Broadband continuous zoom metalens doublet in the visible

XING FENG,1 TIE HU,1 SHENGQI WANG,1 YUHONH WEI,1 YUANXUAN WEI,2 ZHENYU YANG,1 AND MING ZHAO1*

1Nanophotonics Laboratory, School of Optical and Electronic Information, Huazhong University of Science and Technology, Wuhan 430074, China
2Ming Hsieh Department of Electrical and Computer Engineering, University of Southern California, Los Angeles, California 90089, USA
*Corresponding author: zhaoming@hust.edu.cn

Zoom metalens doublet exhibits unprecedented advantages over the traditional zoom lens in many aspects, like ultra-compactness, CMOS compatibility, and miniaturization. However, most of them can only work in a narrow band due to chromatic aberration. Here, we numerically demonstrate a broadband achromatic zoom metalens doublet inspired by the Moiré lens principle. This design is achieved by globally optimizing the multi-wavelength phase profiles of the metalens doublet in the visible. The doublet can achieve achromatic continuous 1-10× zoom at wavelengths of 440 nm, 540 nm, and 640 nm, featuring high focusing efficiency up to 86.5% and polarization insensitivity.

Introduction. Metasurfaces, which can manipulate the phase, amplitude, and polarization at the subwavelength level, have wide applications from biosensors [1], polarization detectors [2, 3] to zoom lenses [4-11]. Especially, zoom metalenses can provide versatile advantages that are difficult or impossible to accomplish with traditional refraction zoom lenses, such as compactness and high integration. Generally, there are mainly two modulating mechanisms to design a zoom metalens, including the electronic modulation [4-7], and mechanically tunability [8-11]. For instance, Shane et al. realized the tunable Alvarez metalens operated by modifying the lateral displacements of two separated metasurfaces at the wavelength of xx nm, with a tuning range of 3 × [9, 10]. Moreover, Wei et al. proposed a rotary zoom metalens doublet working at 1550 nm following Moiré lens principle [11]. Notably, compared with the traditional zoom lens, this metalens doublet can theoretically realize a zoom range from -∞ to ∞ without compromising the compactness and miniaturization of this optical system. However, most tunable or reconfigurable metalenses can only work in a narrow band limited by chromatic aberration.

Fig. 1. Principle of the broadband achromatic zoom metalens doublet and the meta-atom design. (a) Schematic of the broadband zoom metalens doublet. Arbitrary focal length can be realized by modifying the rotation angle of the metalens doublet. SiO2 and TiO2 materials are represented in yellow and blue, respectively. (b) Top view of partial two metasurfaces with a radius of 9 μm. The scale bar is 1 μm. (c) Illustrations of the meta-atoms marked by different colored dots. (d) (e) The phase, and transmittance of the meta-atom library at the wavelength of 440 nm, 450 nm, and 640 nm.
To address the chromatic abberation, most broadband metalenses are based on dispersion engineering and multi-wavelength design. Briefly, the dispersion engineering method can ideally achieve continuous achromatic focusing by simultaneoulsy modulating the group delay and the group delay dispersion of the meta-atoms [12-16]. However, there is usually a trade-off between numerical aperture, diameter, and working band due to the limited group delay range [17]. On the other hand, metalens can also work at multi-wavelength by using interleaving and multi-layer design [18-21]. Multi-wavelength design can ease the challenge of dispersion engineering without requiring strict linear dispersion.

Here, an achromatic continuous zoom metalens doublet is realized by the multi-wavelength design in the visible. For a proof-of-concept, we numerically verify a polarizatoin-insensitive metalens doublet that can achieve achromatically tunable focusing at the wavelength of 440 nm, 540 nm, and 640 nm, featuring a zoom capacity up to 10×, the maximum relative focal length shift below 9.08% and the maximum focusing efficiency of 86.2%.

**Design.** As depicted in Fig. 1(a), the focal length with 1× and 10× zoom are realized by adjusting the mutual rotation angle of 180° and 9°, respectively. Moreover, by continuously adjusting the relative rotation angle of the metalens doublet, this metalens doublet can realize achromatic and tunable focusing simultaneously under the broadband visible light. The partial top view of the doublet shown in Fig. 1(b) exhibits the arrangement of the meta-atoms.

