Meta-Lens in the Sky

CHEN, Mu Ku; CHU, Cheng Hung; LIU, Xiaoyuan; ZHANG, Jingcheng; SUN, Linshan; YAO, Jin; FAN, Yubin; LIANG, Yao; YAMAGUCHI, Takeshi; TANAKA, Takuo; TSAI, Din Ping

Published in:
IEEE Access

Published: 01/01/2022

Document Version:
Final Published version, also known as Publisher's PDF, Publisher's Final version or Version of Record

License:
CC BY-NC-ND

Publication record in CityU Scholars:
Go to record

Published version (DOI):
10.1109/ACCESS.2022.3171351

Publication details:

Citing this paper
Please note that where the full-text provided on CityU Scholars is the Post-print version (also known as Accepted Author Manuscript, Peer-reviewed or Author Final version), it may differ from the Final Published version. When citing, ensure that you check and use the publisher's definitive version for pagination and other details.

General rights
Copyright for the publications made accessible via the CityU Scholars portal is retained by the author(s) and/or other copyright owners and it is a condition of accessing these publications that users recognise and abide by the legal requirements associated with these rights. Users may not further distribute the material or use it for any profit-making activity or commercial gain.

Publisher permission
Permission for previously published items are in accordance with publisher's copyright policies sourced from the SHERPA RoMEO database. Links to full text versions (either Published or Post-print) are only available if corresponding publishers allow open access.

Take down policy
Contact lbscholars@cityu.edu.hk if you believe that this document breaches copyright and provide us with details. We will remove access to the work immediately and investigate your claim.

Download date: 14/04/2024
Meta-Lens in the Sky

MU KU CHEN1,2,3, CHENG HUNG CHU4, XIAOYUAN LIU1, JINGCHENG ZHANG1, LINSHAN SUN1, JIN YAO1, YUBIN FAN1, YAO LIANG1, TAKUO TANAKA4,5,6, AND DIN PING TSAI1,2,3, (Fellow, IEEE)

1Department of Electrical Engineering, City University of Hong Kong, Hong Kong
2Centre for Biosystems, Neuroscience, and Nanotechnology, City University of Hong Kong, Hong Kong
3State Key Laboratory of Terahertz and Millimeter Waves, City University of Hong Kong, Hong Kong
4Innovative Photon Manipulation Research Team, RIKEN Center for Advanced Photonics, Saitama 351-0198, Japan
5Metamaterial Laboratory, RIKEN Cluster for Pioneering Research, Saitama 351-0198, Japan
6Institute of Post-LED Photonics, Tokushima University, Tokushima 770-8506, Japan

Corresponding author: Din Ping Tsai (dptsai@cityu.edu.hk)

This work was supported in part by the University Grants Committee/Research Grants Council of the Hong Kong Special Administrative Region, China, under Project AoE/P-502/20; and under General Research Fund Project 15303521; in part by the Shenzhen Science and Technology Innovation Commission under Grant SGDX2019081623281169; in part by the Department of Science and Technology of Guangdong Province under Grant 2020B1515120073; and in part by the City University of Hong Kong under Grant 9380131.

ABSTRACT Meta-lenses are advanced optical devices composed of artificial nano-antenna arrays. Its flat, light-weight, ultra-thin, compact, customizable, and easy-to-integrate advantages enable widely potential usages in new demands. We demonstrate a GaN-based polarization-independent meta-lens-based camera on a drone. The diameter of the meta-lens is 2.6 mm, and the measured focal length is 5.03 mm under the 532 nm light incident. An array of the 750 nm height cylindrical nano-antennas with various sizes of the meta-lens provides the $2\pi$ phase modulation of the focusing phase distribution. The meta-lens is integrated with an image sensor and mounted on the drone to realize the aerial photography and landing assistance. By taking images of the specific pattern on the ground at different heights through the meta-lens, the flying height of the drone can be detected for landing and flying. We trust meta-lens-camera can reduce the weight burden for prolonging flight time. We believe the meta-lens-based optical devices for imaging and sensing is an important key for micro/nano-robots, micro air vehicles, and intelligent sensing devices in the future.

