1. Introduction

Optical zoom lenses have wide applications in cameras, mobile phones, augmented reality, and microscopy. Most traditional zoom systems rely on varying the axial distance between two or more ordinary refractive lenses to change the effective focal length,[1] making such systems complex and large. Many alternatives have been discussed. This includes Alvarez lens systems based on lateral displacements of two refractive free-form surfaces,[2,3] liquid-crystal-based devices,[4–9] and deformable lenses based on liquids[10–13] or other elastic constituents.[14]

Tunable metasurfaces,[15–19] with the ability to control the wave front dynamically under a subwavelength scale, enables ultrathin adjustable devices. The tunability of metasurface-based lenses or “metalenses”[20–29] has been discussed as well. Examples are metalenses on elastic substrates,[30–32] Alvarez metasystems,[33–35] and tuning of the metalens focal length by stimuli such as temperature[36,37] or static electric fields combined with dielectric elastomer actuators[38] or microelectromechanical systems.[39,40]

More recently, the concept of rotary metalens zoom doublets[41–44] based on Moiré lens concept[45–47] has been introduced. Here, the focal length can be varied by changing the relative angle between the two metasurfaces while fixing their distance. Compared to conventional or multilevel diffractive Moiré lenses, flat metasurfaces subwavelength lattices[48] allow denser sampling of the phase profile, resulting in a higher diffraction efficiency. This compact, simple, and robust design—which has no counterpart for ordinary refractive lenses—has been discussed theoretically.[41–43] Early experiments at microwave frequencies have demonstrated the validity of the concept, albeit in a polarization-dependent manner.[44] The novelty of the present paper lies in presenting an improved polarization-insensitive theoretical design, and in providing corresponding experimental focusing characterizations as well as imaging demonstrations at telecommunication wavelengths, with a zoom varying by as much as a factor of 18.

2. Designs and Principles

The operation principle of the metalens doublet is illustrated in Figure 1a. In order to establish the relationship between focal length and relative angle between the two metasurfaces, we construct an output wave front from the doublet that depends on the angle. We choose the phase profile of a spherical defocusing lens, which results in smaller phase errors than that of a focusing lens (see Section S1, Supporting Information). For the two metasurfaces in the doublet, we choose the two phase profiles (see Section S2, Supporting Information, for details of derivation)

\[
\varphi_1(r, \theta_0) = \text{round} \left[ \frac{1}{\lambda F_0} r^2 \right] \left( \theta_0 + C(r) \right)
\]

(1)
and

$$\varphi_0 (r, \theta_0) = -\text{round}\left[\frac{1}{\lambda F_0} r^2 \right] \left( \theta_0 + C(r) \right)$$  \hspace{1cm} (2)$$

Here, $r$ and $\theta_0$ are the radial coordinates, $\lambda$ is the operating wavelength in free space, and $F_0$ is a reference focal length. The function round[…] replaces its argument by the nearest integer. Thereby, this function ensures that the phase shift varies by an integer multiple of $2\pi$ when increasing $\theta_0$ from 0 to $2\pi$. Deviations from this behavior would result in discontinuities around $\theta_0 = 2\pi$, causing unwanted phase errors of the doublet. The function $C(r)$ is zero for all $r$ for the ideal case of zero axial distance between the two metasurfaces. A nonzero choice of this function serves to compensate distortions of the focal spot that arise from the finite distance. We have optimized this function to $C(r) = \frac{\pi}{r} \text{round}\left[\frac{r^2 \pi}{4R} \right]$. A comparison to the case of $C(r) = 0$ is given in Section S3 (Supporting Information).

Combining the two metasurfaces and neglecting the finite distance between them (the influence of the distance is discussed in Section S4, Supporting Information), the phase profile of the doublet is given by

$$\varphi (r, \theta) = \varphi_0 (r, \theta_0) + \varphi_1 (r, \theta_0 + \theta) = -\text{round}\left[\frac{1}{\lambda F_0} r^2 \right] \left( \theta + \frac{\pi}{r} \text{round}\left[\frac{r^2 \pi}{4R} \right] \right)$$  \hspace{1cm} (3)$$

For reference, the phase profile of a spherical lens with focal length $F$ is given by $\varphi_0 (r) = -\left(\frac{r^2}{2F}\right) \pi$. Comparing $\varphi (r, \theta)$ and $\varphi_0 (r)$, we find that $\varphi (r, \theta)$, which is shown in Figure 1b, is a quantized version of $\varphi_0 (r)$. Moreover, the focal length of the doublet becomes a function of the rotation angle $\theta$ according to

$$F (\theta) = \frac{\pi}{\theta} F_0$$  \hspace{1cm} (4)$$
We define the ratio $k = \frac{\pi}{\theta}$ as the zoom power of the doublet. The mentioned quantization leads to a decrease of the diffraction efficiency. Following the theory of multilevel diffractive lenses,[49] the diffraction efficiency is given by $\eta = (\text{sinc}(1/n))^2$, where $n = 2\pi/\theta$ is the number of quantized levels. For example, we obtain $\eta = 40.5\%$ and $k = 1$ for $\theta = \pi$, $\eta = 81.1\%$ and $k = 2$ for $\theta = \pi/2$, and $\eta = 95.0\%$ and $k = 4$ for $\theta = \pi/4$. Clearly, the diffraction efficiency increases with increasing $F \propto 1/\theta$.

