# Spectroscopy Detection and Imaging System Based on Line Array Single Photon Detectors

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## Abstract

Single-photon detectors, with their exceptional sensitivity, provide a reliable means for single-photon-level detection, demonstrating significant advantages in detecting weak signals in complex environments compared to traditional detectors. With the continuous advancement in semiconductor manufacturing technology, single-photon detectors based on linear array configurations have emerged and rapidly developed. This study utilizes a linear array single-photon detector in free-running mode combined with a scanning mechanism to design and implement a spectral detection and imaging system. Through the spectral scanning unit, this system successfully achieves precise spectral detection in the 890 nm to 1710 nm range, with a spectral resolution better than 2 nm. Utilizing the imaging scanning unit, the system effectively performs target spectral imaging under single and multiple wavelength conditions at 1064 nm, 1310 nm, and 1520 nm. By optimizing algorithms for data processing, the system can achieve rapid and accurate spectral detection and imaging even under low-light conditions where the average photon count per pixel is less than 3. The results of this study are expected to provide strong technical support for the application of spectral imaging technology in the field of high-speed detection and imaging.

## 1. Introduction

In the wake of rapid advancements in photonics and optoelectronics, the demand for high-sensitivity and high-resolution spectral detection and imaging technologies has surged across various fields, including astronomy (Fitzgerald et al., 2019, Philip et al., 2023), biomedicine (Wrobel et al., 2018), environmental monitoring (Cai et al., 2017, Zhang et al., 2023), and national defence (Andrew et al., 2020, Zhou Y. et al., 2022). These technologies are particularly crucial in scenarios characterized by extremely low-light conditions, such as deep-sea exploration, night-vision surveillance, and quantum communication, where the sensitivity and signal-to-noise ratio of detectors are paramount. Against this backdrop, single-photon detection technology, renowned for its exceptional sensitivity and minimal dark count rate, has emerged as a focal point of interest. Single-photon detectors enable highly sensitive detection of single photons and very low dark counts from random thermal noise counts in the device itself. Capable of effectively detecting faint light signals, single-photon detectors stand as a cornerstone in the pursuit of high-sensitivity detection. The progress in nanofabrication techniques and semiconductor materials has propelled semiconductor-based single-photon detectors, notably line-array single-photon avalanche diodes (SPADs) crafted from silicon (Buckley et al., 2017) or InGaAs/InP materials (Zhang, J et al., 2015), to the forefront of potential technological breakthroughs.

Integrating single-photon detection technologies into spectral detection and imaging systems presents a myriad of challenges that are critical to advancing the field. Key research areas include enhancing the spectral resolution and dynamic range of these systems, minimizing system noise, and increasing imaging speed and spatial resolution. Moreover, system integration and the optimization of signal processing algorithms are pivotal for leveraging the full potential of these technologies. Enhancing the quantum efficiency and temporal resolution of detectors also stands as a significant area of investigation (Dam, et al., 2012, Thiel, et al., 2020, Wang, et al., 2023). These challenges are at the forefront of current research endeavours, necessitating a multidisciplinary approach to address the intricate demands of single-photon detection and its application in spectral imaging.

In this research, we delve into the application of single-photon detection technology within the realms of spectral detection and imaging. We have developed an advanced spectral detection and imaging system, incorporating a line-array single-photon detector operating in a free-running mode, complemented by a high-efficiency scanning apparatus. This system is adept at spanning a broad spectral range from 890 nm to 1710 nm, achieving a remarkable spectral resolution exceeding 2 nm, courtesy of a meticulously engineered spectral scanning unit. Furthermore, the incorporation of an imaging scanning module enables the system to conduct efficient spectral imaging across various wavelengths, including 1064 nm, 1310 nm, and 1520 nm. A significant breakthrough of this study lies in the optimization of detection and imaging algorithms, which empowers the system to perform spectral detection and imaging tasks with precision and speed, even under low-light conditions where the average photon count per detector pixel is below three. The findings of this investigation not only underscore the viability of line array single-photon detectors in spectral imaging but also offer valuable insights for the design and enhancement of future spectral imaging systems. These advancements are anticipated to be instrumental across a plethora of domains, such as astronomical observation, biomedical imaging, and environmental surveillance, marking a significant stride in the field.