INDEX TERMS Metasurfaces, meta-devices, meta-lenses, imaging and sensing, unmanned aerial vehicles.

I. INTRODUCTION

The Wright brothers successfully flew into the sky for the first time in human history in 1903 and opened up the ability to have their viewing field in the sky. Before the advent of various types of aircraft, humans observed the world from a horizontal perspective and believed that looking down view was God’s perspective. The perspective of looking down has begun to have practical application for military purposes, which was used to observe the military arrangement of the field. With the development of modern technology, the evolution of aircraft has also begun to evolve from manned to remote control and unmanned aircraft. The current application and development driving force of unmanned aerial vehicles (UAVs) come from various purposes, such as agriculture, military, land survey, resecure activity, entertainment, etc. UAVs are used to replace expensive manned aircraft and respond to extreme situations. With the rapid development of artificial intelligence, deep learning, and other technologies, unmanned aircraft such as drone has moved to public life. The drone usage is an inevitable trend and plays an important role in modern life now. The weight of the drone is inversely proportional to the flight time. The heavier the drone’s load, the shorter its flight time, which seriously affects aerial photography operation. Consequently, the weight reduction of the imaging and sensing devices of the drone is an urgent issue.

Meta-lens is composed of an array of specially designed nano-antennas with a specific layout arrangement for controlling the optical wavefronts [1]–[3]. The phase, amplitude, polarization, etc., of the incident electromagnetic waves can be manipulated to meet the various optical demands. Meta-lenses have been studied and developed for beam shaping [4], anomalous deflection and reflection [5], [6], polarization control and analysis [7]–[10], holography [11]–[13], second-harmonic generation [14]–[17], nano-laser [18], tunability [19], [20], focusing [21]–[23], imaging [24]–[26],...
sensing [27]–[30], color display [31], color routing [32], and high-dimensional optical quantum source [33], etc. The advantages are light-weight, small footprint, broadband, less energy consumption, novel functions, complementary metal-oxide-semiconductor (CMOS) compatibility for mass production, etc. In this work, we report a novel meta-lens device and its demonstration for the imaging and sensing of the drone in the sky. To our knowledge, this is the first meta-lens device operated with a drone in the sky.

We have designed and fabricated a polarization-independent gallium nitride (GaN) meta-lens with a 2.6 mm diameter and 5.03 mm focal length. We integrated this meta-lens with a CMOS sensor to form a meta-lens-based camera and mounted it with a drone, as shown in Figure 1. We have successfully demonstrated aerial photography with this meta-lens-based camera and drone. The flight height can be detected by photographing and analyzing specific patterns on the ground of the platform. The acquisition of the height information can help the drone’s flying height control and accurate landing.

![Figure 1. The flying drone with a meta-lens camera.](image)

**II. METHODS**

Our meta-lens is composed of GaN cylindrical nanostructures for the polarization-independent imaging and sensing operation. We use Computer Simulation Technology (CST) Studio Suite@commercial software for the numerical simulations and design of the nano-antennas of meta-lens. The optical properties of phase and transmittance are calculated and evaluated by tuning the various size of the nano-antennas. The refractive index of GaN is 2.41 at 532 nm of wavelength [34]. The high index of refraction and the excellent physics properties of GaN help to achieve high efficient optical performance. Figure 2 (a) shows the shape of the GaN meta-atoms. The diameter of the meta-atoms is designed from 90 nm to 196 nm with a 260 nm period, and the height is 730 nm to provide 0 to 2\(\pi\) phase modulation at the wavelength of 532 nm. The transmission and phase shift of GaN meta-atoms with various diameters. Figure 2 (b) shows the diameter, H is the height, and p is the period. (b) The corresponding transmission and phase shift of GaN meta-atoms with various diameters.

