.11,21 The theoretical calculation results were rigorously tested via the 3D finite-difference time-domain (FDTD) method, and the two results were in good agreement.

II. DESIGN THEORY AND RESULTS

The VAS theory can be used to precisely describe the propagation of a polarized beam. For an MAM, if the electric field behind the MAM is known, the light intensity can be calculated based on the VAS theory. A schematic diagram of the focusing model of an MAM is shown in Fig. 1.21 For a vector beam, the focusing intensity $|E|^2$ of the MAM is composed of three components: $|E|^2$, $|E|^2$, $|E|^2$. 

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and $|E|^2$. For a linearly polarized beam (LPB) in the x-polarized direction, $|E_y|^2$ is equal to 0. Therefore, the components of the total light intensity $|E|^2$ in the observation plane ($z > 0$) are composed of $|E_x|^2$ and $|E_z|^2$ and can be calculated by $I = |E|^2 = |E_x|^2 + |E_z|^2$, where $I$ is the light intensity.

Based on the GA, a single objective optimization model was established to solve the optimization problem, which characterized the features of the designed main focal spot produced by the MAM. The optimization model is written by

$$\begin{align*}
\text{Minimize} & \quad I(d_0/2, z; T) \\
\text{subject to} & \quad \frac{I(r, z; T)}{I(0, z; T)} \leq 0.3, \quad d_0 \leq r \leq \kappa d_0,
\quad T = [t_1, t_2, t_3, \ldots, t_N] \in \{0, 1\},
\quad \text{NA}_{\min} \leq \sin^{-1}\left(\tan^{-1}\left(\frac{D/2}{z}\right)\right) \leq \text{NA}_{\max},
\end{align*}$$

where $z$ denotes the axial position of the focusing field; $d_0$ restraints the full-width at half-maximum (FWHM) of the main focal spot, and the FWHM is used to characterize the size of the focal spot; $r$ is the radial position; $\kappa$ is a given coefficient; $(\kappa - 1)d_0$ is the radial width of the dark region between the central main lobe and large surrounding side lobes of the main focal spot; the normalized maximum intensity is constrained to be less than 30% of the peak intensity of the central lobe; $N$ is the total ring number of the MAM; $D$ denotes the diameter of the MAM; $\text{NA}$ is the equivalent numerical aperture; and the optimal distance of the main focal spot is constrained between $\text{NA}_{\min}$ and $\text{NA}_{\max}$.

An optimization process was implemented by combining VAS theory with GA, and an MAM with super-resolution focusing ability was designed with a linearly polarized beam (LPB) in an oil immersion medium.
immersion medium ($n = 1.515$). The illumination wavelength was 640 nm. The number of concentric rings with an equidistant annulus width of 200 nm was set to be 35 and the diameter of the MAMs was 14 μm. The MAMs were coded with binary digits {0, 1}, where “0” and “1” denote an opaque annulus and a transparent annulus, respectively. The results of the optimized calculation show that the code of the MAM is 1011110011000110110110101110.

III. RESULTS AND DISCUSSIONS

A. Applicability of the VAS theory

To verify the applicability of the VAS theory, the 3D FDTD method was employed based on the optimized calculation results. The total-field scattered-field boundary and perfectly matched layer absorbing boundary were applied in the FDTD simulation. The MAM was placed in oil ($n = 1.515$). The covered Au film thickness was 100 nm. The 3D simulation area was set to be $x, y$ in the range $-2$ to $2$ μm, and $z$ with $0–7.8$ μm. The mesh size was 15 nm × 15 nm × 10 nm ($x, y, z$).

The intensity distributions in the $x$-$z$ and $y$-$z$ plane were calculated using the VAS theory [Figs. 2(a) and 2(b)] and FDTD method [Figs. 2(c) and 2(d)] and then compared. It can be seen that the intensity distributions agreed fairly well with each other. To further verify the above results, the intensity distributions on the $z$-axis and in the focal plane need to be compared.

The intensity distribution on the $z$-axis was extracted along the middle of Figs. 2(a) and 2(c), as shown in Fig. 3. The curves in Fig. 3(a) were normalized by the peak intensities, as shown in Fig. 3(b). Using VAS theory and the FDTD method, the calculated results for the focal lengths were 4.03 μm and 4.06 μm, the peak intensities of the main focal spot were 66.26 and 63.88, and the FWHM along the $z$-axis were 0.821 μm and 0.93 μm, respectively. The shape of the main focal spots was similar. Furthermore, there were also slight differences in the axial ranges of 1.5–3.2 μm and 5.1–7.8 μm. It can be concluded that VAS theory can be used to predict the $z$-axis intensity distribution for the designed MAMs.

The intensity distribution in the focal plane calculated via the VAS theory at $z = 4.03$ μm [Fig. 4(a)] and the FDTD method at $z = 4.06$ μm [Fig. 4(b)] were also compared. The sizes along the $x$- and $y$-direction were obtained, as shown in Fig. 4(c). It can be seen that the distribution was wider along the $x$-direction than along the $y$-direction. The main focal spot had an elliptical shape, and this can be attributed to the influence of the $z$-polarized ($|E_z|^2$), as shown by the solid black and dashed black lines in Fig. 4(c).