## 2. System construction

In this study, we present a novel spectral detection and imaging system, incorporating a self-developed 256×2 line array single-photon detector and an advanced scanning unit, as illustrated in Figure 1. The detector, fabricated from InGaAs/InP, epitomizes the miniaturization of ultra-low-noise, free-running mode single-photon detectors, capable of operating across a wavelength range of 890 nm to 1710 nm. Figure 1(a) shows the system's schematic, where the line array detection unit is

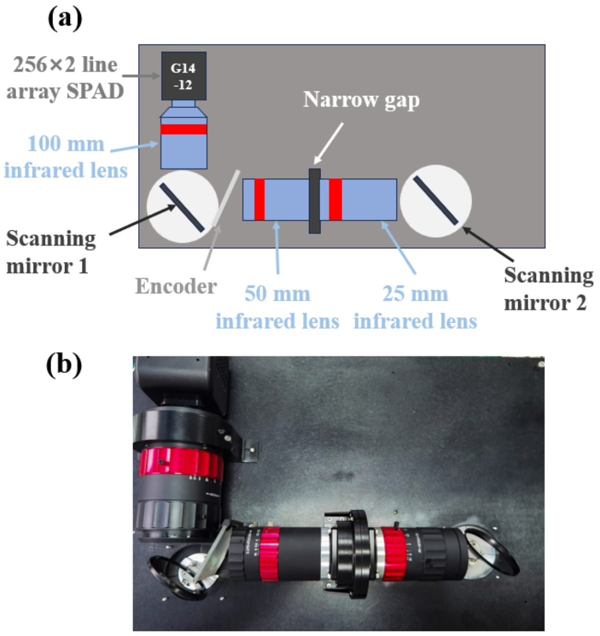


Figure 1. 256×2line array scanning spectral system. (a) Schematic of the spectral imaging system, (b) physical view of the target.

oriented vertically, coupled with an external infrared lens of 100 mm focal length. The detector's array aligns parallel to the grating's stripe direction, enabling spectral scanning through the deflection of various wavelengths by the grating, facilitated by scanning mirror 1, and subsequently captured by the line-array detector.

To concentrate ambient light reflected by scanning mirror 2, infrared imaging lenses with focal lengths of 50 mm and 25 mm are employed. Positioned between these lenses is a narrow slit, measuring 100 μm in width, which serves to restrict the transmitted light beam, thereby safeguarding the system's spectral resolution. Scanning mirror 2 functions as an imaging scanning unit, enabling the capture of spectral imaging across different regional scenes by adjusting its angular orientation. Figure 1(b) shows an actual picture of the system.

Experimentally, differentiation between the two mirrors is achieved through the use of two independently driven motors, positioned vertically to ensure that scanning mirror 1 rotates horizontally, maintaining a perpendicular orientation to the grating's stripe direction. This configuration allows scanning mirror 1 to encompass spectral bands ranging from 890 nm to 1710 nm. Meanwhile, scanning mirror 2 is calibrated for a 5° horizontal rotational angle, facilitating the scanning of specific scene targets in the horizontal plane.

Furthermore, the spectral detection and imaging system is equipped with a desktop power supply, a signal generator, and a data acquisition computer, as delineated in Figure 2. The desktop power supply is designed to deliver multiple DC voltages across various specifications, boasting a maximum output power exceeding 60 W. The signal generator is adept at producing a range of waveform signals with adjustable voltages and frequencies, serving to actuate the system's motors. It offers a versatile output range, including but not limited to triangular and sinusoidal waves, with the capability to flexibly modulate both frequency and amplitude. The data acquisition computer plays a pivotal role in the system's functionality, facilitating rapid data capture and storage from the spectral system. It is tasked with the subsequent analysis and processing of the collected detection data, ensuring the system's operational efficiency and data integrity.