![Figure 2. Design of meta-atoms (a) The shape of the meta-atom. D is the diameter, H is the height, and p is the period. (b) The corresponding transmission and phase shift of GaN meta-atoms with various diameters.](image)

**III. RESULTS AND DISCUSSION**

Figure 3(a) shows the photograph of the GaN meta-lens on the sapphire substrate. The whole meta-lens can be recognized by the bare eyes. The detailed nanostructures observed by the scanning electron microscope (SEM) are shown in Figures 3(b) and 3(c). Figure 3(b) is the zoomed-in top-view SEM image of the meta-lens. The cylindrical nanostructures with various diameters are well defined and arranged according to the focusing phase distribution. The cylindrical nanostructures are relatively straight with a height where \(\varphi\) is the phase requirement, \(r\) is the distance away from the meta-lens center, \(\lambda\) is the working wavelength, and \(f\) is the focal length. The diameter of our meta-lens is as 2.6 mm, the focal length is 5 mm, and the working wavelength is designed at 532 nm. The fabrication layout of our meta-lens can be readily generated accordingly.

For the fabrication of the meta-lens, a 750-nm thick GaN layer is grown on a double-sided polished c-axis sapphire substrate by using metalorganic chemical vapor deposition (MOCVD). A 200-nm thick SiO\(_2\) layer is subsequently deposited with an electron-beam evaporator. Then a 200-nm PMMA electron-beam resist layer is spin-coated onto the sample and baked at 180°C for 3 minutes as a positive tone resist. Based on the designed mask layout, we can use E-beam lithography (EBL) (ELS-HS50, ELIONIX INC.) and the dry etching fabrication process to produce the meta-lens. Typically, after the nanopillar nano-antennas patterned by the EBL system, we developed the resist with a 1: 3 methyl isobutyl ketone (MIBK): isopropyl alcohol (IPA) solution for 75 seconds, and followed by rinsing with IPA for 20 seconds. Then a 40-nm-thick Cr layer as a hard mask for the SiO\(_2\) layer is deposited using an electron-beam evaporator. The sample lift-off process is performed in acetone to remove the photore sist. Inductively-coupled-plasma reactive ion etching (ICP-RIE) system (Samco, RIE-200iPT) with CF\(_4\) gas is used to transfer the pattern from Cr mask to SiO\(_2\). The residual Cr is removed by a chromium etchant. After the second ICP-RIE step using a mixture gas of Cl\(_2\) and Ar, the pattern is transferred to GaN. Finally, the remaining SiO\(_2\) layer is removed by the buffered oxide etch (BOE) solution, and only GaN nanopillar nano-antennas remain on the sapphire substrate.
of 730 nanometers through a precise dry etching process, as shown in Figure 3(c). We measured and characterized the fabricated meta-lens to verify that the focal length of the lens is as designed. A continuous-wave laser with a wavelength of 532 nm is utilized as the incident light. The original laser beam is shaped into parallel light and expanded to be larger than the whole size of the meta-lens. Figure 3 (d) is the zoomed-in focusing profile on the x-z plane. The white dashed line is the maximum intensity spot position, and the focal length is 5.03 mm. At this position, the 2D and 3D point spread functions of the meta-lens are displayed in Figure 3 (e). The theoretical spatial resolution is 1.03 µm which is calculated by Equation 2.

\[
\text{Spatial resolution} = \frac{0.5\lambda}{NA}, \quad NA = \frac{D}{2f},
\]

where \(\lambda\) is the operation wavelength, \(NA\) is the numerical aperture, \(f\) is the focal length of the meta-lens, and \(D\) is the diameter of the metalens. The measured full width at half maximum (FWHM) is 1.12 µm, which is close to the theoretical spatial resolution.

The measured focal length is 5.03 mm (white dash line). (e) The point spread function of the focal spot.

Figure 3. Meta-lens characterization. (a) The GaN-based meta-lens with 2.6 mm of diameter. (b) The zoomed-in top-view SEM image. (c) The zoomed-in tilted view SEM image of the meta-lens edge. (d) The zoomed-in focusing profile under 532 nm of wavelength laser. The measured focal length is 5.03 mm (white dash line). (e) The point spread function of the focal spot.