We target a free-space operation wavelength of the metalens zoom doublet of $\lambda = 1550$ nm. To achieve the above phase profiles in this wavelength regime, we consider metasurfaces composed of silicon (Si) nanocylinders, with cylinder radius $R$ and height $H$, arranged on a square lattice with period $P$ on a silica (SiO$_2$) substrate as shown in Figure 2a. The cylindrical geometry of the Si nanopillars combined with the square array ensures insensitivity with respect to the polarization of the incident light.

The material combination Si and SiO$_2$ provides high refractive index contrast and high optical transmission at the same time. The resulting optical response has been calculated and optimized by using a finite-difference time-domain (FDTD) approach. Because the two metasurfaces in the doublet are placed face to face, light impinges from the bottom of the first metasurface and from the top of the second metasurface. As diffraction of light is involved, the corresponding optical transmissions are not necessarily identical. Therefore, we investigate both propagation directions. Our optimization of the parameters $R$, $H$, and $P$ follows two rules. First, we optimize the three parameters to obtain high transmittance for both propagation directions and full phase control. Second, the response of the nanocylinders should depend only weakly on the angle of incidence, as oblique incidence plays a role in most practical circumstances. We arrive at $P = 600$ nm and $H = 700$ nm at $\lambda = 1550$ nm.

Figure 2. Design of the silicon nanocylinders. a) Calculated phase shift and transmittance of a square array of nanocylinders with varying radius $R$, fixed height $H = 700$ nm, fixed lattice constant $P = 600$ nm, for linearly polarized incident light, and for normal incidence with respect to the silica substrate plane. Results are shown for light impinging from the bottom (solid curve) and the top (dashed curve) with respect to the substrate. b) Calculated angular dependence of phase shift and transmittance with light impinging from the bottom. The upper (lower) two panels correspond to linear incident polarization oriented along the x-direction (y-direction). c) Dependence of phase shift and transmittance versus angle of incidence for light impinging from the top, again for the two different orthogonal linear polarizations of light. d) Optical microscopy image of the fabricated metalens doublet. Scale bar is 250 $\mu$m. e) Scanning electron microscopy image of the area marked in (d). Scale bar is 7.5 $\mu$m. f) Scanning electron microscopy image of the area marked in (e). Scale bar is 1 $\mu$m.
The transmittances and phase shifts of the nanocylinders versus $R$ under normal incidence of light are shown in Figure 2a. Responses under different incident angles are depicted in Figure 2b,c. With the radius $R$ varying from 60 nm to 260 nm, a phase shift of nearly $2\pi$ and a transmittance above 75% is achieved for normal incidence. Furthermore, within the range if radii investigated by us, Si nanocylinders which exhibit only a weak dependence on the incidence angle within an angular range of $20^\circ$ cover more than 70% of the total phase shift range.

3. Results and Discussions

3.1. Focusing with the Metalens Doublet

To experimentally test the above design, we have fabricated a corresponding metasurface doublet with a diameter of 1 mm and a minimum focal length of 3 mm. Details of the fabrication and the designed phase profile are discussed and shown in Section S5 and Figure S6 (Supporting Information). Optical microscopy images of two fabricated metasurfaces and scanning electron microscopy images for one of them are shown in Figure 2d and Figure 2e,f, respectively. A SiO$_2$ layer with a thickness of about 2.5 $\mu$m has additionally been deposited around the nanocylinder area for both metasurfaces to protect the nanocylinders from being scratched, which corresponds to the yellow ring in Figure 1a. Additional alignment markers have been applied to guide the rotation alignment.

The focusing behavior of the doublet was measured under collimated illumination at a wavelength of $\lambda = 1550$ nm. Details of the experimental characterization setup are given in Figures S7 and S8 (Supporting Information).

Figure 3a depicts the measured (normalized) intensity of light, depicted in the $xz$ plane and in the focal plane under six different rotation angles $\theta$. The focal length changes from 3 to 54 mm. Correspondingly, the doublet zooming power varies...
from $k = 1$ to $k = 18$, and the doublet numerical aperture (NA) from 0.164 to 0.001. At each value of $\theta$, the position of the focal plane fits well with the designed focal length. As to be expected, the depth and the size of the focus increases with increasing focal length. We have also measured the focal length of the doublet for varying the angle $\theta$ in steps of 10°. The results shown in Figure 3b cover both positive and negative focal lengths. The average relative deviation between experiment and theory is as small as 1.7%. This error can be traced back to errors in experimentally determining $\theta$.

