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Meta-Lens in the Sky

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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 2π 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],

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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.

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 2π phase modulation at the wavelength of 532 nm. The transmission and phase shift of GaN meta-atoms with various diameters is shown in Figure 2 (b). The meta-lens focusing formula for the focusing phase is shown in Equation (1):

$$\varphi(r,\lambda) = -[\frac{2\pi}{\lambda}(\sqrt{r^2+f^2}-f)], \tag{1}$$

where φ is the phase requirement, r is the distance away from the meta-lens center, λ 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 photoresist. 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.

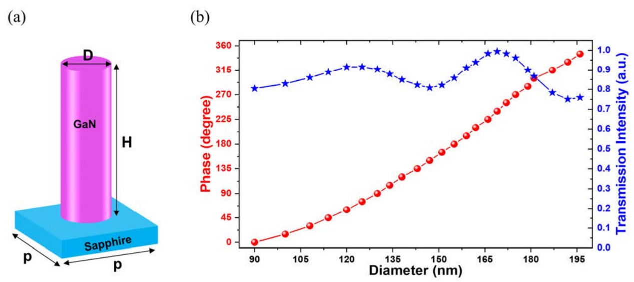

FIGURE 2. Design of meta-atoms (a) The shape of the meta-atom. D is the diameter, H is the height, and p is the period. (b) The corresponding transmission and phase shift of GaN meta-atoms with various diameters.

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 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.

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

where λ 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.

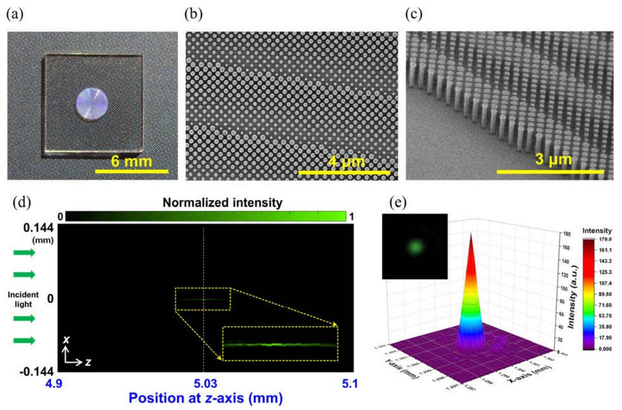

FIGURE 3. **Mete-lens characterization. (a) The GaN-based meta-lens with 2.6 mm of diameter. (b) The zoomed-in top-view SEM image. (c) The zoomed-in tilted view SEM image of the meta-lens edge. (d) The zoomed-in focusing profile under 532 nm of wavelength laser. The measured focal length is 5.03 mm (white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

Figure 4(a) shows the configuration of the meta-lens-based camera, including a rear camera case, a CMOS sensor, meta-lens, a front camera case, and a 532 nm bandpass filter. The meta-lens is integrated with a CMOS sensor directly because the polarization-independent meta-lens can work for arbitrary polarization light. The meta-lens is designed to work for monochromic focusing and imaging, so a 532 nm bandpass filter is set at the front of the meta-lens-based camera. The camera is compact and straightforward. Figure 4(b) is the photograph of the meta-lens-based camera, which is mounted on the drone. Compared with the general lenses on the drone camera, this meta-lens-based camera brings several advantages. The thickness of the traditional lenses is depended on the focal length. Lenses with various focal lengths have different thicknesses, requiring several or hundreds of wavelengths to effectively manipulate the light. The meta-lens can obtain the demanded focal length according to the arrangement of different phases under the same thickness (subwavelength thickness). When a traditional camera lens needs to filter polarized light or specific wavelengths of light, additional optical wave plates, such as polarizers or filters, need to be added. For meta-lenses, these requirements can be considered at the design stage along with the focusing phase without adding additional optical components [9], [26], [32]. Meta-lenses reduce the space required and bring the multi-functionalities for imaging components that are more suitable for integrated and compact optical systems.

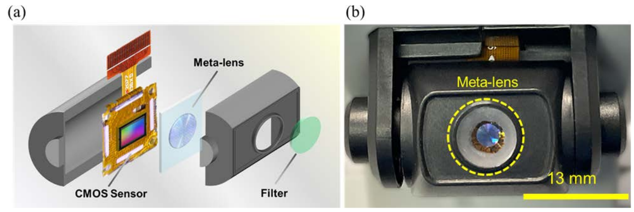

FIGURE 4. **The meta-lens integrated camera. (a) The schematic diagram of the meta-lens integrated camera. (b) The photograph of the meta-lens integrated camera on the drone.**

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 Ⓗ, 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,

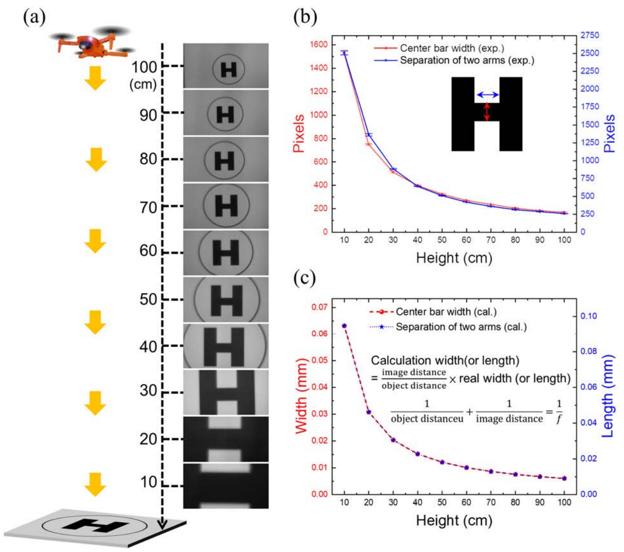

FIGURE 5. (a) The Aerial photography and landing. The experimental (b) and calculation (c) results of the imaging properties versus the height of the drone.

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.

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

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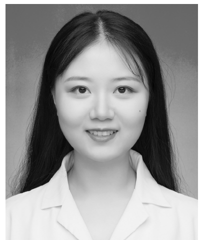

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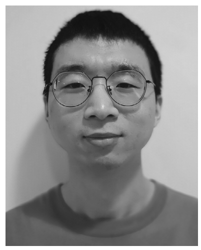

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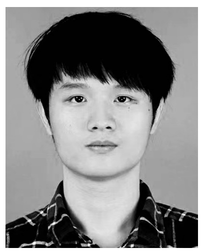

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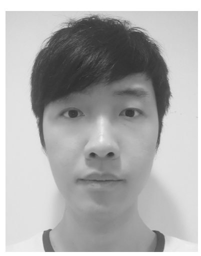

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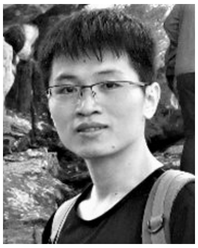

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