

Antidisturbance near-infrared-imaging detection based on an arrayed Si-based nanotip optical antenna

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An arrayed silicon-based nanotip optical antenna (NOA) architecture for guiding efficient near-infrared imaging detection is proposed. The NOA can be effectively actuated based on the geometric field enhancement due to the tip effect and the patterned redistribution of the surface net charges, leading to a highly localized electron accumulation at the tips, a strong field electron emission away from the tips, and continuously visible cathodoluminescence. The photoelectronic response measurements reveal an effective spectral transformation from the initial infrared region to the visible band with a central wavelength of 544 nm. Spectral characterized analyses exhibit a strong electric-field amplitude gain of 84.77 at 1000 nm and an ultralow radiation transmittance of less than 2% across a broad wavelength range from 400 nm to 14 μm . The measured output electric signal is sensitive to the incident radiation, reaching a high value of 186.05 mV under illumination of 2.47 W. The photoelectric measurements indicate an intense output voltage signal with a nanosecond-level time interval between adjacent output peaks and a shorter duration of a single peak in both the visible and near-infrared regions. The point-spread function of the emitted light beams away from a single nanotip presents a remarkably strengthened and expanded nanofocusing, which means a notable arrayed light-field enhancement in the Si-based NOA configuration. A nanotip-based imaging detector (NID) architecture has been effectively constructed by closely coupling a common complementary metal-oxide semiconductor sensor array with a compact Si-based NOA chip. An obvious improvement in the imaging performance has been realized using the NID construction with a wider radiation response range.

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I. INTRODUCTION

Near-infrared spectroscopy, based on rapidly developing photosensitive complementary metal-oxide semiconductor (CMOS) technology, will conveniently deliver information that is difficult to obtain from other, traditional infrared wavelength bands, such as the atmospheric absorption of molecules (greenhouse gases) or their thermal radiation emission, leading to meteorological

maps or biological imaging [1–3]. Unlike conventional imaging in the visible region, the current mainstream infrared detection schemes already exhibit numerous merits, such as target intrinsic radiation sensing and imaging, deeper penetration in complex environmental media, and a remarkably enhanced signal-to-clutter ratio, especially in night vision and biological imaging [4–7]. Moreover, despite sunlight being predominantly composed of visible light (71%), the energy density in specific near-infrared bands is substantially lower. The reduced solar background in specific near-infrared bands allows for higher-contrast imaging with remarkably improved performance during the daylight period. However, the key limitation on the imaging efficiency of current CMOS sensors lies in their inherently low quantum efficiency, particularly in the near-infrared region, which can be attributed to several factors, such as the inherent metal-semiconductor

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energy-band architecture or configuration, relatively strong radiation penetration in the depletion layer, and generally insufficient incident photon flux, which remarkably restrain the generation of photon-induced hole-electron pairs and thus result in a relatively weak photoelectric signal creation [8,9]. Therefore, developing strategies to promote carrier generation is critical.

As typical optical antennas, cone-shaped nanotips enable remarkable light-wave accumulation and even nanofocusing, providing a promising micro-nano-optical platform for highly localized and resonantly amplified incident light waves [10–15], which can be further used to realize highly sensitive infrared imaging detection by reasonably matching with a CMOS photosensitive chip. As demonstrated, an arrayed semiconductive nanotip optical antenna (NOA) can offer a large number of tip surface states due to its large top specific surface area over the apex region. Consequently, it enables a highly efficient collection or spatial compression of massive surface “free electrons” toward the sharp apex of a single tip, leading to an incredibly strong surface “free electron” converging at or even focusing on the apex [16]. It should be noted that the above effect is also accompanied by a strong resonant surface electromagnetic wave field toward the nearest-neighbor tip apex, followed by a highly localized geometric surface light-field enhancement, which means a strong surface light-field resonant accumulation [17–19]. Due to a temporally coherent response [20–22], there is a significant enhancement of the surface light field, which is closely related to a dense surface net charge, including electron distribution over the apex. Therefore, a highly localized surface light field around the apex of a single nanotip, induced by incident light waves with a featured frequency in a narrow band, also indicates a remarkable boost in near-field radiation detection at a similar frequency to that mentioned above [23–25].

As shown, a type of microchannel plate (MCP) is usually constructed as a beehivelike array comprising tens or even hundreds of millions of hollow-core glass fibers, acting as an electron multiplier for guiding electron or photoelectron enhancement and transport. The MCP enables the electron multiplication through a primary electron entering a microscopic channel and then being accelerated by a strong electric field applied across the whole channel. After an electron obtains sufficient energy, it will strongly collide with the channel inner wall and then eject several secondary electrons. The secondary electrons are further accelerated by the electric field, and then strike the inner wall and thus release even more electrons. This cascaded collision will create exponential growth in the electron population and ultimately actuate a single input electron into a dense cloud of electrons at the output, thereby achieving highly efficient signal amplification. Finally, a large voltage signal V can be produced, as presented on a common oscilloscope. According to the product

parameters of the intrinsic electric capacity of the oscilloscope C , the electron number n can be simply expressed as $n = \frac{C \times V}{\alpha \cdot e}$, where the signal amplification gain of the MCP is α , and the charge of a single electron is e . Thus, n can be easily obtained through the measured V . Generally, a very fast electron amplification through an MCP enables a variety of surface net-charge measurements based on some featured behaviors of the surface “free electrons” after resonant excitation, patterned redistribution, and short-range transportation over the optical antenna, so as to provide the needed spatial and/or temporal information according to the detected photons, electrons, ions, or neutrons [26–29]. Hence, it also offers a potential approach for evaluating the weak radiation-induced surface electrons in the near-field or far-field region of the NOA, utilizing an almost real-time MCP measurement.

In this paper, an efficient and low-cost light-wave manipulation strategy based on the localized geometric field enhancement, mainly using a silicon-based NOA structure to perform near-infrared imaging of several typical small objectives with relatively weak electromagnetic radiation levels, is proposed. The remarkably enhanced electric field and corresponding featured net-charge behavior, as well as the imaging performance based on the NOA architecture, are carefully investigated. The near-infrared photoelectronic response principally concerns several crucial factors, including (1) the geometric field enhancement closely coupled with the surface net charge, including “free electron” vibration and short-range tipward transportation; (2) the field electron emission away from the apex of a single tip with a top angle θ ; (3) the photoelectric signal collection for the next imaging operation; and (4) the point-spread function (PSF) measurement and imaging performance testing of the constructed nanotip-based imaging detector (NID) architecture. The featured photoelectrical response exhibits ideal agreement in spectral electric-field amplitude gain, which already presents a sharp resonant peak of 84.77 at 1000 nm wavelength and an ultralow radiation transmittance of less than 2% across the whole measured waveband from 400 nm to 14 μm . The output voltage signal, recorded by directly coupling the NOA with a commercial MCP, presents a high sensitivity of the incident light power at a specific wavelength. Numerically, the strongest photoelectric response can reach 186.05 mV with an average duration of 16 ns under laser illumination of 2.47 W at 980 nm. The results of the PSF testing, based on various measurement configurations, show that the proposed NOA enables a distinct expansion of the focused light spots and a higher intensity corresponding to a single nanotip, manifesting a significant increase in the light intensity incident on the followed CMOS photosensitive plane. In comparison with the same type of CMOS detector recoupled with a similar silicon wafer without any patterned structure, the constructed NID exhibits a more durable and clearer presentation of the drone

exposed directly to intense sunlight illumination. Notably, our research already expands the scope of antidisturbance near-infrared imaging and serves as a catalyst for further exploration in advanced infrared imaging photography. The unique combination of nanosecond-scale response and remarkable near-infrared imaging performance enables potential applications in advanced light-field photography, single-shot ultrafast imaging, electrically tunable weak infrared information transportation, and photoelectronic interconnection.

II. RESULTS AND DISCUSSION

A. Simulated spectral characters

To characterize the light-wave manipulation efficiency of the arrayed NOA, both performance simulations and evaluation measurements are conducted, as shown in Fig. 1. The schematic drawing of the simulated system is provided in the inset of Fig. 1(a). The three-dimensional electromagnetic fields are simulated using the common finite-difference time-domain method. A perfectly matched layer boundary condition is applied corresponding to the computational domain. The converged broadband imaging light beams, spanning the visible and infrared regions within a wavelength range of 400 nm to 14 μm , are directly incident over the planar back of the thinned NOA to obtain the radiation transmittance and electric-field amplitude gain data via the power and field monitors, respectively, which have been normalized according to $|E/E_0|^2_{\text{max}}$, where E denotes the electric-field amplitude along the surface of the NOA and E_0 denotes the electric-field amplitude of the incident beams. As illustrated in Fig. 1(a), the value of $|E/E_0|^2_{\text{max}}$, basically defined as an electric-field amplitude ratio, exhibits a wavelike variance trend across the whole wavelength range selected but obviously presents a resonant peak with a height of 84.77 at 1000 nm wavelength (orange curve). The spectral analysis further reveals an ultralow radiation transmittance, which almost maintains a very low transmittance of less than 2% throughout the whole waveband mentioned (blue curve). Notably, both the electric-field amplitude gain and the radiation transmittance demonstrate an almost consistent spectral variance trend. Considering the constrained relationship between the spatial electric-field distribution and the surface net-charge arrangement, the light-wave transmission should be dominantly manipulated by the patterned surface net-charge distribution, which is mainly converged or even nanofocused over the arrayed nanotips. Both the spectral electric-field amplitude gain and the beam transmittance within the relatively narrow wavelength range of 400–2200 nm are further enlarged, as shown in Fig. 1(b). The spatial $|E/E_0|^2$ over the x - z cross section at 1000 nm is also given in Fig. 1(c). The maximum value of $|E/E_0|^2$ demonstrates an almost 90 unit peak according to the color scale, which can be easily explained

based on the traditional half-wavelength theory of common radio frequency dipole antennas. It should be noted that the main net-charge accumulating region currently occurs in the middle of a single NOA without any metallic coating, which is still consistent with previous work [16].

In order to evaluate the simulation analysis, both the beam reflection and transmittance characteristics are measured corresponding to the silicon samples with and without upright nanotips, using the same type of silicon wafer with a thickness of approximately 150 μm , as indicated by the two curves colored red and black, respectively. As shown in the left panel of Fig. 1(d), the reflection spectrum of the NOA sample presents a gradually decreasing trend in the visible region, from an initial 28% to a relatively stable value of 10%, and the silicon sample without any nanotip structure decreases from a maximum of 68% to a minimum of 30% and then reaches a relatively stable value of 45% in the near-infrared region. As for the right panel, the transmittance of the NOA sample presents an almost stable value of less than 2%, corresponding to a rapid rise of more than 50% of the silicon sample after crossing the approximately 1000 nm wavelength point. The measured transmittance data show significant agreement with the simulation demonstrated in Fig. 1(b), with the transmitted value nearing 0 in the infrared band selected. It can be expected that the difference in the variance trends, especially at 700 nm, may result from a combination of factors, including the edge effects of the measurement instrument, the thickness differences of the silicon substrate used, the accuracy limitations of the testing equipment, and the light-wave dissipation in the measuring environment. A similar spectral variance trend in the two samples can also be observed in a narrow waveband from 400 to 900 nm. A remarkable broadband radiation absorption can also be derived from both the ultralow light-wave reflection and the radiation transmission. The action above suggests that the efficient light-wave manipulation stems from a broadband resonant response mode with two basic features: (1) the generation of very strong spatial near-field electromagnetic radiation; and (2) the patterned surface net charge, including “free electron” rearrangement in an oscillated fashion over the surface of the NOA structure. It should be noted that when compared with the strictly defined absorber with an absorption maximum of nearly 100% [30–32], the reflection of the NOA remains about 10% within the wavelength region of 600–2200 nm, which can be attributed to the lack of an insulator layer, designed for presenting better imaging performance, and the fact that incident near-infrared light beams are not sufficiently trapped in the NOA architecture designed. So, the light waves are predominantly backscattered along their original incident path, resulting in a higher level of observed reflection.