As shown in Fig. 1(c), the meta-atom is composed of a TiO2 nanopillar based on the square SiO2 substrate, with a period of 300 nm and a height of 900 nm. To enrich the meta-atom library, we use some unique nanopillars such as squares, holes, circles, rings, concentric rings, crosses, and cross holes nanopillars, which are represented by different colored dots. Thus, we can manipulate the phase of the meta-atoms by modifying the radius or length of the fourfold symmetry meta-atoms. Here, the finite time domain difference (FDTD) method is used to calculate the complex amplitude of the meta-atoms. And Figs. 1(d) and 1(e) show the phase and the transmittance of the meta-atoms with different geometric parameters, respectively. The phase can cover -π to π, and the transmittance mainly approaches unity at the three design wavelengths.

Following the Moiré lens principle, the phase profiles of metalens doublet can be described as [11]:

\[ \phi_1(r, \theta_1, \lambda) = \text{round}\left(\frac{\pi}{\lambda F_0} r^2\right) \theta_0 + C(r, \lambda), \]

\[ \phi_2(r, \theta_0, \lambda) = -\phi_1(r, \theta_0, \lambda) = -\text{round}\left(\frac{\pi}{\lambda F_0} r^2\right) \theta_0 - C(r, \lambda), \]

\[ \phi_{\text{sum}}(r, \theta_1, \lambda) = \phi_1(r, \theta_1, \lambda) + \phi_2(r, \theta_0 + \theta_1, \lambda) = -\text{round}\left(\frac{\pi}{\lambda F_0} r^2\right) \theta_0, \]

where the phase \( \phi_{\text{sum}} \) is the total phase of the metalens doublet, which is the sum of \( \phi_1 \) and \( \phi_2 \), and \( \phi_1 \) and \( \phi_2 \) represent the phase profiles of the two metalenses, respectively. The first term of \( \phi_1 \), shown in Fig. 2(a), is the product of the quantification of a spherical lens phase and the angle \( \theta_0 \). \( \lambda F_0 \) is the focal length of the spherical lens and \( C(r, \lambda) \) is a function of \( r \) and \( \lambda \) used as an optimization term. Here, the quantization function ensures that when \( \theta_0 \) increases from 0 to 2π, \( \phi_1 \) changes to an integer multiple of 2π. Otherwise, the discontinuous phase around \( \theta_0 = \pm 2\pi \) will result in unwanted errors in the output phase \( \phi_{\text{sum}} \). Figs. 2(b) and 2(c) depict the phase profiles of \( \phi_{\text{sum}} \) with \( \theta_0 \) of \( \pi \) and \( \pi/2 \), which corresponds to the zoom factor of 1× and 2×, respectively. Here, the zoom factor of the metalens doublet is defined as \( K = \pi / \theta_0 \), and the corresponding quantization order \( N \) of \( \phi_{\text{sum}} \) is 2K.

Then, the focal length of \( \phi_{\text{sum}} \) can be expressed as

\[ F(\theta) = F_0 / \theta. \] (4)

Where \( F(\theta) \) can vary from \( F_0 / \theta \) to \( \infty \) when \( \theta \) varies from \( \pi \) to 0. Furthermore, this doublet realizes a zoom range from \( -\infty \) to \( -F_0 / \pi \) when \( \theta \) varies from \( -\pi \) to 0.

![Fig. 2](image)

**Phase Error.** During the optimization of the achromatic metalens doublet, the term \( C(r, \lambda) \) is utilized to reduce the average phase errors between the required phase profile and the real phase library \( \Phi(\lambda) \) at the three designed wavelengths. Here the average phase errors \( \Delta P_1 \) and \( \Delta P_2 \) of the two metalenses are defined as

\[ \Delta P_1 = \sum_{r, \theta_0, \lambda} \sum_{n_0} \min \left[ \sum_{\lambda} \left| \phi_1(r, \theta_0, \lambda) - \Phi(\lambda) \right| \right] / n_0, \] (5)

\[ \Delta P_2 = \sum_{r, \theta_0, \lambda} \sum_{n_0} \min \left[ \sum_{\lambda} \left| \phi_2(r, \theta_0, \lambda) - \Phi(\lambda) \right| \right] / n_0, \] (6)

where \( n_0 \) is the total number of the meta-atoms in one metalens. Here, we set the radius of this doublet as 25.05 μm and \( n_0 \) is 21629. Then, the optimal \( C(r, \lambda) \) and \( F_0 \) are found to realize the smallest errors of 0.83 rad (\( \Delta P_1 \)) and 0.86 rad (\( \Delta P_2 \)), through a global optimization algorithm. The optimized phase \( \Phi_1(\lambda) \) and \( \Phi_2(\lambda) \) of the doublet in three wavelengths are respectively shown in Figs. 2(d) and 2(e).