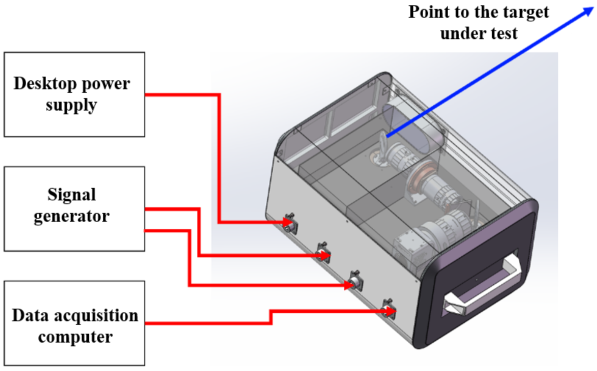


Figure 2. Composition of line array scanning spectroscopy system

## 3. Experiments and Results

To assess the viability of the line array single-photon detector for scanning spectroscopy and imaging, we conducted practical experimental tests focusing on the system's spectral detection capabilities using the aforementioned experimental setup. The experiment entailed sunlight spectral detection, wherein the system was oriented towards the solar region to collect sunlight spectral data via the scanning unit. Conducted during the evening to mitigate potential damage to the single-photon detector from intense sunlight exposure, this setup is depicted in Figure 3.

The alignment of scanning mirror 2 was fixed to direct the system towards the sun, while precise adjustments to scanning mirror 1 enabled the coverage of an extensive spectral range from 1000 nm to 1650 nm. This approach facilitated the successful capture of primary absorption bands and spectral features present in sunlight, as illustrated in Figure 4. Spectral

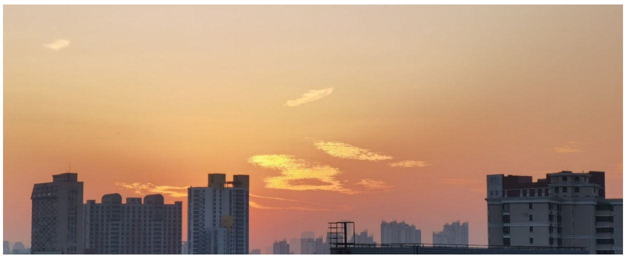

Figure 3. Scanning spectroscopy system solar spectrum imaging scene.


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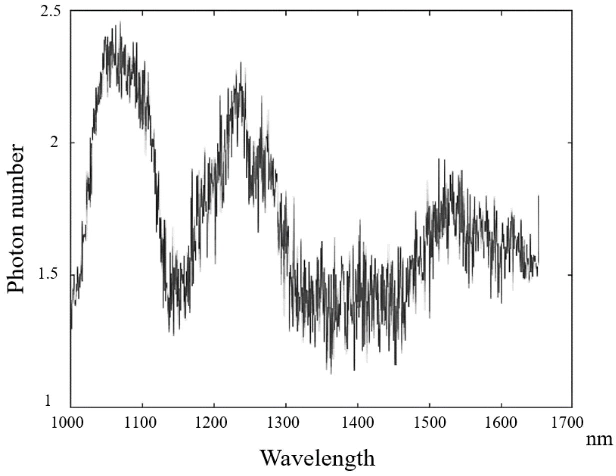


Figure 4. Transmission spectra of sunlight detected by a scanning spectroscopy system

data were acquired in real-time by the data acquisition system and subsequently processed and analysed using the data processing algorithm tailored for the line array single-photon detector.

The experimental outcomes, presented in Figure 4, demonstrate the system's proficiency in distinctly identifying subtle features within the solar spectrum, including atmospheric absorption lines and water vapor. This evidence underscores the system's effectiveness and potential for detailed spectral analysis in various applications.

To elucidate the spectral detection capabilities of the system across various wavelengths with greater clarity, an experiment utilizing a monochromator system was conducted. This setup aimed to analyse the scanning spectral imaging system's proficiency in detecting different wavelengths. The monochromator boasts a spectral accuracy of 0.001 nm, allowing for the generation of specific output light sources by setting distinct output wavelengths.

Figure 5 shows the adeptness of the spectral detection system, as constructed in this study, in discerning spectral bands at wavelengths of 890 nm, 1311 nm, 1549 nm, and 1709 nm within the operational wavelength range of 890 nm to 1710 nm. This experiment underscores the system's refined capability to accurately detect and resolve spectral features across a broad spectrum, affirming its potential for diverse applications in spectral analysis and imaging.