To evaluate the spatial extent of the near-field electromagnetic radiation, simulations of a gradual decline in the

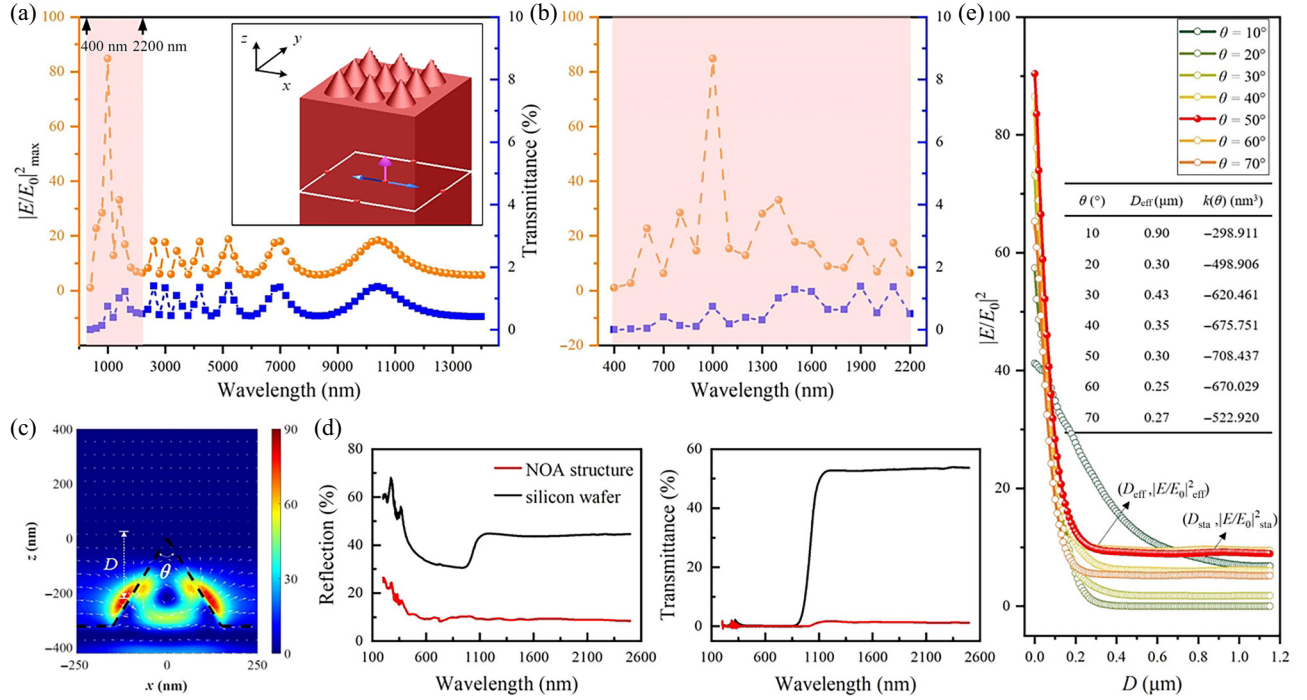


FIG. 1. Spectral photoelectronic response characteristics of the arrayed silicon-based NOA, corresponding to the silicon sample without any micro-nano-structures, in a wavelength range from the visible to the broad infrared region. (a) Typical cases of the spatial electric-field amplitude gain, roughly indicated by $|E/E_0|^2_{\text{max}}$, and the spectral transmittance in a broad waveband of 400 nm–14 μm. The simulated drawing is presented in the inset. Note that the inset only describes the simulated configuration and not the actual size (e.g., the thickness of the silicon substrate). (b) An enlarged view of $|E/E_0|^2_{\text{max}}$ and the radiation transmittance in a narrow waveband of 400–2200 nm. (c) The strongest electric-field component is presented mainly in the middle of a single nanotip with a top angle θ , shown only in the x - z cross section illuminated by a plane wave with a central wavelength of 1000 nm, where the electric-field vectors are highlighted by white arrows and the NOA is depicted by a black dotted line. See the enhanced visualization in Sec. 1 of the Appendix. (d) Both the reflection and transmittance spectrum of the silicon sample, with and without nanotip distribution, measured in the visible and near-infrared regions. (e) The spatial electric-field character expressed by $|E/E_0|^2$ upon the distance between the NOA with different θ values and the observing distance. The distance D_{eff} corresponding to each $k(\theta)$ is listed in the inserted table.

spatial electric-field strength as a function of the distance between the observing location and the silicon-based NOA structure were conducted, as shown in Fig. 1(e). Note that the distance between the main net-charge accumulation region and the observed point is measured only along the z -direction, as labeled in Fig. 1(c). Currently, the simulation results present a rapid reduction of $|E/E_0|^2$, such as from 90.39 to 9.95, but only undergoing a 0.3 μm distance increase when $\theta = 50^\circ$ is selected, where D is the observing distance. So, a normalized difference parameter diff, which is introduced to directly characterize the electric intensity reduction ratio, can be defined as

$$\text{diff} = \frac{|E/E_0|^2 - |E/E_0|^2_{\text{sta}}}{|E/E_0|^2_{\text{sta}}} \times 100\%, \quad (1)$$

where $|E/E_0|^2_{\text{sta}}$ indicates a relatively stable state with a different base level of roughly less than 11 units, corresponding to θ varying from 10° to 70° with designed

intervals of 10° , which are labeled by different colors in this figure.

Furthermore, $|E/E_0|^2_{\text{eff}}$ is defined as a featured $|E/E_0|^2$ corresponding to a still strong enhancement of the spatial electric-field strength, and it later turns into a stable state with a continuously increased D , which can be easily observed as the point where the decline levels off and stabilizes. The distance corresponds to the variance $|E/E_0|^2_{\text{eff}}$, which is defined as D_{eff} . Generally, $|E/E_0|^2$ will rapidly decrease to 10% of its initially large value. The coefficient $k(\theta)$, which is introduced to highlight the numerical linear relation between $|E/E_0|^2$ and the change in distance ΔD^{-3} varied from θ , can be calculated as an average of every $k(\theta)_i$ through an empirical relation of $|E/E_0|^2_{i+1} - |E/E_0|^2_i = k(\theta)_i (D_{i+1} - D_i)^3$ ($i = 1, 2, \dots, 116$ corresponds to different points with featured D). As demonstrated in experiments, a sharp top angle with a very small θ will usually introduce a strong Coulomb blockade, leading to a small $k(\theta)$, especially at 10° . And a gentle nanotip top will result in a relatively

weak spatial electric field and a finite enhancement, such as occurs in a typical top angle region from 60° to 70° . Noting that $|E/E_0|_{\max}^2$ can reach 10 at 800 nm, which seems to conflict with the results of NOA in Fig. 1(d), this discrepancy can be attributed to the relatively thin substrate of 10 μm utilized in the simulation. Consequently, the numerical simulation indicates an optimal nanotip top angle of 50° for maximizing the top electron number and the localized extent of the spatial electric fields stimulated around a single tip, which means an ideal photoelectronic response.

B. Photoelectric response

The basic experimental configuration for performing photoelectric response measurements of the Si-based NOA, which plays a role as a photocathode for an electronic supplier, is illustrated in Fig. 2. The basic structural sizes of the Si-based nanotip array are as follows: a single nanotip has an average bottom diameter of 309 nm, a top angle of 50.85° , and a height of 325 nm. The adjacent nanotips share a basic structural period of 1130 nm in both the horizontal and perpendicular orientations according to the scanning electron microscopy (SEM) photograph, with several key parameters labeled, as shown in Fig. 2(a). An MCP characterized by a single anode and an average single microchannel diameter of 12 μm is effectively introduced to collect the incident electrons away from the Si-based NOA, illuminated by near-infrared radiation with a central wavelength of 980 nm, and then export several typical output voltage signals, as shown in Fig. 1(b). Consequently, the photoelectric response of the proposed Si-based NOA coupled with the MCP, leading to an N-MCP assembly, can be clearly characterized by the recorded output voltage signal. After roughly aligning the Si-based NOA with the MCP, they are tightly secured using yellow packaging tape, so as to finish the preliminary adjusting of the N-MCP, as demonstrated in Fig. 2(c).

The measuring schematic is given in Fig. 2(d). As shown, a laser beam directly illuminates the back (without any patterned structure) of the Si-based nanotip sample through an incident window positioned at the bottom of the vacuum chamber with a working vacuum of approximately 10^{-6} mBar, which allows a further tight coupling between the Si-based NOA and the MCP chip, which has a thickness of 600 μm and a diameter of 27 mm. First, a rotary vane pump is utilized to perform an initially short-time preliminary vacuuming of the chamber. After reaching a rough vacuum environment of approximately 10^{-2} mBar, it is then switched to the working state using a molecular pump to further increase the vacuum degree until it ultimately reaches a level of 10^{-6} mBar. A relatively small electron flux away from the Si-based NOA is thus amplified by the MCP by applying a bias voltage between the NOA and the MCP and then recording the output

voltage signal using a nanosecond-scale high-speed oscilloscope (MSO54B, Tektronix Inc). Therefore, the recorded time-varied output voltage signal is continuously utilized to characterize the photoelectric response behavior, including the tip electron excitation and the *in vitro* emission of the NOA stimulated by the incident light waves. Considering the unidirectional and spatially averaged nature of the applied electric field across the NOA + MCP system, the voltage signal directly presents the net-charge accumulation characteristics over the NOA, especially the electron number. The basic electric circuit of the MCP is also given in the right panel. Moreover, a vacuum monitoring and electrical control system has already been added according to the testing configuration, as shown in Fig. 2(e). A top view from the observation window of the vacuum chamber is also illustrated in the inset.

Currently, the photoelectric response of the N-MCP is mainly indicated by the output voltage signal recorded under different beam incident conditions, as shown in Fig. 3. Firstly, the N-MCP without any illumination is selected as a blank comparison basis, exhibiting a systematic noise of 1 mV but having a relatively high abnormal value of 10 mV at the zero-point, as shown in Fig. 3(a). The incident light wave with a central wavelength of 980 nm is generated from a continuous near-infrared laser source (MRL-III-980, Lier-opto Technology Ltd.). Adjusting the bias current I of the laser source at 1.50, 2.00, and 2.50 A means an output laser power of 1.80, 2.00, and 2.47 W, respectively. Note that the actual incidence intensity over the N-MCP is substantially lower than the output power of the laser device above, due to an obvious light attenuation of the window material in the region. A comparison of the photoelectric response under various incident intensities mentioned above is illustrated in Fig. 3(b). As shown, the maximum amplitudes of the voltage signal are 20.77, 84.80, and 186.05 mV, respectively, presenting a significant increasing trend as the incidence radiation intensity strengthens. Moreover, the duration between adjacent voltage peaks is shorter, and the larger peak value can be clearly observed after undergoing more intense illumination. It can be expected that a more significant voltage signal can be obtained by further increasing the illumination intensity, which means that a stronger photoelectric response of the proposed N-MCP can be achieved by continuously raising the bias current of the laser source used.