The meta-lens can obtain images of the ground or any scene under the drone when the drone flies in the sky. In order to demonstrate the practical aerial photography ability of the meta-lens-based camera, a helipad pattern \(\mathcal{H}\), is used as the target, and the original diameter of the pattern’s circle is 12 cm. Figure 5(a) displays the captured images at different flight heights of the drone, from 100 cm to 10 cm. The helipad pattern can be clearly recognized in the aerial photographs. The height information of the flying drone can be readily analyzed and found. Figures 5(b) and 5(c) are the “H” pattern line width in experiments and calculations, respectively. We can choose the horizontal bar in the middle of the “H” and the inner distance between the two arms of the “H” as the parameters for acquiring the height determination. In Figure 5(b), there are two curves, which are the width of the center horizontal bar and the length of the inner separation between the two arms. The trends of the two curves at different heights are consistent, showing that the imaging resolution of the meta-lens is even in the horizontal and vertical directions. According to the lens formula and the magnification formula, the calculated width of the center horizontal bar and the calculated length of the inner separation between the two arms can be obtained. The actual width of the center horizontal bar and the length of the inner separation between the two arms of the helipad pattern are 1.2 and 1.8 cm, respectively. The experimental results have a good agreement with the calculated results, which indicate that height information can be accurately measured and detected. The aerial photography imaging and sensing capabilities of the meta-lens-based camera provide a novel, light-weight, and compact device for the drone. It will play an important new role in agriculture, forestry and plant protection, energy inspection,
logistics and transportation, fire and disaster relief, public safety, meteorological and environmental security, etc.

IV. CONCLUSION

In summary, a polarization-independent GaN meta-lens is designed and fabricated. An array of the 750 nm height cylindrical nano-antennas with various sizes provides the 2π phase modulation of the focusing phase distribution. The diameter of the meta-lens is 2.6 mm, and the measured focal length is 5.03 mm under the 532 nm laser incident, which is close to the designed focal length of 5 mm. We have successfully demonstrated a meta-lens-based camera on a drone. The meta-lens is directly integrated with a CMOS sensor and set on the drone. The aerial photography and landing assistance are realized. By taking photographs of the specific pattern on the ground at different heights through the meta-lens, the flying height of the drone can be detected and used for landing. The acquired images are analyzed to obtain the height information of the flying drone. Meta-lens is a promising way to make the camera components lighter and more compact. The weight burden of the mini/micro drone can be reduced for prolonged flight time. Meta-lens-based drones are smart devices and will be an extension of human vision. In the future fields of smart cities, smart homes, and Industry 4.0, meta-lens-assisted unmanned aerial vehicles will be a key factor in the development of artificial intelligence. We expect the meta-lens-based optical devices for imaging and sensing will play an important role in micro/nano-robots, micro air vehicles, and intelligent sensing devices in the future.

ACKNOWLEDGMENT

(Mu Ku Chen and Cheng Hung Chu contributed equally to this work.)

REFERENCES


CHENG HUNG CHU received the Ph.D. degree in opto-electronic science from the National Taiwan Ocean University, Taiwan. He is currently a Post-doctoral Researcher with the Innovative Photon Manipulation Research Team, RIKEN. His current research interests include phase-change materials, plasmonics, and metasurface, along with their applications.

XIAOYUAN LIU received the B.Eng. degree in electronic information engineering from Tianjin University, in 2020. She is currently pursuing the Ph.D. degree with the Department of Electrical Engineering, City University of Hong Kong. Her research interests include meta-lens array and deep learning for the design and application of meta-devices.

JINGCHENG ZHANG received the M.Eng. degree in electronic information engineering from Northwestern Polytechnical University, in 2019. He is currently pursuing the Ph.D. degree with the Department of Electrical Engineering, City University of Hong Kong. His research interests include metasurface, meta-lens array, and application of meta-devices.

LINSAN SUN received the B.S. degree from the Department of Physics, Nankai University, in 2020. He is currently a Research Assistant with the Department of Electrical Engineering, City University of Hong Kong. His research interests include metasurface, non-hermitian optics, and application of meta-devices.

MU KU CHEN received the Ph.D. degree from the Department of Physics, National Taiwan University, in 2019. He was a Research Assistant Professor with the Department of Electronic and Information Engineering, The Hong Kong Polytechnic University. He is currently a Research Assistant Professor with the Department of Electrical Engineering, City University of Hong Kong. His research interests include photonic information, nanophotonics, micro and nano-electronics fabrication, and artificial nano-antenna array-based meta-devices for the photonic applications.