To further assess the spectral resolution capabilities of the system, we employed a monochromator to isolate two laser wavelengths at 1379.7 nm and 1381.4 nm for illumination purposes. During the experiment, the laser was uniformly projected onto the entrance pupil of the spectral detection and imaging apparatus, ensuring consistent illumination across the slit before commencing data collection. Figure 6 presents a comparative analysis of the spectral data captured by the system at these two wavelengths.

Upon examining the collected data, it is evident that the system is capable of discerning a wavelength difference of 1.66 nm between the two lasers. This clear distinction between the spectral signatures at 1379.74 nm and 1381.4 nm underscores the system's spectral resolution, which is confirmed to be

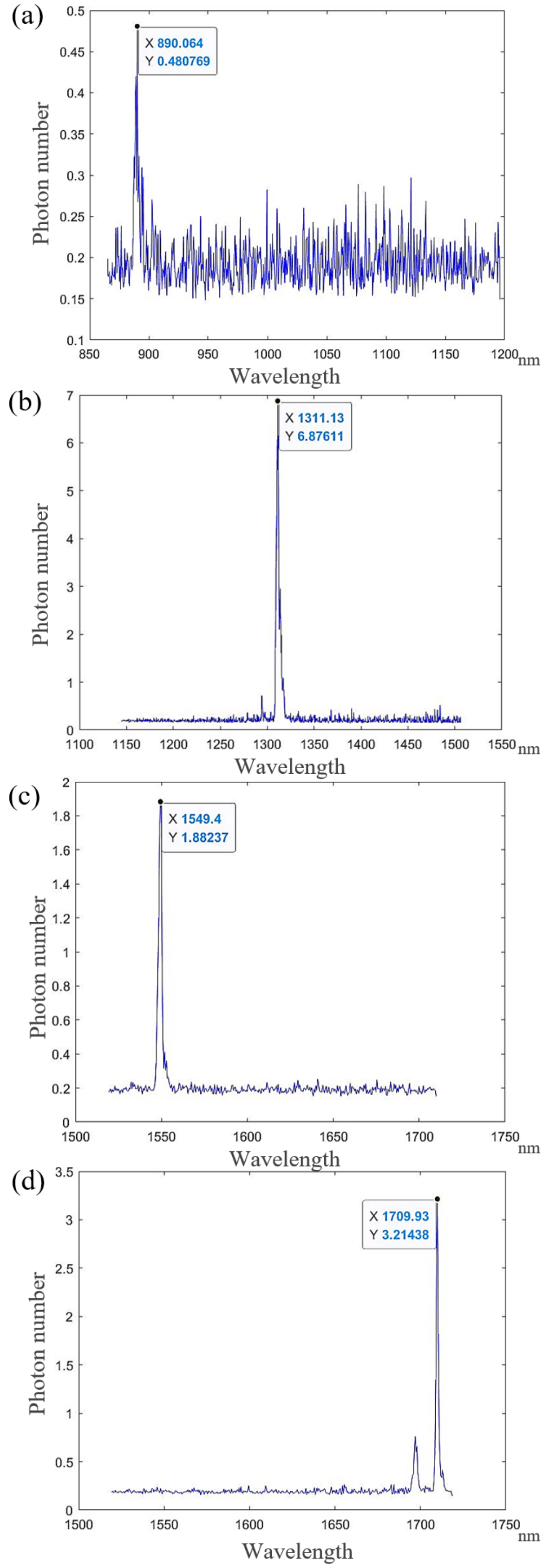


Figure 5. Analysis of the spectral detection ability of the experimental system at different wavelengths. (a), (b), (c) and (d) represent the spectral detection capabilities of the system at 890 nm, 1311 nm, 1549 nm and 1709 nm, respectively.