The photoelectric measurements under different incident wavelengths λ of 473, 655, 980, and 2200 nm are also performed, as shown in Fig. 3(c). The incident light waves with different λ are generated from varied light sources featuring the central wavelength mentioned. The output power of the sources mentioned is set to a uniform 0.40 W, which is also the maximum output power of the 2200 nm laser source. Considering an approximate 10% power loss through the optical window (fused silica)

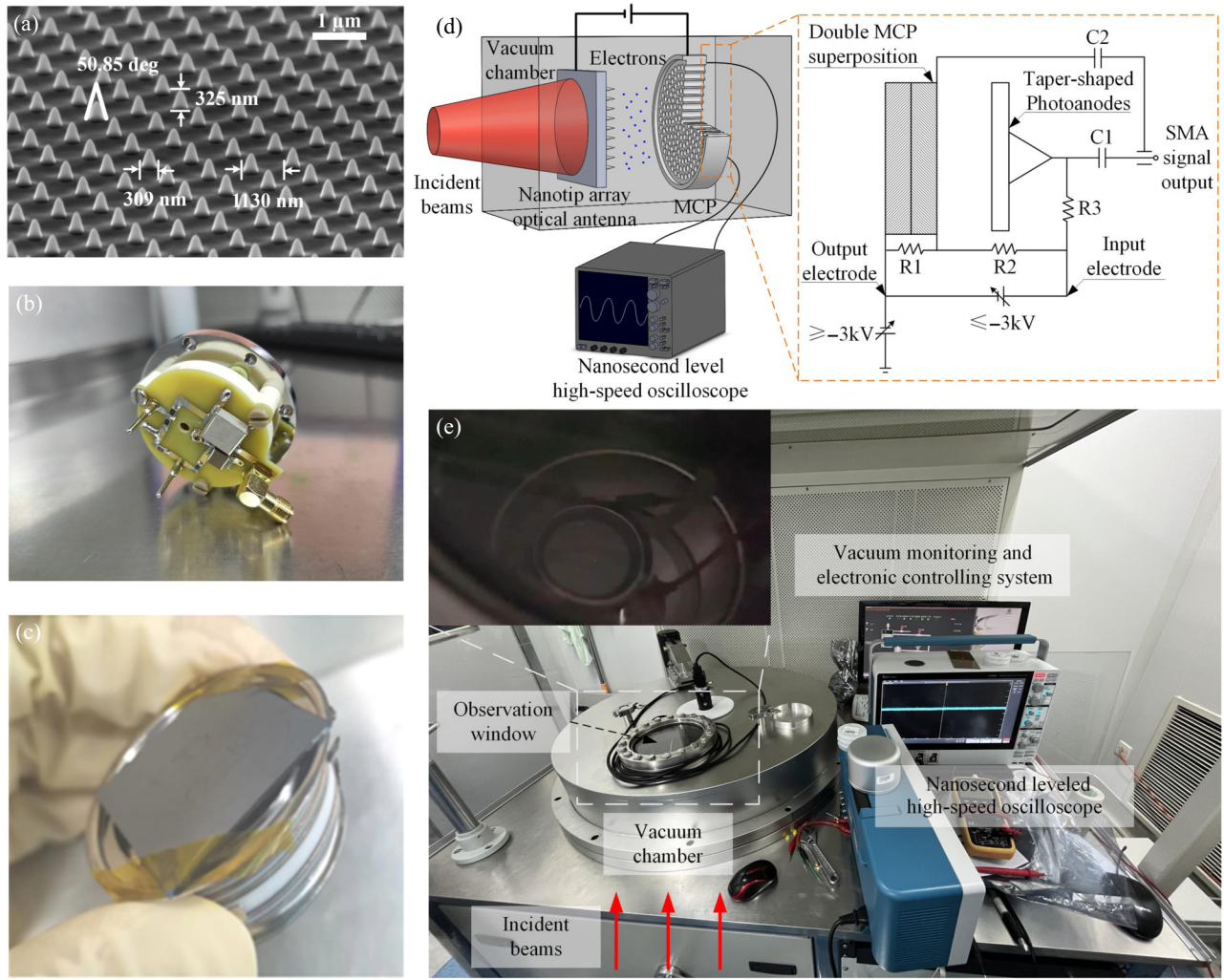


FIG. 2. Experimental configuration for performing the photoelectric measurements of the Si-based NOA. (a) Scanning electron microscopy photographs of an arrayed Si-based nanotip leading to an optical antenna with several key parameters labeled. See the detailed geometric parameters of NOA in Sec. 2 of the Appendix. (b) The applied MCP assembly has a single anode and an average single microchannel diameter of $12\ \mu\text{m}$. (c) Alignment between an initial Si-based NOA proposed and an MCP fixed by yellow packaging tape. (d) Testing schematic with a Si-based NOA and an electrical circuit of the MCP coupled. See the key parameters of the N-MCP measuring circuit in Sec. 3 of the Appendix. (e) On-site measurement configuration under a working vacuum of approximately 10^{-6} mBar for the electronic delivering requirement. A view from the top observation window of the vacuum chamber is also presented. Noting that the schematic diagram in subfigure (d) only describes a configuring relationship but not the actual matching.

located at the bottom of the vacuum chamber, the incident power at the NOA can be regarded as about $0.36\ \text{W}$. The transmission of the optical window is provided in Sec. 4 of the Appendix. To the visible beams of 473 and $655\ \text{nm}$, the output voltage signals exhibit an obvious periodicity with a relatively stable time interval between adjacent peaks. The periodicity at $655\ \text{nm}$ is more significant, with an average time interval of $17.4\ \mu\text{s}$, as well as an average duration of $500\ \text{ns}$. However, both the electrical signals generated under the visible beam illumination are comparatively weak, with peaks of $2.5\ \text{mV}$ and $4.5\ \text{mV}$. To the beams, two extremely high maximum amplitudes of 186.0

and $87.1\ \text{mV}$ can be observed at 980 and $2200\ \text{nm}$, respectively. Nonetheless, it is strange that it no longer exhibits a periodic voltage signal output in the near-infrared region. Except for the significantly higher maximum amplitude of the output voltage signal, a relatively short duration of the voltage signal wave of $16\ \text{ns}$ at a $980\ \text{nm}$ wavelength can be clearly observed, in comparison with the similar case of $20\ \text{ns}$ at a $2200\ \text{nm}$ wavelength. The time dependence of the measured voltage signal may be linked to the resonant frequency of the net charge over the NOA surface. So, the comparison under a series of incident wavelengths from the visible to the infrared region suggests that the

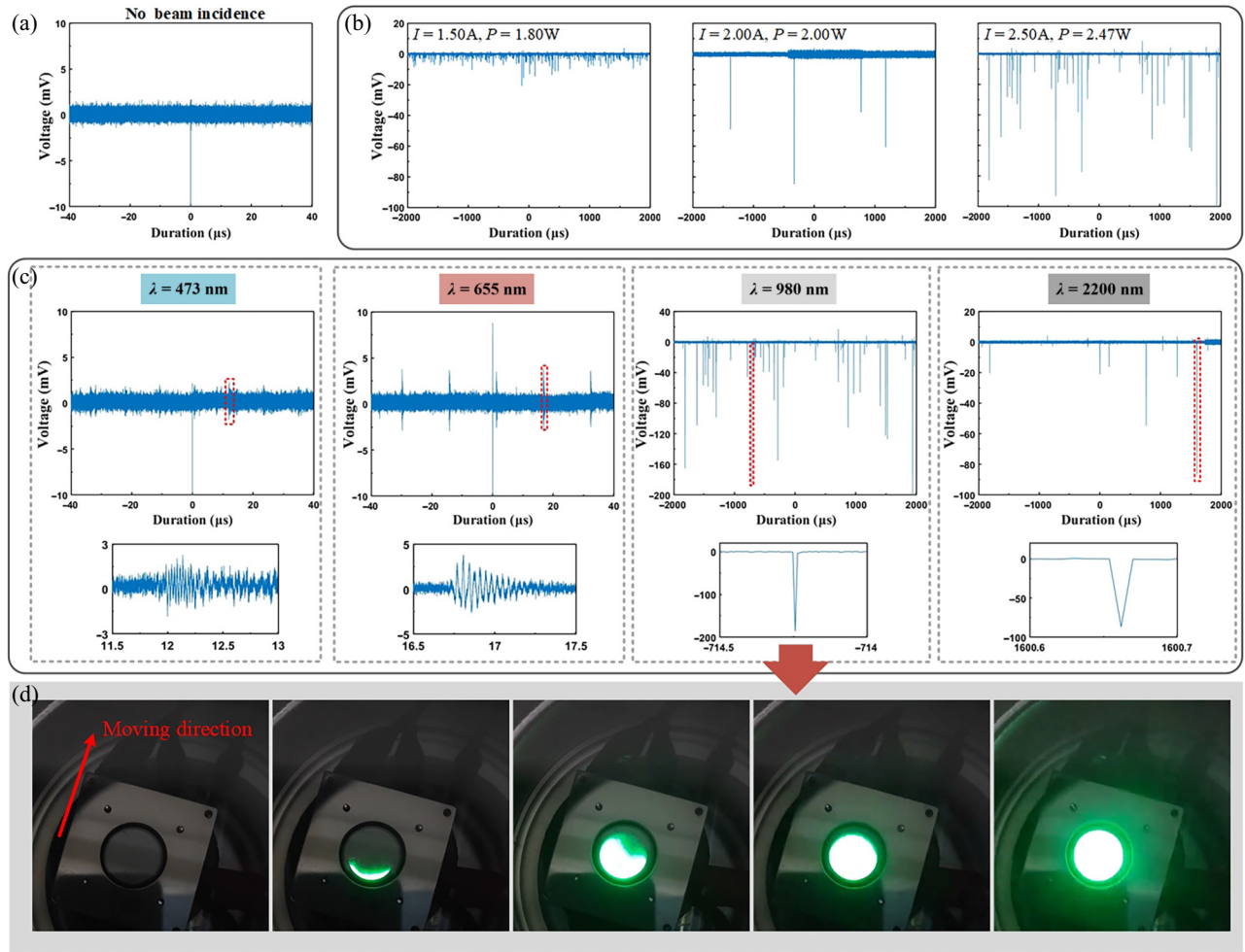


FIG. 3. Comparison of the photoelectric response of the proposed N-MCP under incident illumination with different intensities and central wavelengths in both the visible and near-infrared bands. (a) Output voltage signal of the N-MCP without any incidence. (b) Photoelectric responses under the illumination of 980 nm radiation with different light intensities of 1.80, 2.00, and 2.47 W, respectively. (c) Photoelectric responses by the incident radiation with different wavelengths λ of 473, 655, 980, and 2200 nm, respectively. Several typical voltage peaks are labeled by red dotted boxes, and the corresponding enlarged views are also given in the panel below. (d) Fluorescent irradiation stimulated by the electron flows away from an assembly of an MCP and a NOA directly illuminated by a moving 980 nm laser with an average incident power of 22 μW . The moving direction of the laser source is indicated by a red arrow. The dynamic illumination process is displayed in Video 1.

most remarkable photoelectric response currently appears at 980 nm, which is consistent with the simulations at a 1000 nm wavelength. The above phenomenon should be attributed to an adaptability between the structural parameters of the Si-based NOA and the incident wavelength, as well as the intrinsic infrared response characteristics of the silicon material used.