To analyze the phase error at three separate wavelengths, the phase errors \( \Delta \phi_1(\lambda) \) and \( \Delta \phi_2(\lambda) \) of the two metalenses are defined as:
The calculated $\Delta \rho_1(\lambda)$ and $\Delta \rho_2(\lambda)$ are 0.12 rad, 0.29 rad, 0.39 rad and 0.14 rad, 0.31 rad, 0.41 rad at the wavelength of 440 nm, 540 nm and 640 nm, respectively. It is noted that the increased phase errors versus the related wavelengths are due to the insufficient phase coverage at long wavelengths.

$$
\Delta \rho_1(\lambda) = \sum_{r_1=0}^{N_r} \sum_{r_2=0}^{N_r} \left[ \rho_1(r, \lambda, \theta_1) - \Phi_i(\lambda) \right] / n_1,
$$

(7)

$$
\Delta \rho_2(\lambda) = \sum_{r_1=0}^{N_r} \sum_{r_2=0}^{N_r} \left[ \rho_2(r, \lambda, \theta_2) - \Phi_i(\lambda) \right] / n_2.
$$

(8)

Once the two optimized metalenses are achieved, we can form the metalens doublet by placing them face to face with an air gap of 1400 nm. The complex amplitude of the doublet can be obtained at the exit surface after the second metalens. The distance between the doublet needs to be fixed at 1400 nm, which is twice the distance where the selected plane is to get the transmitted complex amplitude after meta-atoms, avoiding unwanted dispersion. Next, we use the Rayleigh Sommerfeld diffraction theory to calculate the focusing fields under different varifocal wavelengths.

**Results.** Fig. 3 shows the achromatic tunable focusing performances of our proposed metalens doublet. The normalized intensity distributions of the $xz$ plane with different focal lengths, at the three wavelengths of 440 nm, 540 nm, and 640 nm, are depicted respectively in Figs. 3(a), 3(d) and 3(g). These results reveal the tunability of the metalens doublet. Moreover, we plot the normalized intensity profiles of the partial focal plane and $x$ cut (exhibited in Figs. 3(b-c), (e-f), (h-i), respectively). Notably, as mentioned above, the zoom factor can achieve from $-\infty$ to $+\infty$ in theory, but when it is greater than 10, the simulated focal length will gradually deviate from the theoretical value due to the small NA and increased phase error.

Fig. 3. The achromatic focusing performances of the continuous zoom metalens doublet. (a-c) The simulated results at the wavelength of 440 nm. (a) The normalized intensity distributions in the $xz$ plane when the zoom factor varies from 1 to 10. The actual focal planes are marked with white dash lines. (b) The normalized intensity distributions of the partial focal plane with different focal lengths. (c) The normalized intensity distributions along the $x$ cut of the focal plane. The simulation results are marked with red circles, and the black lines are the fitted Gaussian curves. (d-f) The normalized intensity distributions at the wavelength of 540 nm. (g-i) The normalized intensity distributions at the wavelength of 640 nm.

Once the two optimized metalenses are achieved, we can form the metalens doublet by placing them face to face with an air gap of 1400 nm. The complex amplitude of the doublet can be obtained at the exit surface after the second metalens. The distance between the doublet needs to be fixed at 1400 nm, which is twice the distance where the selected plane is to get the transmitted complex amplitude after meta-atoms, avoiding unwanted dispersion. Next, we use the Rayleigh Sommerfeld diffraction theory to calculate the focusing fields under different varifocal wavelengths.

**Results.** Fig. 3 shows the achromatic tunable focusing performances of our proposed metalens doublet. The normalized intensity distributions of the $xz$ plane with different focal lengths, at the three wavelengths of 440 nm, 540 nm, and 640 nm, are depicted respectively in Figs. 3(a), 3(d) and 3(g). These results reveal the tunability of the metalens doublet. Moreover, we plot the normalized intensity profiles of the partial focal plane and $x$ cut (exhibited in Figs. 3(b-c), (e-f), (h-i), respectively). Notably, as mentioned above, the zoom factor can achieve from $-\infty$ to $+\infty$ in theory, but when it is greater than 10, the simulated focal length will gradually deviate from the theoretical value due to the small NA and increased phase error.