FIG. 5. Comparison of the sizes of the main focal spot along the $x$- and $y$-direction with a varying refractive index.
FWHM\textsubscript{x} and FWHM\textsubscript{y} calculated by VAS theory were 341.8 nm and 260.8 nm, respectively. With the FDTD method, the FWHM\textsubscript{x} and FWHM\textsubscript{y} were 323 nm and 254 nm, respectively. The results show that the differences between the results of VAS theory and the FDTD method were fairly small. This demonstrated that VAS theory can be effectively employed to predict the intensity distribution in the focal plane.

According to the comparison between the VAS theory and FDTD calculation results, we can see that VAS theory can be used to predict the light intensity distribution of an MAM in an oil-based immersion medium on LPB illumination.

### B. Influence variation of immersion medium

The refractive index of the immersion medium may deviate from the intended one in practical application. Therefore, VAS theory was employed to analyze the influence of a change in the refractive index on the properties of the main focal spot. For the MAM sample, the designed refractive index was 1.515, and it had a single main focal spot in the region of 0–7.8 \( \mu \)m. Using VAS theory, the size of the main focal spot was determined to be 341.8 nm (0.534\( \lambda \)) and 260.8 nm (0.408\( \lambda \)) along the x- and y-direction, respectively. It was found that along the y-direction, super-resolution could be realized.
The reason for this is that an LPB was used, and the size of the focal spot along the x-direction was bigger than that along the y-direction. Therefore, the main focal spot was not circularly symmetric. Furthermore, based on VAS theory, the sizes of the main focal spot along the x- and y-direction were calculated with a refractive index ranging from 1.245 to 1.785 in increments of 0.03. The sizes along the x- and y-direction were termed FWHM<sub>x</sub> and FWHM<sub>y</sub>, respectively. For the x-direction shown in Fig. 5, a negative general trend can be observed, and the curve was fitted with the formula s = 0.2n<sup>2</sup> – 0.8n + 1.1, where s is the size of the focal spot, and n is the refractive index. For the y-direction, the trend was also negative. It can be observed that a higher refractive index is beneficial for reducing the size of the main focal spot. A larger refractive index sharpens the main focal spot.

The focal length and the peak intensity of the main focal spot were also compared with the refractive index ranging from 1.245 to 1.785 with increments of 0.03 using the LPB. The results in Fig. 6(a) show that the focal length had a good linear relationship with the refractive index. The peak intensity first increased and then declined as the refractive index increased, as shown in Fig. 6(b). It can be concluded that the intensity of the secondary focal spot increased as the refractive index increased, while the total intensity remained constant.

To study the influence of the refractive index on the z-axis intensity distribution, the theoretical calculation results were compared for refractive indexes in the range of 1.245–1.785 in increments of 0.09 using the LPB. The z-axis intensity distributions calculated by VAS theory are plotted in Fig. 7. All the curves in Figs. 7(a) and 7(c) were normalized by their respective peak intensities and are shown in Figs. 7(b) and 7(d), respectively. The black lines correspond to the results obtained with the designed refractive index. As shown in Figs. 7(a) and 7(b), when the refractive index was smaller (n < 1.515) than the designed refractive index, the z-axis intensity distributions were similar but with an equidistant focal shift. The z-axis intensity distribution retained a similar shape to a refractive index of 1.245, but had a negative shift, as shown in Figs. 7(a) and 7(b). An increase in the refractive index above the designed value (n > 1.515) had a more severe influence than for a refractive index below 1.515, as shown in Figs. 7(c) and 7(d). The intensity ratios between the main focal spot and the secondary focal spot were 0.2045, 0.3627, 0.5338, and 0.6884 corresponding to a refractive index of 1.515, 1.605, 1.695, and 1.785, respectively. This demonstrated that the z-axis intensity distribution was significantly influenced by an increase in the refractive index. An equidistant focal shift, similar to when the refractive index decreased below the designed value, was also observed.

It can be concluded that the position of the main focal spot will generally shift along the positive z-direction as the refractive index increases. The z-axis intensity distributions retained its shape when the practical refractive index was smaller than the designed refractive index. A deviation above the designed refractive index had a larger influence on the z-axis intensity distribution as well as the shape of the main focal spot along the z-axis.

IV. CONCLUSIONS

The influence of the refractive index on the focal properties of an MAM was studied on deviation from the designed refractive index. By combining VAS theory with the GA, an MAM with super-resolution focusing ability was designed with LPB illumination in an oil immersion medium. The focusing field calculated by VAS theory was validated by rigorous electromagnetic testing using the FDTD method. The theoretical calculation results showed that an obvious focal shift occurred, and the focal length increased approximately linearly with the refractive index in the range of 1.245–1.785. The size of the focal spot demonstrated a negative trend with an increasing refractive index. Deviation above the designed refractive index had a more significant influence than deviation below the intended value. The refractive index was determined to have an impact on the focal properties of the MAM. Therefore, the MAM performance on deviation from the designed refractive index needs to be verified for practical applications. The results provide theoretical guidance for super-resolution focusing and imaging.

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