After adopting a traditional fluorescent screen to replace the oscilloscope and then setting a guiding voltage of approximately 5500 V across an approximately 1.5 mm gap between the MCP and the fluorescent screen, the bright fluorescent spot variance, resulting from the accumulated electron emission away from the NOA and finally striking the fluorescent screen, is recorded using a common

CMOS sensor (see the experimental principle and the setup design in Sec. 5 of the Appendix). So, a 980 nm laser driven by a bias current I of 1.5 A is used to directly illuminate the back of the NOA sample, which is also loaded with a relatively low operating voltage of approximately 200 V corresponding to the MCP, and thus the screen is brightened sequentially from the initial all-black state to the final bright state indicated by the leftmost and the rightmost figures, respectively, as the laser source moves along the direction labeled in Fig. 3(d). Consequently, the measured results confirm that a strong electron flow can be efficiently emitted from the proposed NOA structure, highlighting the action of performing a spectral conversion from the initial infrared region selected to the

visible band with a central wavelength of approximately 544 nm.

C. Imaging performance

Furthermore, a comparison of the PSF according to different detection architectures is also carried out, as shown in Fig. 4. The measuring light path is given in Fig. 4(a). As shown, a linearly polarized laser with a central wavelength of 980 nm and a diameter of approximately 1.7 cm is shaped after continuously passing through a well-designed beam expander and a linear polarizer. Then, a liquid-crystal (LC) device applied with a bias voltage of 10 Vrms is utilized to produce an arrayed focusing spot [33–35]. The approximate focal length can be calculated based on the measured interference pattern, as shown below,

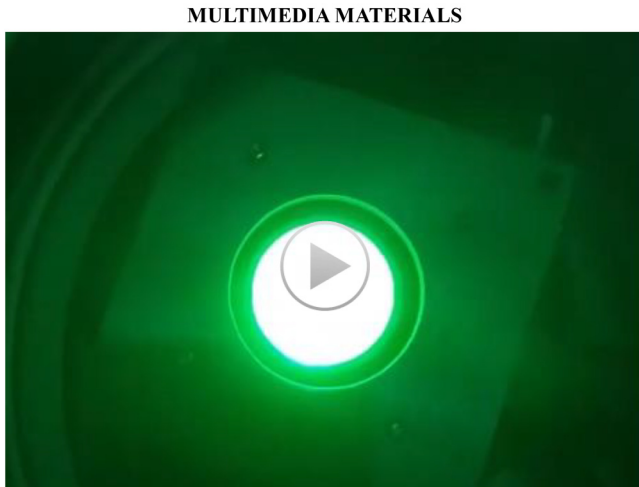
$$f = r^2/2\lambda N, \quad (2)$$

where r represents the radius of the lens aperture, λ the wavelength of the incident lasers, and N the number of observed rings, which should be negatively correlated with the magnification of the objective.

Based on the traditional Fresnel approximation imaging expression [36], the PSF intensity distribution over a Fourier plane selected with an axial depth z can be obtained in a basic relation of

$$I(u, v; z) \propto \left| \text{FFT}_2 \left\{ \exp \left(i \cdot P(x, y) + \frac{2i\pi M}{\lambda f} \cdot (u \cdot \Delta x + v \cdot \Delta y) - \frac{i\pi M^2 \cdot z}{\lambda f^2} (x^2 + y^2) \right) \right\} \right|^2, \quad (3)$$

where FFT_2 denotes a fast Fourier transformation, $P(x, y)$ the phase distribution loaded over the Fourier plane selected in the Cartesian coordinate system (x, y) , M the



VIDEO 1. Visualization of electron fluorescence excitation.

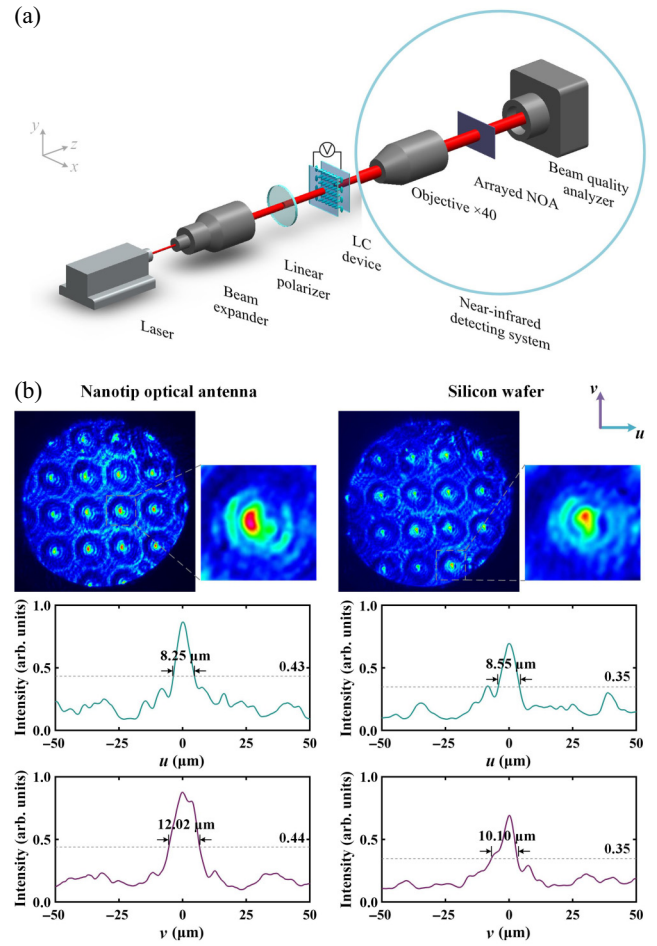


FIG. 4. Measurement setups and the infrared imaging performance comparison based on the PSF measured with and without a Si-based NOA. (a) Measuring the light path. (b) Measured light-field distributions for different infrared detecting configurations. The enlarged views and the intensity variation along the u - and v -directions of a single focused spot are also given. Note that the schematic diagrams in the subfigure only describe the configuration relationship without conducting a structural size matching; arb. units denotes arbitrary units.

magnification of the near-infrared detecting system, Δx and Δy the lateral displacement, and (u, v) the position over the focal plane of the objective with $f \approx 30$ cm.

So, the intensity morphology over the focal plane being axially shifted Δz distance can be expressed as

$$I(u, v; z + \Delta z) \propto \left| \text{FFT}_2 \left\{ \exp \left(i \cdot P(x, y) + \frac{2i\pi M}{\lambda f} \cdot (u \cdot \Delta x + v \cdot \Delta y) - \frac{i\pi M^2 \cdot z}{\lambda f^2} \cdot (x^2 + y^2) - \frac{i\pi M^2 \cdot \Delta z}{\lambda f^2} \cdot (u^2 + v^2) \right) \right\} \right|^2, \quad (4)$$

where $\Delta z = f - z$. Finally, the featured incident light field can be properly regulated by the detecting system configured with an objective of $40\times$, the proposed NOA, and a beam-quality analyzer (Edmund Optics Beam Profiler 4M) [37]. Through using a silicon wafer of the same thickness to offset the light energy variance by the silicon material utilized, the focusing performance according to different detecting configurations is found and is shown in Fig. 4(b).

As shown, the focusing spots, distributed in an orderly manner through the regulation of the LC device, can be observed clearly. A higher intensity and a larger beam convergence size can be obtained using the proposed Si-based NOA in contrast to that only employing a silicon wafer of the same thickness, according to the enlarged views of a single focusing spot. The intensity variance along the u - and v -orientations corresponding to a single focusing spot, obtained by introducing a NOA and then a silicon wafer, respectively, is also provided in the lower panels. The full width at half maximum of the peak with $\{8.25 \mu\text{m}/u, 12.02/v\}$ of the NOA and $\{8.85 \mu\text{m}/u, 10.10/v\}$ of the silicon wafer can be easily acquired along the gray dotted lines. As shown, an intensity peak based on the NOA already reaches values of 0.86 and 0.88 along the u - and v -orientations, respectively, while the maximum intensity acquired using only the silicon wafer is 0.7 along the same orientations. So, the obvious inconsistency of the full width at half maximum can be attributed to errors during manual focusing, and the proposed NOA presents a better surface electron collecting and emitting efficiency. It should be noted that a higher and wider PSF being formed indicates that a greater number of the surface electrons have swarmed into the tip apex, thereby expanding the effective light-field emission area of the nanotip top, and thus there follows a significant improvement of the detection performance.

Meanwhile, the developed Si-based NOA is further applied to perform a nearly real-time CMOS-based infrared imaging detection of an unmanned drone, as demonstrated in Fig. 5. During outdoor imaging measurements, a common unmanned drone, used as a target, is exposed directly to intense sunlight. The reflective beams from the drone are received by the NID, shown by a blue dashed box in Fig. 5(a), and the imaging data are continuously uploaded to a PC. The prototyped near-infrared imaging system is constructed successfully by reasonably configuring an imaging lens and a common CMOS detector chip coupled tightly with a developed Si-based NOA, which should be correctly mounted over the CMOS photosensitive end face [37]. A key coupling process is shown in the right subfigure, where an ideal configuration is realized because of a faint yellow light spot indicating the Si-based NOA chip is almost in contact with the CMOS photosensitive surface, which is roughly labeled by a red dashed line perpendicular to the adjusting direction indicated by a green arrow. For the practical

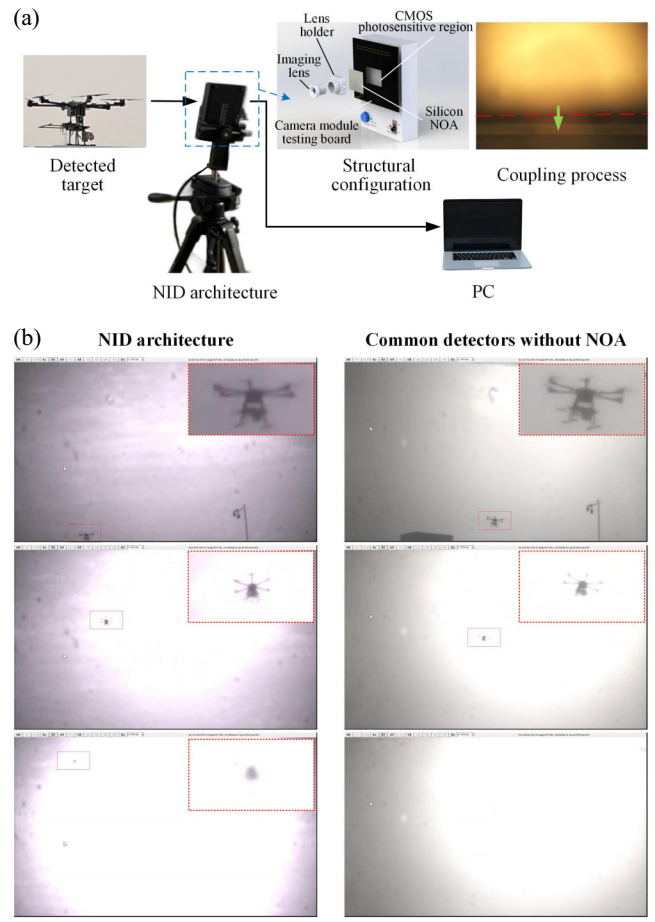
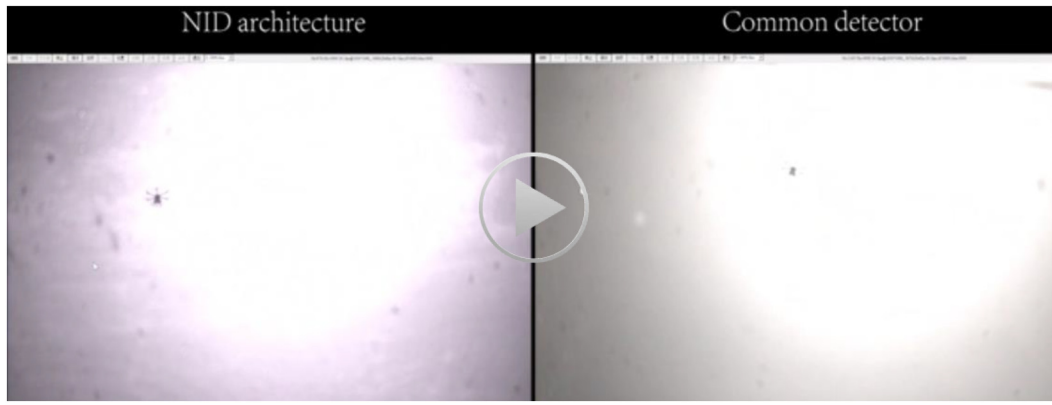