Figure 3c characterizes the focusing efficiency and the full width at half maximum (FWHM) for positive focal lengths. Such measurements are not easily possible for negative focal lengths. The focusing efficiency is defined as the power gathered in a circular area with a diameter of $2 \times$ FWHM and the total power in a circular area with 1 mm diameter in the focal plane. The center of both circular areas is the point of the maximum intensity. The average measured FWHM is 27% larger than the diffraction limit of $0.514 \lambda/NA$. For $\theta = 10^\circ$, the FWHM is 60% larger than the diffraction limit. This behavior results from a weak focusing behavior at a small numerical aperture of NA = 0.001. The focusing efficiency exhibits a minimum of $\eta = 23\%$ at $\theta = 180^\circ$, where the focal length has its minimum of 3 mm, and increases to $\eta = 82\%$ at $\theta = 10^\circ$, where the focal length has its maximum of 54 mm. This overall behavior is expected from the doublet phase profile discussed earlier. The average focusing efficiency is 54%, which is slightly smaller than the numerically determined value of 63%. We attribute this difference partly to the finite axial separation of the two metasurfaces, which has been neglected in the design process and which leads to phase distortions. Fabrication imperfections of the Si nanocylinders and their arrangement may also contribute. In addition, the remaining dependence on the angle of incidence (cf. Figure 2b,c), which has not been accounted for in the design process, is likely yet another contribution.

### 3.2. Imaging with the Metalens Doublet

We have also experimentally characterized the zooming ability of the metalens doublet in imaging experiments using a 4f system.

![Figure 4](image_url)

Figure 4. Zooming images measured with a 4f system consisting of the metalens doublet and a conventional refractive lens. (a–f) Different rotations angles $\theta$ as indicated in the lower left-hand side corners. Magnification factor in parentheses. The total zoom range is 18-fold. Scale bar is 1 mm. (g–i) Magnified images for $\theta = 50^\circ$, $90^\circ$, and $180^\circ$. The magnification factor is chosen as $9/k$, with the zoom factor $k(\theta)$. Scale bars are 400 µm in (g), 222 µm in (h), and 111 µm in (i).
system, which consists of the metalens doublet and a conventional lens with a focal length of 200 mm (see Figure S9, Supporting Information, for details). We have manufactured a dedicated test sample (see Figure S10, Supporting Information). The narrowest line width of the ideal image of this sample is about 1.1 μm, the focal spot FWHM for θ = 180°. The slenderest part of the “HUST” logo is still close to the diffraction limit, making it dimmer than other areas. The zooming image was recorded under the rotation angles θ of 10°, 20°, 30°, 50°, 90°, and 180°, corresponding to zooming powers of k = 18, 9, 6, 3.6, 2, and 1. In order to avoid light going around the doublet aperture contributing to the images, which would reduce image contrast, the whole sample image has been captured part by part with an aperture and then reconstructed. Reconstructed images are depicted in Figure 4a–f. Under these conditions, the overall resolution of the system varies only slightly. We have also magnified the systems for θ = 180°, 90°, and 50° to the same ideal magnification of k = 9 in Figure 4g,h. All of them are clearly imaged with approximately the same sizes. The test sample is clearly imaged for all zoom factors, spanning a range from k = +1 to k = +18.

4. Conclusion

In summary, we have presented experimental results following an optimized design of a zoom metalens doublet, based on rotating two metasurfaces with respect to each other at fixed distance between them, at an operation wavelength of 1550 nm. The focal length could be adjusted from ±3 mm to ±54 mm, corresponding to external zoom factors of ±18× at an average focusing efficiency of 54%. Such compact and easy-to-use tunable zoom metalens doublets can be scaled to other operation wavelengths and could find niche applications where compactness is key and only a narrow wavelength range is needed.

Supporting Information

Supporting Information is available from the Wiley Online Library or from the author.

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Conflict of Interest

The authors declare no conflict of interest.

Author Contributions

Y.X.W., Y.Y.W., and X.F. contributed equally to this work. Y.Y.W. had the original idea, conceived the study, and finished the simulations; Y.X.W. fabricated the samples and analyzed them with the help from J.W.S.; X.F. performed the measurements with the help from Y.X.W., S.Y.X., Z.K.W., and T.H.; J.S.X. supervised the fabrication; M.Z., Z.Y.Y., and M.W. supervised the work and the manuscript writing. All authors discussed the results. Y.X.W. wrote the first draft of the manuscript, which was refined by contributions from all authors.

Keywords

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