Fig. 3. The achromatic focusing performances of the continuous zoom metalens doublet. (a-c) The simulated results at the wavelength of 440 nm. (a) The normalized intensity distributions in the $xz$ plane when the zoom factor varies from 1 to 10. The actual focal planes are marked with white dash lines. (b) The normalized intensity distributions of the partial focal plane with different focal lengths. (c) The normalized intensity distributions along the $x$ cut of the focal plane. The simulation results are marked with red circles, and the black lines are the fitted Gaussian curves. (d-f) The normalized intensity distributions at the wavelength of 540 nm. (g-i) The normalized intensity distributions at the wavelength of 640 nm.

To quantitatively analyze the achromatic focusing performances of continuous zoom metalens doublet, we take the following evaluation indices: the full width at half maxima (FWHM), focal length shift, coefficient of variation (CV=SD/MN×100%),
efficiency, focal length error at the different wavelengths as the metric of figure. Here, SD and MN are the standard deviation and average of the focal lengths with the same zoom factor, the focal length error is defined as the ratio of the average focal length shift to the theoretical value with the same zoom factor, and efficiency is defined as the ratio of the power of a circular area with a diameter of 3 times the FWHM to the total power in the focal plane.

Fig. 4(a) shows the simulated focal length versus the zoom factor at the three designed wavelengths. The focal lengths at the three designed wavelengths agree well with the theoretical values at every zoom factor, revealing the robust achromatic continuous tunability of our metalens doublet. To further characterize the achromatic focusing performance, the concepts of the CV and the focal length error are introduced. The CVs (marked with red prismatic) and the focal length errors (marked with black crosses) versus the zoom factors are illustrated in Fig. 4(b). All the calculated CVs are below 5%, which is within the range of the international standard of chromatic aberration, proving the excellent achromatic capability of our proposed zoom metalens doublet. Additionally, the focal length errors are below 5% at all designed zoom factors except factors 1 and 2, which also verifies the achromatic focusing performance and continuous tunability of the designed doublet. Here, the overlarge focal length errors at the zoom factor 1 and 2 are attributed to the small-order quantized phase.

Then, we use the FWHMs to evaluate the focusing capability of the focused spots. As is shown in Fig. 4(c), the FWHMs fit well with the diffraction limits (DL=0.514×λ/NA) corresponding to every selected wavelength, at the zoom factor range from 3 to 10. Also, it is noted that the small-order quantized phases lead to slight deviations from the theoretical values at the zoom factors 1 and 2. Besides, efficiency is another crucial metric of metalens. The efficiency increases with the zoom factor and can reach the maximum value of 86.2% at the wavelength of 540 nm with the zoom factor of 10, as Fig. 4(d) shows. The calculated efficiencies are lower than the theoretical value (denoted as a black line in Fig. 4(d)), which might result from the phase error and the low transmittance of these selected meta-atoms. A high-efficiency zoom metalens doublet can be achieved by further optimization of complex amplitude.

Additionally, Fig. 4(e) describes the zoom performances in the visible band from 440 nm to 640 nm in a step of 20 nm. The simulated focal lengths versus the wavelength at different zoom factors are marked by various color circles, and the theoretical values are denoted by color dash lines. These results strongly prove that though our zoom metalens doublet is designed at the three discrete wavelengths, it can realize achromatic continuous zoom in the whole visible band, which further demonstrates the advantages of our proposed metalens doublet. In summary, we have designed a broadband continuous zoom metalens doublet in the visible band. This doublet can realize continuous zoom as large as 10×. Our achromatic zoom metalens doublet features the relatively low simulated focal length errors (below 10%), the small coefficient of variation (about 5%), and the high efficiency (up to 86.2%). Furthermore, this design can realize a more excellent zoom capability through a more abundant library and precise optimization of the phase of the doublet. Generally speaking, our proposed zoom metalens doublet provides great potential to achieve integrated and miniaturized optical zoom systems, which can be applied in various areas such as mobile phone cameras, microscope lenses and augmented reality.