FIG. 5. Outdoor real-time infrared imaging measurements based on a common CMOS imaging detector with and without a Si-based NOA under intense sunlight illumination. (a) Key infrared imaging configuration leading to an NID architecture, where a coupling process is attached by a microscope assembly of a Si-based NOA and a CMOS photosensitive chip. (b) Imaging comparison according to the detection architecture with and without the Si-based NOA structure. The enlarged views of the electronic targets are also inserted.

coupling process in detail and the coupling tolerance, see Secs. 6 and 7 of the Appendix, respectively. Note that the mentioned NOA + MCP structure is formed for efficiently extracting the field electron away from the NOA, which can be obviously observed according to the simulations via the measured voltage signal recorded by the oscilloscope. Considering the case of performing an electron delivery operation, the experimental condition with a working vacuum of approximately 10^{-6} mBar is set. In contrast, the proposed NOA-CMOS architecture for performing near-infrared imaging is based on the localized resonant electric-field enhancement of the NOA, which can be conducted under common atmospheric conditions.

In order to exhibit the imaging efficiency improvement based on the Si-based NOA configuration, a pure silicon wafer with the same thickness as the NOA chip is



VIDEO 2. Test comparison of antidisturbance near-infrared-imaging.

alternatively inserted between the imaging lens and the CMOS detector, so as to construct a similar infrared imaging architecture for observing the same flying drone. The practical measurement conditions are as follows: ambient temperature of $25.3\text{ }^{\circ}\text{C}$ and direct sunlight illumination of $7.2 \times 10^8\text{ lux}$. The imaging measurements with and without a Si-based NOA chip in the takeoff stage of the drone are illustrated in Fig. 5(b). Two compared imaging configurations were measured within a 20 min interval, during which we monitored and confirmed the stability of key environmental factors, such as the temperature. Both comparable videos are provided in Video 2. It should be noted that the silicon material functions as a spectral filter that will effectively block the visible beam while allowing the near-infrared radiation into the CMOS detector, thereby enhancing the near-infrared imaging performance, especially through reducing the solar background.

First, the drone will reach a suitable altitude of more than 10 m in direct sunlight illumination after takeoff, and its entire construction, including the wings and several attachments, can be clearly imaged by the NID architecture as well as by a common CMOS detector without any NOA structure; in other words, it is only being configured with the common silicon wafer mentioned, as shown in both the upper subfigures. After a relatively slow flight, the images of the drone are already fuzzy at a distance of approximately 60 m from the observing site, where the image obtained by the NID is relatively clearer than that obtained by the common CMOS detector against a strong sunlight background, and the drone's frame and its wings can still be distinguished, as shown by both the middle subfigures. As the drone gradually nears its altitude limit at a distance of approximately 150 m, its outline is barely discernible in the image obtained by the NID architecture, in which its propellers and wings have almost disappeared. As a comparison, the image of the drone has completely disappeared in the image using the common CMOS detector only configured with a silicon wafer, as shown by both the bottom subfigures. So, a gradually disappearing view of

the drone's body can still be recognized by the NID, especially under intense sunlight illumination, which indicates a wider radiation response range of the NID architecture. Finally, the drone is totally buried by the background radiation. It should be noted that although the imaging signals from a small drone target and the background radiation are both enhanced by the NOA used, a strong signal only generated by direct sunlight will result in a rapid saturation of the photosensitive signal of partial CMOS pixels only sensing incident sunlight in the region. Consequently, the relatively weak signals from the drone are remarkably highlighted, which also obviously increases the imaging contrast.

The imaging detection measurements above demonstrate that the Si-based NOA can be effectively employed to significantly improve the antidisturbance ability of the constructed imaging system, so as to obviously improve or even strongly enhance the imaging detection performance. It can be expected that the current imaging detection efficiency can be further boosted by utilizing a better imaging lens and configuring an efficient matching algorithm, for example, by adopting machine learning to enhance the target recognition efficiency. So, the approach will highlight the continuous development of the imaging detection method based on the basic NID architecture proposed.

III. CONCLUSION

In summary, an arrayed silicon-based NOA architecture is successfully developed for guiding efficient imaging detection based on geometric field enhancement and patterned surface net charge, such as through "free electron" redistribution, leading to highly localized tip electron accumulation, strong field electron emission away the tips, and continuously visible cathodoluminescence. Spectral characterization analyses exhibit a strong electric-field amplitude gain of 84.77 at a 1000 nm wavelength and an ultralow radiation transmittance of less than 2% across a broad wavelength range from 400 nm to 14 μm . The

output voltage signals of the MCP, tightly coupled with a developed NOA, which induces electrically controlled electron amplification and spatial transportation in a high vacuum environment, are sensitive to the incident radiation power, reaching a high value of 186.05 mV under an illumination of 2.47 W. Additionally, the photoelectric response measurements also present an intense output voltage signal, as well as a nanosecond-level time interval between adjacent output peaks and a shorter duration of a single peak at a 980 nm wavelength. A clear visualization, derived from directly striking a small fluorescent screen with the electrically adjusted electron flows from the proposed Si-based NOA, is realized experimentally. The PSF, according to different measurement configurations, indicates that the proposed NOA exhibits a remarkably strengthened and expanded light-wave nanofocusing, which results in a notable light-field enhancement thanks to the Si-based NOA chip. Furthermore, a type of NID architecture has already been proposed by tightly coupling a common CMOS photosensitive array with a highly compact Si-based NOA chip. An effective improvement in the antidisturbance imaging detection has been realized by utilizing the NID architecture, which demonstrates a wider radiation response range corresponding to the CMOS sensor without any NOA structure. It can be expected that the proposed imaging method, with an extremely short electric pulse duration and a unique imaging detection architecture, can be utilized in many potential applications such as advanced light-field photography, single-shot ultrafast infrared imaging, single low-energy-state photon sensing and tracking, and so on.

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T.L. and X.Z. conceived the idea. T.L. and Z.W. fabricated the devices and performed photoelectric measurements, along with X.S. and F.Y. T.L. and X.S. carried out the imaging performance testing. Data were analyzed by T.L. and W.Z. Z.C., M.Y., and K.L. provided software support. The results were discussed and their implications agreed upon by all authors. The manuscript was prepared by T.L. and Z.W., and reviewed by H.W. and X.Z. with useful input from all authors.

DATA AVAILABILITY

The data that support the findings of this study are available from the corresponding authors upon reasonable request.

APPENDIX

1. Enhanced visualization of the spatial electric-field distribution

As an appendix to Fig. 1(c), an enhanced visualization of the spatial electric-field distribution is provided in Fig. 6. This view features an extended measurement distance and uses a color bar with a relatively low maximum to better resolve the field details, with the featured point highlighted for clarity.

2. Geometric measurement of the NOA structure

Additional to the overall SEM image of the silicon nanotip array shown in Fig. 2(a), a close-up with higher resolution taken at a 70° tilt (left panel) and an enlarged view of a single nanotip (right panel) are provided to reveal the detailed morphology, as shown in Fig. 7.

An additional geometric measurement based on atomic force microscopy (AFM) is displayed in Fig. 8. The average surface roughness Ra can be represented as

$$Ra = \frac{1}{L} \int_0^L |h_e - h_i| dx \quad (A1)$$

where L denotes the measured horizontal length, and h_e and h_i denote the experimentally measured and

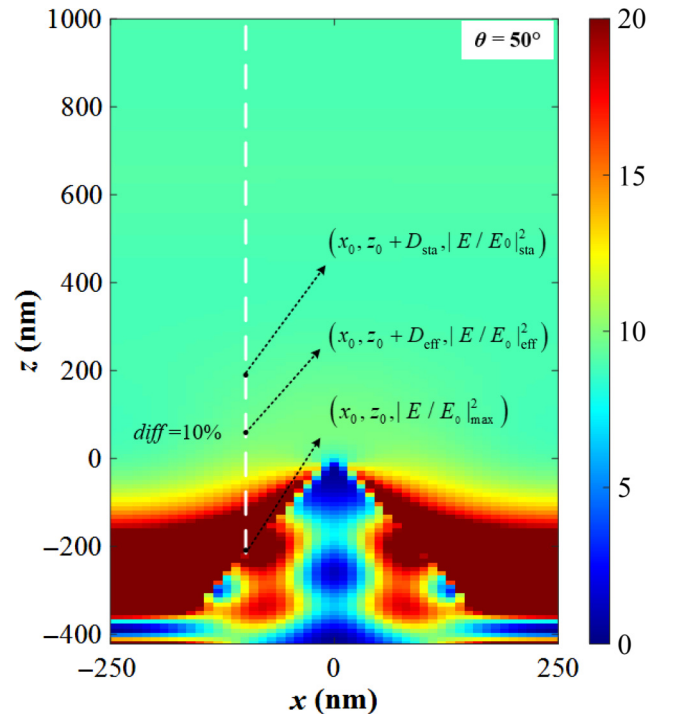


FIG. 6. Enhanced visualization of the spatial electric-field distribution over the x - z cross section. This supplementary figure to Fig. 1(c) presents the field profile over an extended measured distance, with an adjusted color bar maximum to improve contrast. The featured point is also highlighted.

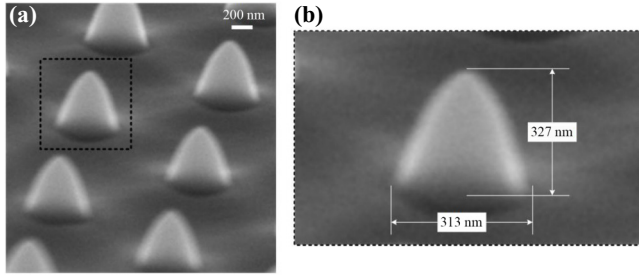


FIG. 7. Additional SEM image of the NOA structure. (a) A close-up with higher resolution taken at a 70° tilt of the nanotip array and (b) an enlarged view of a single nanotip highlighted in the box with a black dashed line.

ideal height, respectively. With R_a calculated as low as 1.145 nm, the component is well within the acceptable range for micro-nano fabrication processes.

3. Parameters of the N-MCP measuring circuit

The working circuit of the MCP is displayed in the right panel of Fig. 1(d). The detailed parameters of the key electronic components are as follows: $C1 = 130$ pF/7.2 kV; $C2 = 130$ pF/10 kV; $R1 = 20$ M Ω ; $R2 = 1$ M Ω ; $R3 = 1$ M Ω . The potential at each end is given as NOA: -200 V; input electrode of the MCP: 0 V, in order to direct the excited electrons from the surface of the NOA to the MCP. Additionally, the potential difference between the input and output electrode is set to 2000 V, which enables the acceleration and amplification of the electrons mentioned above.