JIN YAO received the Ph.D. degree from the Institute of Electromagnetics and Acoustics, Xiamen University, Xiamen, China, in 2021. He is currently a Postdoctoral Fellow with the Department of Electrical Engineering, City University of Hong Kong. His research interests include metasurface, nonlinear optics, and application of meta-devices.
YUBIN FAN received the B.S. degree from the Department of Physics, Harbin Institute of Technology, in 2017, and the Ph.D. degree in material physics and chemistry, in 2021. He is currently a Postdoctoral Research Fellow with the Department of Electrical Engineering, City University of Hong Kong. His research interests include metasurface, meta-lens array, and application of meta-devices.

YAO LIANG received the Ph.D. degree from the Centre for Translational Atomaterials, Swinburne University of Technology, in 2020. He is currently a Postdoctoral Researcher with the Department of Electrical Engineering, City University of Hong Kong. His research interests include plasmonics, bound states in the continuum, surface lattice resonances, integrated photonics, and functional meta-devices.

TAKUO TANAKA received the Ph.D. degree from Osaka University, in 1996. After that, he joined the Faculty of Engineering Science, Osaka University, as an Assistant Professor. In 2003, he moved to RIKEN as a Research Scientist with the Nanophotonics Laboratory. He was promoted to an Associate Chief Scientist, in 2008, and a Chief Scientist, in 2017. His research interests include three-dimensional microscopy, such as confocal microscope and two-photon microscope. Recently, he is studying about nanophotonics, plasmonics, and metamaterials fields with developing many new nanofabrication techniques. He has also experimental and theoretical experiences about high precision optical measurements and spectroscopy.

TAKESHI YAMAGUCHI received the master’s degree from the Tokyo Institute of Technology, in 1992. He was the Technical Specialist of Japan Display Inc. He is currently the Technical Staff of the Innovative Photon Manipulation Research Team, RIKEN Center for Advanced Photonics. His current research interest includes nano-structure fabrication for metamaterials.

DIN PING TSAI (Fellow, IEEE) received the Ph.D. degree from the University of Cincinnati, USA, in 1990. He is currently a Chair Professor with the Department of Electrical Engineering, City University of Hong Kong. His current research interests include meta-devices, quantum information technology, nano-photonics, advanced micro/nano fabrication, and design. He is an Elected Fellow of AAAS, APS, COS, EMA, IAE, JSAP, NAI, OSA, and SPIE. He received more than 40 prestigious recognitions and awards, including “Global Highly Cited Researchers,” Web of Science Group (Clarivate Analytics), in 2020 and 2019, respectively; China’s Top Ten Optical Breakthroughs, in 2020 and 2018; and the “Mozi Award” from International Society for Optics and Photonics (SPIE) (2018). He was an Editor of the Progress in Quantum Electronics journal (2016–2021) and an Associate Editor of the Journal of Lightwave Technology (IEEE/OSA) (2016–2021). He is a member of the Editorial Board of research journals, such as APL Photonics, ACS Photonics, Advanced Optical Materials, Nano Letters, Physical Review Applied, Optics Communications, Small Methods, Advanced Quantum Technologies, Opto-Electronic Advances, Plasmonics, Optoelectronics Letters, and Frontiers of Optoelectronics, respectively.

**VOLUME 10, 2022**

**IEEE Access**

**YAO LIANG** received the Ph.D. degree from the Centre for Translational Atomaterials, Swinburne University of Technology, in 2020. He is currently a Postdoctoral Researcher with the Department of Electrical Engineering, City University of Hong Kong. His research interests include plasmonics, bound states in the continuum, surface lattice resonances, integrated photonics, and functional meta-devices.

**YUEYING ZHANG** received the M.S. degree from the Department of Electrical and Computer Engineering, University of Florida, in 2018. She is currently a Ph.D. student in Electrical Engineering at City University of Hong Kong. Her research interests include metasurface, meta-lens array, and application of meta-devices.