**Funding.** This work is supported by the Natural Science Foundation of China (No.62075073, 62135004 and 62075129), the Fundamental Research Funds for the Central Universities (No. 2019kyky051JC038), State Key Laboratory of Advanced Optical Communication Systems and Networks, Shanghai Jiao Tong University (No. 2021GZKF007), and Key R & D project of Hubei Province (No.12345678).

**Acknowledgment.** The authors would like to thank Dr. Xing Feng and Dr. Tie Hu for the revisions and the suggestions on this letter.

**REFERENCES**

1. S. Zeng, K. V. Sreekanth, J. Shang, T. Yu, C. K. Chen, F. Yin, D. Baillargeat, P. Coquet, H. P. Ho, A. V. Kabashin, and K. T. Yong, Adv. Mater. 27, 6163 (2015).
2. Y. Wang, Z. Wang, X. Feng, M. Zhao, C. Zeng, G. He, Z. Yang, Y. Zheng, and J. Xia, Photonics Res. 8(2020).
3. Z. Yang, Z. Wang, Y. Wang, X. Feng, M. Zhao, Z. Wan, L. Zhu, J. Liu, Y. Huang, J. Xia, and M. Wegener, Nat. Commun. 9, 4607 (2018).
4. W. Bai, P. Yang, J. Huang, D. Chen, J. Zhang, Z. Zhang, J. Yang, and B. Xu, Sci. Rep. 9, 5368 (2019).
5. Z. Zhang, X. Qi, J. Zhang, C. Guo, and Z. Zhu, Opt. Express 28, 28101 (2020).
6. S. Qin, N. Xu, H. Huang, K. Jie, H. Liu, J. Guo, H. Meng, F. Wang, X. Yang, and Z. Wei, Opt. Express 29, 7925 (2021).
7. F. Callewaert, V. Velev, S. Jiang, A. V. Sahakian, P. Kumar, and K. Aydin, Appl. Phys. Lett. 112(2018).
8. K. Iwami, C. Ogawa, T. Nagase, and S. Ikezawa, Opt. Express 28, 35602 (2020).
9. S. Colburn and A. Majumdar, ACS Photon. 7, 120 (2019).
10. S. Colburn, A. Zhan, and A. Majumdar, Optica 5(2018).
11. Y. Wei, Y. Wang, X. Feng, S. Xiao, Z. Wang, T. Hu, M. Hu, J. Song, M. Wegener, M. Zhao, J. Xia, and Z. Yang, Adv. Opt. Mater. 8(2020).
12. X. An, Y. Cao, Y. Wei, Z. Zhou, T. Hu, X. Feng, G. He, M. Zhao, and Z. Yang, Opt. Lett. 46, 3881 (2021).
13. W. T. Chen, A. Y. Zhu, and F. Capasso, Nat. Rev. Mater. 5, 604 (2020).
14. W. T. Chen, A. Y. Zhu, V. Sanjeev, M. Khorasaninejad, Z. Shi, E. Lee, and F. Capasso, Nat. Nanotechnol. 13, 220 (2018).
15. S. Wang, P. C. Wu, V. C. Su, Y. C. Lai, C. Hung Chu, J. W. Chen, S. H. Lu, J. Chen, B. Xu, C. H. Kuan, T. Li, S. Zhu, and D. P. Tsai, Nat. Commun. 8, 187 (2017).
16. W. Zang, Q. Yuan, R. Chen, L. Li, T. Li, X. Zou, G. Zheng, Z. Chen, S. Wang, Z. Wang, and S. Zhu, Adv. Mater. 32, e1904935 (2020).
17. S. Shrestha, A. C. Overvig, M. Lu, A. Stein, and N. Yu, Light Sci. Appl. 7, 85 (2018).
18. O. Avayu, E. Almeida, Y. Prior, and T. Ellenbogen, Nat. Commun. 8, 14992 (2017).
19. K. Li, Y. Guo, M. Pu, X. Li, X. Ma, Z. Zhao, and X. Luo, Opt. Express 25, 21419 (2017).
20. A. McClung, M. Mansouree, and A. Arbabi, Light Sci. Appl. 9, 93 (2020).
21. Y. Zhou, Kravchenko, II, H. Wang, J. R. Nolen, G. Gu, and J. Valentine, Nano Lett. 18, 7529 (2018).