4. Power loss of the vacuum chamber's optical window

Considering the material of fused silica, the transmission of the optical window located at the bottom of the

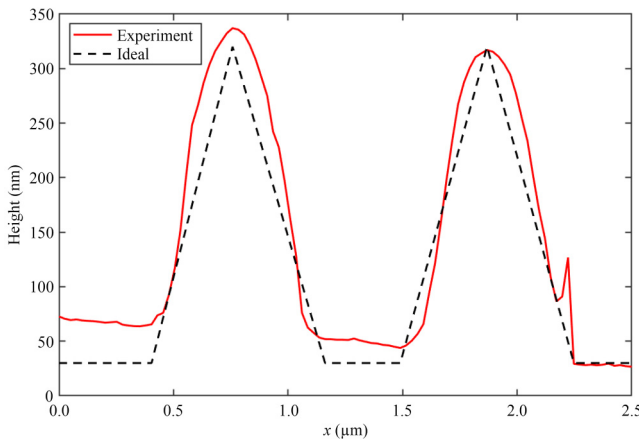


FIG. 8. Geometric measurement based on AFM. The ideal contour of the NOA structure is plotted with a black dashed line.

TABLE I. Measured transmission of the optical window at 473 nm.

Wavelength	Bias current (A)	Power from laser source (W)	Power through optical window (W)	Transmission
473 nm	0.5	0.20	0.20	100.0%
	1.0	0.25	0.24	96.0%
	1.5	0.31	0.30	96.8%
	2.0	0.35	0.33	94.3%
	2.5	0.43	0.43	100.0%
Average				97.4%

vacuum chamber is additionally tested. The transmission variation from incident wavelength is listed in Tables I–IV.

The average transmission is valued as 97.4%, 97.7%, 88.4%, and 78.3% at an incident wavelength of 473, 655, 980, and 2200 nm, respectively, yielding an overall average transmittance of approximately 90.0%.

5. Illumination measurement setup

To enable direct visualization of the electronic *in vitro* emission from the proposed NOA, a P46 phosphor-coated fluorescent screen (Photek Ltd., model FS-60) is substituted for the oscilloscope. An accelerating potential of 200 ± 5 V is applied across the 1.50 ± 0.05 mm vacuum gap separating the MCP and the fluorescent screen, establishing an electric-field gradient of approximately 133 V/mm to ensure efficient electron bombardment (Fig. 9). Luminescence intensity variations are then recorded using a CMOS detector. This configuration permitted real-time spatial mapping of electron emission patterns across the 25×25 mm active screen area, with temporal resolution limited by the phosphor persistence ($\tau = \sim 80$ μ s for P43).

The emitted electrons from NOA will be continuously guided into an MCP consisting of a large number of microscopic glass tubes, which are already precoated with a type of electron multiplier material in their inner walls for

TABLE II. Measured transmission of the optical window at 655 nm.

Wavelength	Bias current (A)	Power from laser source (W)	Power through optical window (W)	Transmission
655 nm	1.0	0.05	0.05	100.0%
	1.1	0.15	0.14	93.3%
	1.2	0.23	0.23	100.0%
	1.3	0.36	0.35	97.2%
	1.4	0.50	0.49	98.0%
Average				97.7%

TABLE III. Measured transmission of the optical window at 980 nm.

Wavelength	Bias current (A)	Power from laser source (W)	Power through optical window (W)	Transmission
980 nm	0.5	0.34	0.31	91.1%
	1.0	0.77	0.68	88.3%
	1.5	1.79	1.63	91.0%
	2.0	2.03	1.80	88.7%
	2.5	2.47	2.05	83.0%
Average				88.4%

TABLE IV. Measured transmission of the optical window at 2200 nm.

Wavelength	Bias current (A)	Power from laser source (W)	Power through optical window (W)	Transmission
2200 nm	0.5	0.16	0.12	75.0%
	1.0	0.22	0.17	77.3%
	1.5	0.29	0.23	79.3%
	2.0	0.36	0.29	80.6%
	2.5	0.39	0.31	79.5%
Average				78.3%

inducing a strong secondary electron emission. Generally, the initial output electrons from the NOA, before entering the MCP, are first accelerated by an external spatial electric field labeled V_{MN} and then continuously driven by an inner electric field of V_{MCP} with a suitable amplitude, which can be adjusted easily. Consequently, successive collisions in the inner wall of each tube channel will result in a quick electron number amplification. To prevent any possible ion feedback, which would significantly degrade the device's

durability and lifespan, a protective microstructure corresponding to the NOA is already coupled or integrated into the MCP. As the fluorescent screen located at the MCP's exit is directly struck by the amplified output electron flows under the guiding voltage V_{FM} , the incident infrared radiation in a conventional short-, mid-, or long-wavelength atmospheric window can be efficiently converted into the visible region, currently at a central wavelength of approximately 544 nm. To efficiently regulate the electron flow

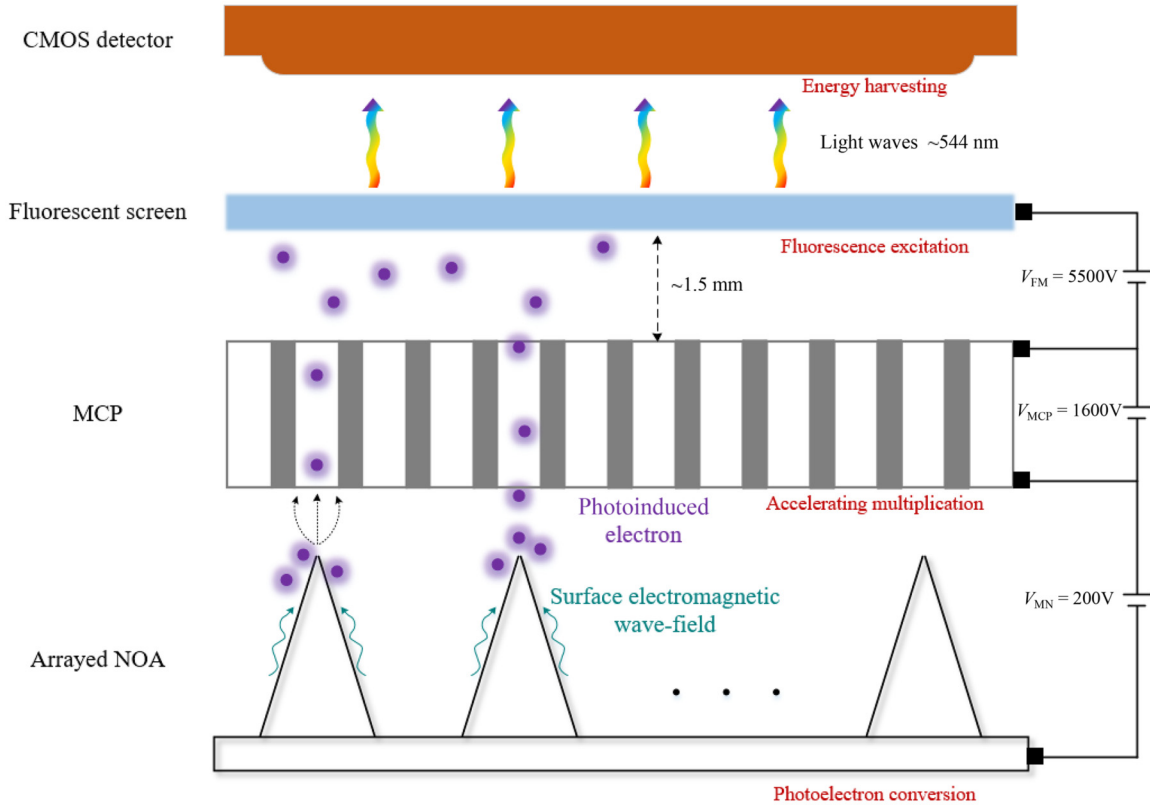


FIG. 9. Experimental principle and setup of the illumination measurement. An effective light-wave collection by common CMOS sensing, based on the direct striking to the fluorescent screen of electronic *in vitro* emission from the proposed NOA, can be achieved by adding a set of voltages including a V_{MN} loaded between the MCP and the NOA, a V_{MCP} for actuating the MCP, and a V_{FM} between the phosphor film and the MCP with a minimum distance of approximately 1.5 mm through utilizing a voltage source adjusted in the range of 0–10 kV.

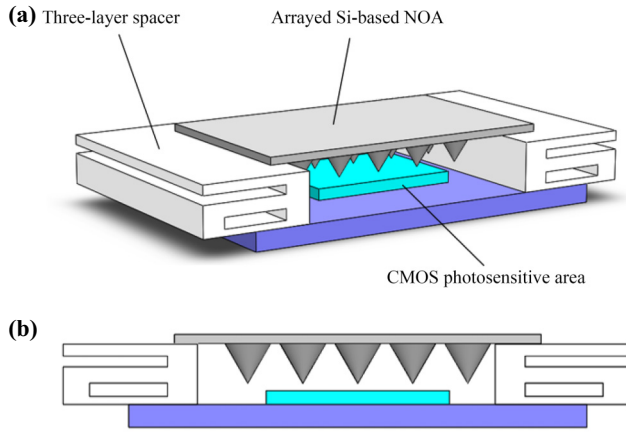


FIG. 10. The schematic of the coupling process between the arrayed Si-based NOA and the commercial CMOS photosensitive area from (a) the side and (b) the front perspective.

between the NOA and the terminal fluorescent screen, all functional components, such as the arrayed Si-based NOA, the MCP, and the fluorescent screen, are encapsulated in a high vacuum cavity of approximately 10^{-6} mBar.

6. The coupling process of the NOA and CMOS

In order to achieve near-field alignment of the arrayed NOA and detector, the applied CMOS sensor is a customized product without a protective glass cover, and thus the photosensitive region is directly exposed. According to our group's earlier publications [33,38–40], spacers for stress are used to securely connect the surfaces of the CMOS sensor and the nonstructured portion of the NOA sample, as shown in Fig. 10. Here, the spacers are selected as three paper layers, equal to a thickness of approximately 600 μm , which enable as relatively tight a coupling as possible without damaging the photosensitive components. This coupling method can also be adopted with the MCP and the beam-quality analyzer shown in Figs. 2 and 4, respectively.

In order to ensure the accuracy of the coupling between the nanotips and the photosensitive region, a square contour of a size consistent with that of the NOA sample is previously etched on the surface of the CMOS detector, and the architectural parameters of the NOA sample are well designed for coupling when prepared. The entire coupling process is performed under the microscope, and the directly exposed photosensitive region is as shown in Fig. 11.

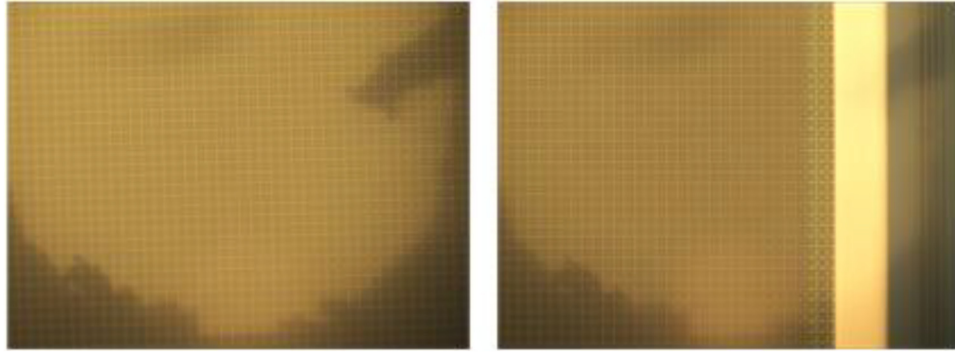


FIG. 11. The directly exposed photosensitive region and the previously etched square contour of the CMOS detector under the microscope.