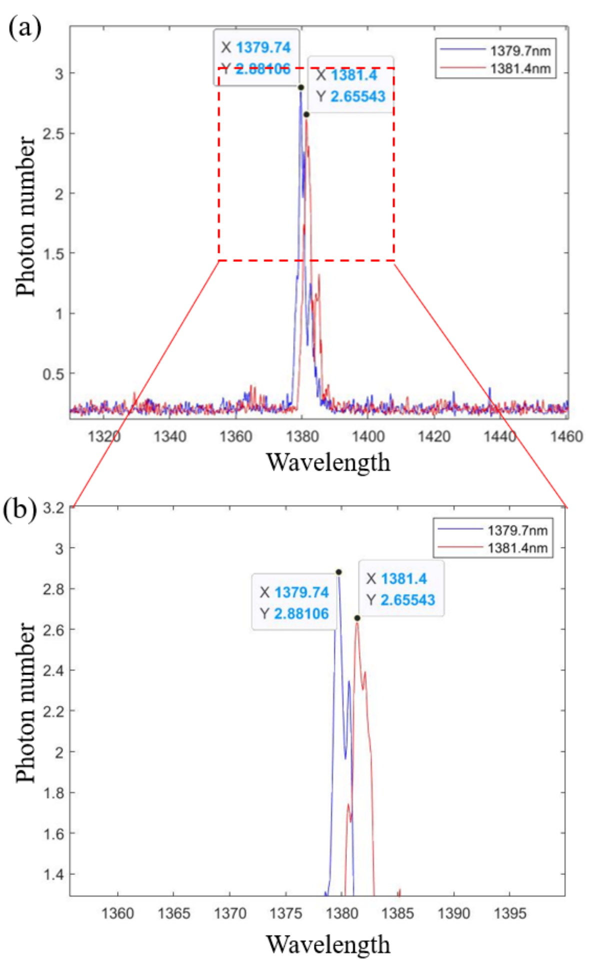


Figure 6. Spectral resolution measurements.(a) Comparison of large-scale images, (b) Spectral detail image.

superior to 2 nm. This finding validates the system's high-resolution capabilities, highlighting its effectiveness in distinguishing closely spaced spectral features.

The spectral analysis conducted with our designed line-array single-photon detector scanning spectral detection system confirms its capability to encompass spectral detection within the 890 nm to 1710 nm band range. To further validate the system's spectral imaging proficiency, we employed scanning mirror 2 to capture the indoor streak target shown in Figure 7 and the building scene depicted in Figure 8. The experimental scenes of illuminating a streak target by a broad spectrum of continuous laser illumination in a room are shown in Figure 7 in (a) and (b), and the full-band spectral imaging results of the streak target is shown in (c). The outdoor experiment was conducted in the morning, taking advantage of the natural sunlight illumination, which introduced a dynamic range of brightness and shadows across the scene.

During the experiment, scanning mirror 1 was activated to concurrently acquire spectral information of the imaging scene while scanning mirror 2 undertook the imaging scan of the target scene. The operational parameters were set with scanning mirror 2 moving at a rate of 0.1°/s and scanning mirror 1 performing spectroscopic scans at 10 Hz/s, covering the spectral range from 890 nm to 1710 nm. The region delineated by the red box in Figure 8 was selected for detailed spectral imaging analysis.

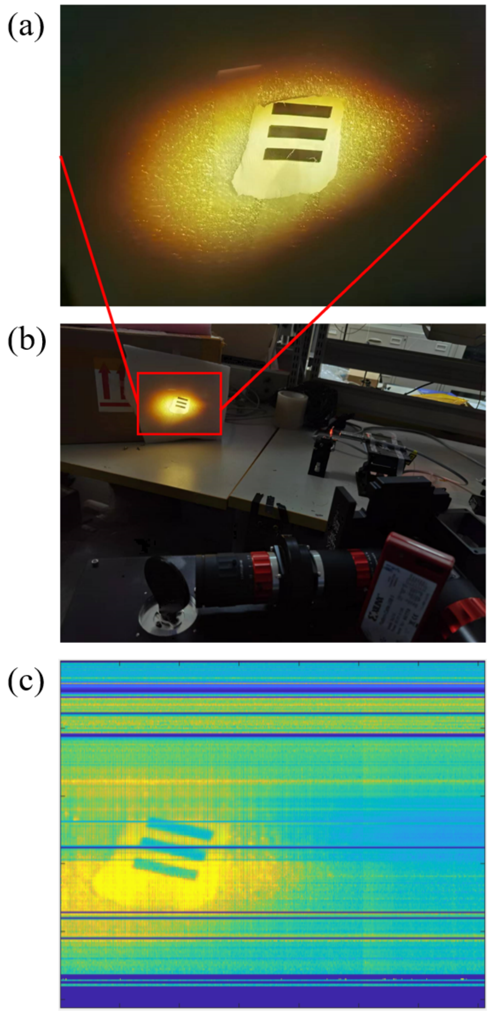


Figure 7 Indoor imaging experiments. (a) Streak target, (b) indoor continuous laser lighting scene, (c) full-band spectral imaging results for streak targets.