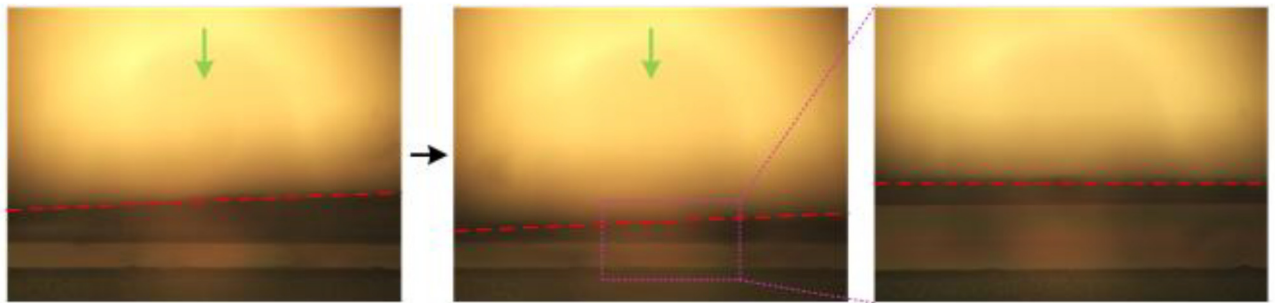


FIG. 12. The coupling process along the vertical direction. The outline of the NOA sample is highlighted by the red dashed line, and the green arrows point to the coupling direction. Note that the outline of the NOA sample is relatively fuzzy because the microscope is mainly focused on the surface of the CMOS sensor here.

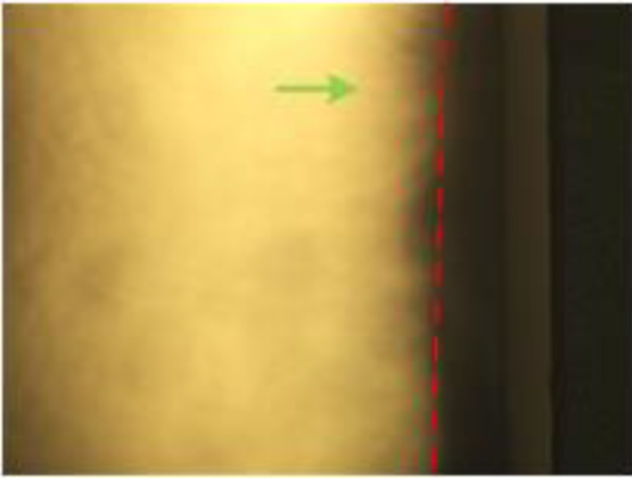


FIG. 13. The coupling process along the horizontal direction.

The coupling process under the microscope along the vertical and horizontal directions is presented in Figs. 12 and 13, respectively. As illustrated, the outline of the NOA sample is highlighted with a red dashed line, the green arrows point to the coupling direction, and the square contour over the CMOS surface can be clearly observed. As the NOA sample fits the square contour, the NOA and the photosensitive pixel are accurately coupled considering that both of them are periodically arrayed. In addition, the structural region of the NOA sample is slightly larger than the photosensitive region of the CMOS sensor, to compensate for allowable matching errors during the coupling process.

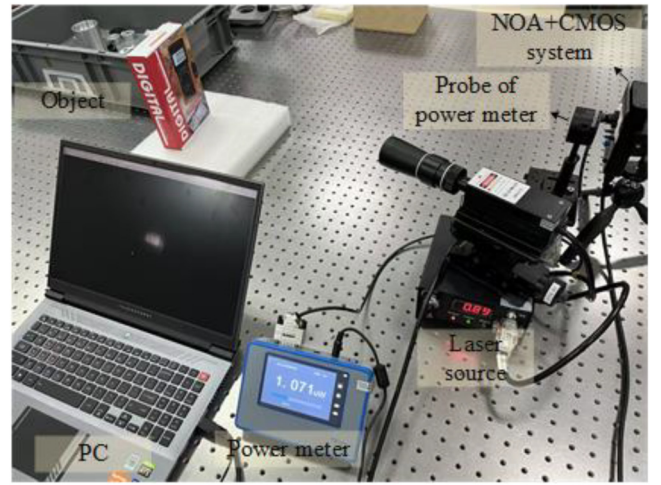


FIG. 15. Measuring optical path for performing near-infrared imaging detection based on the NID configuration.

7. Coupling tolerance measurement

In an ideal design, the periodicity of the NOA should be rationally related to the CMOS pixel pitch to optimize light-field sampling and minimize artifacts. As shown in Fig. 2(a), the periodicity is measured as 1130 nm, which was first designed to be 1 μm . The applied CMOS detector features a native resolution of 1096×1936 pixels, with a single pixel size of $3 \mu\text{m} \times 3 \mu\text{m}$. The coupling relation can be calculated from the configuration where each 3×3 nanotip submatrix maps to an individual detector pixel. The whole NOA structure is arrayed in $6 \text{ mm} \times 6 \text{ mm}$, which is relatively bigger than the size of the entire photosensitive area of the CMOS detector. Although unavoidable

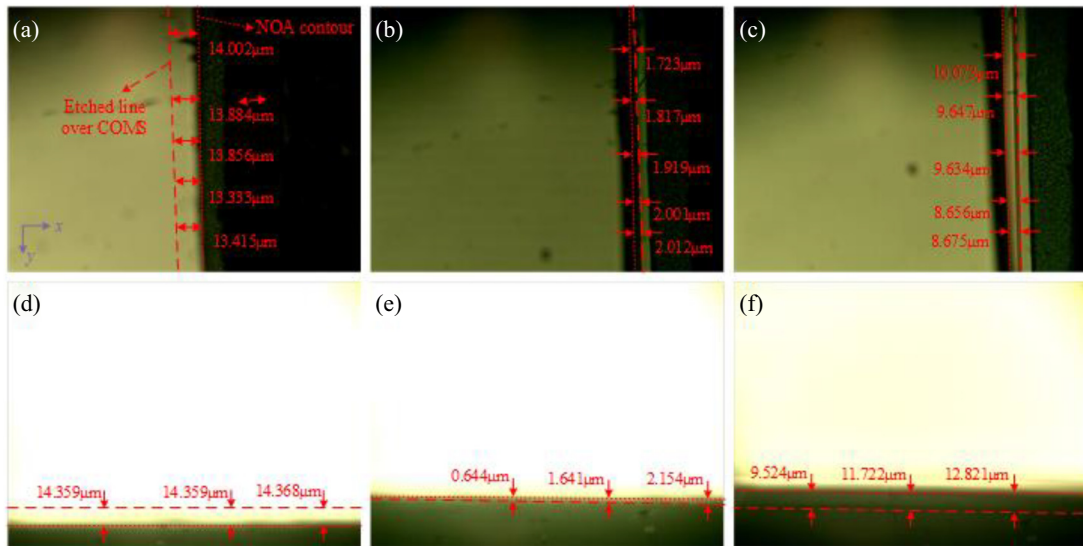


FIG. 14. Different coupling conditions observed under the optical microscope. The etched line (mentioned in Sec. 6 of the Appendix) on the surface of the CMOS detector and the NOA contour are highlighted by the long dashed and short dashed lines, respectively. The multipoint measured coupling offsets are also labeled.

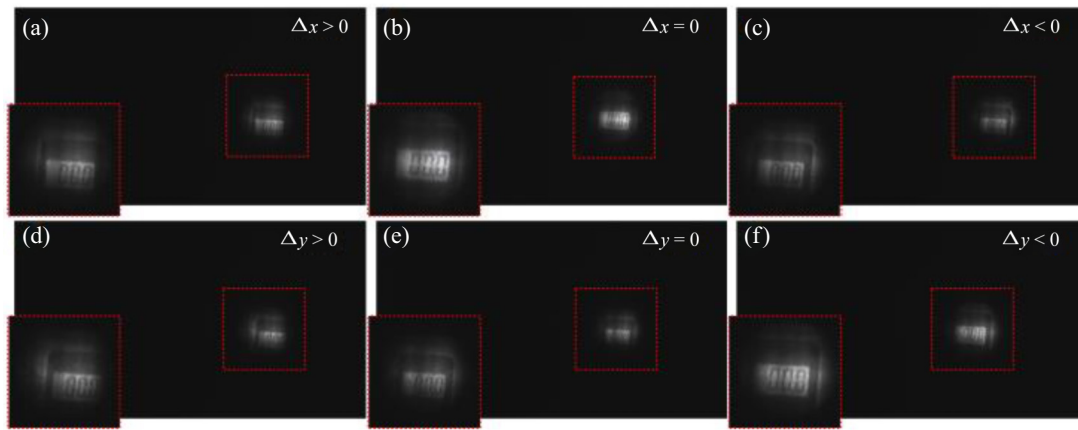


FIG. 16. Comparison of imaging performance under varying coupling conditions. The reproduced object is highlighted with a dashed red box, and an enlarged view in each case is provided in the inset located at the lower-left corner.

fabrication errors exist in the structural parameters of the NOA, their impact on the enhancement gain of a single pixel becomes negligible when averaged over the entire photosensitive area of the CMOS detector.

In order to determine the alignment tolerance, we have intentionally increased the coupling offset and calculated D^* of the NOA + CMOS imaging architecture. The alignment offset is divided into the horizontal and vertical directions, corresponding to Δx and Δy , respectively. A positive value of Δx is defined as the condition where the NOA contour (short dashed line) extends beyond the line previously etched on the CMOS detector surface (long dashed line), as shown in Fig. 14(a). Here, we list six coupling positions tested via multipoint measurements, including average values of $\Delta x = +13.698 \mu\text{m}$, $-1.894 \mu\text{m}$, $-9.337 \mu\text{m}$ and $\Delta y = +14.362 \mu\text{m}$, $-1.480 \mu\text{m}$, $-11.356 \mu\text{m}$.

The basic experimental setup for performing CMOS-based near-infrared imaging detection with different coupling conditions is illustrated in Fig. 15. The object is first illuminated by a laser beam with a central wavelength of 980 nm, and then the reflective light is received by the proposed NOA + CMOS imaging system. The incident near-infrared power at NID is measured by a power meter for D^* calculation. A comparison of the imaging performance under various coupling conditions is provided in Fig. 16. According to the near-infrared reproduction of the object, D^* expressed in units of $10^{10} \text{ cm Hz}^{1/2} \text{ W}^{-1}$ can be calculated as 4.489, 4.758, 4.073, 4.489, 3.602, and 4.773, respectively. As shown, although the best imaging performance is observed at $\Delta x = 0$ and $\Delta y < 0$, the performance under various coupling conditions is nearly identical, demonstrating good tolerance to coupling errors.

However, the cause of the performance difference remains unclear and cannot be pinned to either system error or coupling conditions. Moreover, measuring the angular tolerance between the NOA and the CMOS

detector poses a significant challenge due to the difficulty of controlling the angle precisely. In future work, we will focus on further modifying the coupling process to facilitate precise alignment control, thereby enabling a rigorous assessment of its effect on imaging.

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- [1] A. Xomalis, X. Zheng, R. Chikkaraddy, Z. Koczor-Benda, E. Miele, E. Rosta, G. A. E. Vandenbosch, A. Martínez, and J. J. Baumberg, Detecting mid-infrared light by molecular frequency upconversion in dual-wavelength nanoantennas, *Science* **374**, 1268 (2021).
 - [2] A. H. Ashoka, I. O. Aparin, A. Reisch, and A. S. Klymchenko, Brightness of fluorescent organic nanomaterials, *Chem. Soc. Rev.* **52**, 4525 (2023).
 - [3] C. Li, Y. Pang, Y. Xu, M. Lu, L. Tu, Q. Li, A. Sharma, Z. Guo, X. Li, and Y. Sun, Near-infrared metal agents assisting precision medicine: from strategic design to bioimaging and therapeutic applications, *Chem. Soc. Rev.* **52**, 4392 (2023).
 - [4] Y. Harikane, M. Ouchi, M. Oguri, Y. Ono, K. Nakajima, Y. Isobe, H. Umeda, K. Mawatari, and Y. Zhang, A comprehensive study of galaxies at $z \sim 9\text{--}16$ found in the early JWST data: ultraviolet luminosity functions and cosmic star formation history at the pre-reionization epoch, *Astrophys. J., Suppl. Ser.* **265**, 5 (2023).
 - [5] H. Li, Y. Kim, H. Jung, J. Y. Hyun, and I. Shin, Near-infrared (NIR) fluorescence-emitting small organic molecules for cancer imaging and therapy, *Chem. Soc. Rev.* **51**, 8957 (2022).
 - [6] S. Kumar, T. Fukuoka, R. Takahashi, M. Yoshida, Y. Utsumi, A. Yamaguchi, K. Namura, and M. Suzuki, Highly stable and reproducible Au nanorod arrays for near-infrared optofluidic SERS sensor, *Mater. Lett.* **286**, 129106 (2020).
 - [7] J. Qi, C. Sun, A. Zebibula, H. Zhang, R. T. K. Kwok, X. Zhao, W. Xi, J. W. Y. Lam, J. Qian, and B. Z. Tang, Real-time and high-resolution bioimaging with bright aggregation-induced emission dots in short-wave infrared region, *Adv. Mater.* **30**, 1706856 (2018).

- [8] S. Zhang, C. Bi, T. Qin, Y. Liu, J. Cao, J. Song, Y. Huo, M. Chen, Q. Hao, and X. Tang, Wafer-scale fabrication of CMOS-compatible trapping-mode infrared imagers with colloidal quantum dots, *ACS Photonics* **10**, 673 (2023).
- [9] T. Knobloch, Y. Y. Illarionov, F. Ducry, C. Schleich, S. Wachter, K. Watanabe, T. Taniguchi, T. Mueller, M. Waltl, M. Lanza, M. I. Vexler, M. Luisier, and T. Grasser, The performance limits of hexagonal boron nitride as an insulator for scaled CMOS devices based on two-dimensional materials, *Nat. Electron.* **4**, 98 (2021).
- [10] T. Paschen, L. Brückner, M. Wu, E. Spiecker, and P. Hommelhoff, Highly localized optical field enhancement at neon ion sputtered tungsten nanotips, *Nano Lett.* **23**, 7114 (2023).
- [11] Z. Y. Zhang and G. P. Wang, Resonant coherent acoustic oscillation in nanoscale Ruddlesden-Popper perovskite films, *Adv. Funct. Mater.* **33**, 2214542 (2023).
- [12] D. Hümmer, O. Romero-Isart, A. Rauschenbeutel, and P. Schneeweiss, Probing surface-bound atoms with quantum nanophotonics, *Phys. Rev. Lett.* **126**, 163601 (2021).
- [13] S. Huang, C.-W. Lin, J. Qi, A. M. Iyer, Y. He, Y. Li, N. M. Bardhan, D. J. Irvine, P. T. Hammond, and A. M. Belcher, Surface plasmon-enhanced short-wave infrared fluorescence for detecting sub-millimeter-sized tumors, *Adv. Mater.* **33**, 2006057 (2021).
- [14] K.-D. Park, M. A. May, H. Leng, J. Wang, J. A. Kropp, T. Gougousi, M. Pelton, and M. B. Raschke, Tip-enhanced strong coupling spectroscopy, imaging, and control of a single quantum emitter, *Sci. Adv.* **5**, eaav5931 (2019).
- [15] J. Budai, Z. Pápa, I. Márton, P. Wróbel, T. Stefaniuk, Z. Márton, P. Rácz, and P. Dombi, Plasmon-plasmon coupling probed by ultrafast, strong-field photoemission with < 7 angstrom sensitivity, *Nanoscale* **10**, 16261 (2018).
- [16] T. Liu, J. Shi, S. Duan, W. Ji, Z. Wang, and X. Zhang, Research on the localized lightfield features of metallic nano-cone-tip optical antenna via investigating near-field lightwave and correlated net-charge distribution, *Sci. Rep.* **13**, 22002 (2023).
- [17] M. L. Tseng, M. Semmlinger, M. Zhang, C. Arndt, T.-T. Huang, J. Yang, H. Y. Kuo, V.-C. Su, M. K. Chen, C. H. Chu, B. Cerjan, D. P. Tsai, P. Nordlander, and N. J. Halas, Vacuum ultraviolet nonlinear metalens, *Sci. Adv.* **8**, eabn5644 (2022).
- [18] H. Groß, J. M. Hamm, T. Tufarelli, O. Hess, and B. Hecht, Near-field strong coupling of single quantum dots, *Sci. Adv.* **4**, eaar4906 (2018).
- [19] H. Karaagac and M. S. Islam, Enhanced field ionization enabled by metal induced surface states on semiconductor nanotips, *Adv. Funct. Mater.* **24**, 2224 (2014).
- [20] H. Zhao, T. Jiang, L. Yi, and L. Tang, DNA sequence-mediated fine-tuning of nanostructures and their plasmonic properties over gold nanorods, *Optik* **228**, 166137 (2020).
- [21] A. J. Moilanen, K. S. Daskalakis, J. M. Taskinen, and P. Törmä, Spatial and temporal coherence in strongly coupled plasmonic bose-einstein condensates, *Phys. Rev. Lett.* **127**, 255301 (2021).
- [22] T. B. Hoang, G. M. Akselrod, A. Yang, T. W. Odom, and M. H. Mikkelsen, Millimeter-scale spatial coherence from a plasmon laser, *Nano Lett.* **17**, 6690 (2017).
- [23] A. Daus, S. Vaziri, V. Chen, Ç. Köroğlu, R. W. Grady, C. S. Bailey, H. R. Lee, K. Schauble, K. Brenner, and E. Pop, High-performance flexible nanoscale transistors based on transition metal dichalcogenides, *Nat. Electron.* **4**, 495 (2021).
- [24] J. Neto, A. S. Dahiya, A. Zumeit, A. Christou, S. Ma, and R. Dahiya, Printed n- and p-channel transistors using silicon nanoribbons enduring electrical, thermal, and mechanical stress, *ACS Appl. Mater. Interfaces* **15**, 9618 (2023).
- [25] M. Kim, S. Kim, and H. Yoo, Nanoscale channel gate-tunable diodes obtained by asymmetric contact and adhesion lithography on fluoropolymers, *Small* **19**, 2208144 (2023).
- [26] I. P. Csorba, Current gain parameters of microchannel plates, *Appl. Opt.* **19**, 3863 (1980).
- [27] C. Pollock, *et al.*, Fast plasma investigation for magnetospheric multiscale, *Space Sci. Rev.* **199**, 331 (2016).
- [28] S.-H. Wang, Y.-X. Yin, T.-T. Zuo, W. Dong, J.-Y. Li, J.-L. Shi, C.-H. Zhang, N.-W. Li, C.-J. Li, and Y.-G. Guo, Stable Li metal anodes via regulating lithium plating/stripping in vertically aligned microchannels, *Adv. Mater.* **29**, 1703729 (2017).
- [29] W. Cao, B. Zhu, X. Bai, P. Xu, B. Wang, J. Qin, Y. Gou, F. Lei, B. Liu, J. Guo, J. Zhu, and Y. Bai, High-sensitivity and long-life microchannel plate processed by atomic layer deposition, *Nanoscale Res. Lett.* **14**, 153 (2019).
- [30] S. Duan, J.Q. Hu, T. Liu, Z. Wang, J. Shi, and X. Zhang, Cascaded nanocavity-shaped metasurfaces for realizing an intensive radiation absorption in the mid-to-long infrared region based on electromagnetic wavefield resonance response and accumulation, *Opt. Mater. Express* **14**, 2303 (2024).
- [31] Z. Gao, W. Ji, T. Liu, and X. Zhang, Infrared radiation absorption in a wide wavelength range of 3–14 μm mainly based on spatial magnetic plasmon excitation and accumulation in an arrayed nanocavity-shaped metasurface, *J. Vac. Sci. Technol. B* **42**, 042211 (2024).
- [32] D. Wei, C. Hu, M. Chen, *et al.*, Light absorption and nanofocusing on a tapered magnetic metasurface, *Appl. Phys. Lett.* **117**, 243102 (2020).
- [33] Z. Xin, B. Deng, D. Wei, M. Chen, C. Hu, X. Zhang, H. Wang, C. Xie, Z. Liu, and H. Peng, Macroscale single crystal graphene templated directional alignment of liquid-crystal microlens array for light field imaging, *Appl. Phys. Lett.* **115**, 071903 (2019).
- [34] M. Chen, H. Wang, W. Dai, L. Niu, J. Liu, Q. Shao, X. Zhang, H. Wang, and C. Xie, Electrically controlled liquid-crystal microlens matrix with a nested electrode array for efficiently tuning and swinging focus, *Opt. Express* **27**, 23422 (2019).
- [35] Z. Wang, M. Chen, C. Hu, K. Liu, Z. Li, M. Ye, Z. Chen, X. Yuan, H. Wang, C. Xie, and X. Zhang, Arrayed dual-mode integrated liquid crystal microlens driven jointly by both independent signal voltages, *Opt. Express* **29**, 40617 (2021).
- [36] S. Quirin, S. R. P. Pavani, and R. Piestun, Optimal 3D single-molecule localization for superresolution microscopy with aberrations and engineered point spread functions, *Proc. Natl. Acad. Sci. U. S. A.* **109**, 675 (2012).

- [37] T. Liu, J. Shi, S. Duan, Z. Wang, and X. Zhang, Nanotip-based CMOS photosensitive architecture for highly sensitive near-infrared imaging detection, *Appl. Phys. Lett.* **123**, 143503 (2023).
- [38] Z. Xin, D. Wei, X. Xie, M. Chen, X. Zhang, J. Liao, H. Wang, and C. Xie, Dual-polarized light-field imaging micro-system via a liquid-crystal microlens array for direct three-dimensional observation, *Opt. Express* **26**, 4035 (2018).
- [39] C. Hu, T. Liu, K. Liu, J. Shi, M. Ye, and X. Zhang, Lightwave nano-converging enhancement by an arrayed optical antenna based on metallic nano-cone-tips for CMOS imaging detection, *Sci. Rep.* **12**, 15761 (2022).
- [40] M. Chen, W. He, D. Wei, C. Hu, J. Shi, X. Zhang, H. Wang, and C. Xie, Depth-of-field-extended plenoptic camera based on tunable multi-focus liquid-crystal microlens array, *Sensors* **20**, 4142 (2020).