Figure 8. Outdoor Test Scene Photos

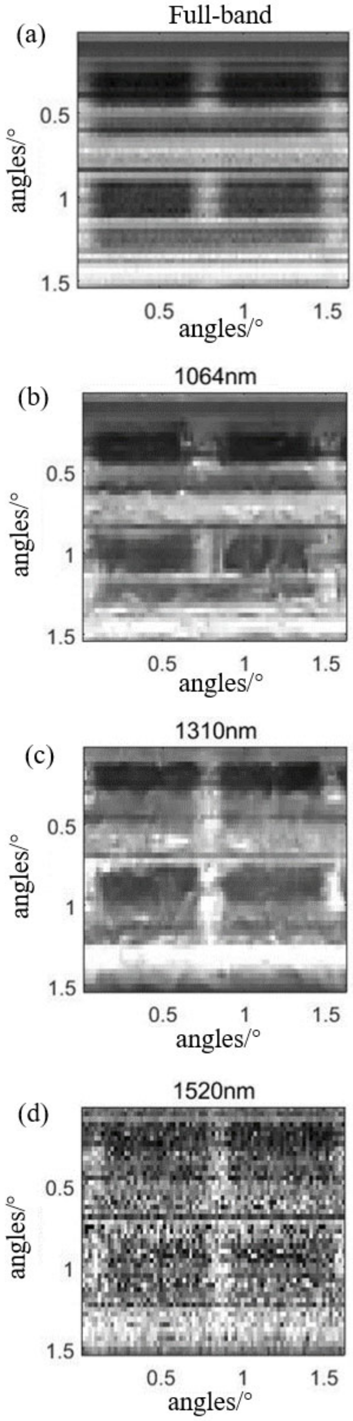


Figure 9. Outdoor spectral imaging reflectance grey-scale map imaging results. (a) Accumulation of full-band spectral data in the target area, (b) 1064 nm single-wavelength spectral imaging, (c) 1310 nm single-wavelength spectral imaging, and (d) 1520 nm single-wavelength spectral imaging.

Figure 9 presents the processed imaging spectrogram of the target scene. Specifically, Figure 9(a) displays the grayscale map of target reflectance, compiled from accumulated data across the full 890 nm-1710 nm wavelength band. To dissect the reflectivity of the target at distinct single wavelengths, three bands—1064 nm, 1310 nm, and 1520 nm—were chosen for individual imaging analysis of the detection scene. The grayscale images of target reflectance at these three wavelengths are illustrated in Figures 9(b), (c), and (d), respectively. The images reveal that the 1064 nm and 1310 nm bands reflect more light, resulting in superior imaging quality, whereas the 1520 nm wavelength reflects less light, yielding poorer imaging quality. This experiment not only underscores the system's adeptness at spectral imaging but also highlights its ability to discern variations in reflectivity across different wavelengths, showcasing its potential for diverse applications in spectral analysis.

## 4. Conclusions

In this research, we successfully developed and validated a sophisticated spectral detection and imaging system, utilizing a 256×2 line array single-photon detector. The system's exceptional sensitivity and precise spectral resolution were showcased in sunlight spectral detection experiments, where it adeptly captured the nuanced features of the solar spectrum, including atmospheric and water vapor absorption lines. Further evaluation with a monochromator reaffirmed the system's superior spectral resolution, exceeding 2 nm, enabling it to distinctly differentiate between lasers of closely matched wavelengths. The system's exemplary performance extended across a broad spectral range from 890 nm to 1710 nm. During outdoor building imaging experiments, the system, through meticulous control of the scanning mirror, achieved high-quality spectral imaging, particularly at 1064 nm and 1310 nm wavelengths, demonstrating robust reflectivity and clear imaging capabilities. Overall, this study not only confirms the high efficacy of the developed system but also establishes a strong foundation for future applications in high-sensitivity spectral detection and imaging across low-light conditions and extensive spectral domains.

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