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Quantum Camera Module for Digital Imaging

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Abstract

The Quantum Camera Module is a cutting-edge imaging system that utilizes Single-Photon Avalanche Diodes (SPADs) to capture both static and dynamic images with exceptional detail, even in low-light conditions. Inspired by insect vision, this versatile module can function independently or in arrays, offering omnidirectional and panoramic imaging. Its advanced optical design includes specialized lenses and microchannels that optimize light capture, reduce noise, and improve image quality. The module's compact size makes it ideal for integration into devices like smartphones, endoscopes, and deep-sea cameras, revolutionizing modern imaging technology.

Keywords: Single-Photon Avalanche Diodes (SPADs), Omnidirectional Imaging, Microchannel Optics, Photon Detection Efficiency (PDE), Low-Light Sensing, Bioinspired Vision Systems, Panoramic Imaging Arrays

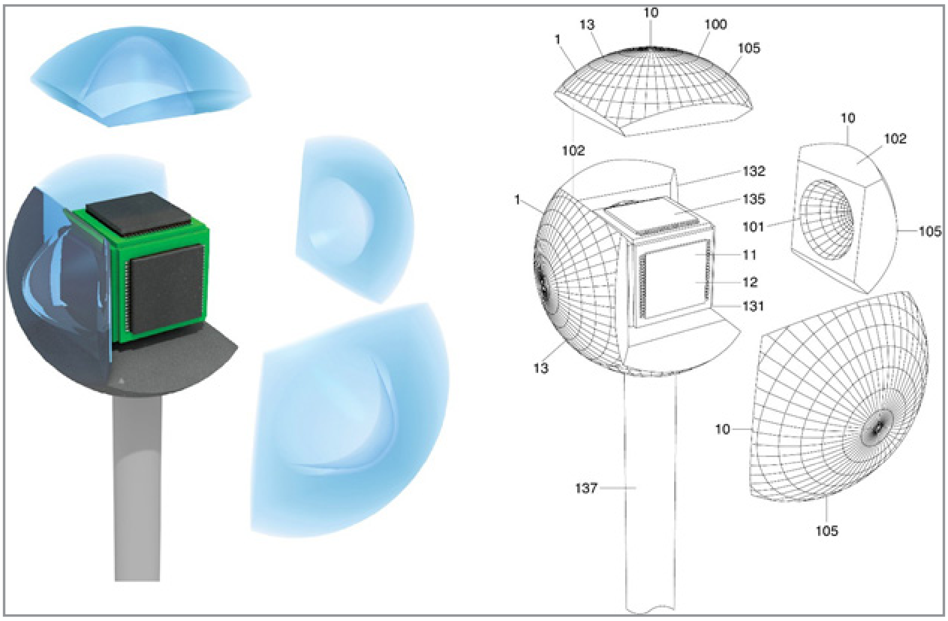

Figure: 1

Introduction

This invention introduces a versatile quantum camera module capable of functioning independently or as part of a planar or spatial array comprising multiple modules, connecting seamlessly to various devices. Each camera module operates as an optical system designed to transform light originating from an object point into an image point within a directed light cone towards the module's center. This design enables the recording of both static and dynamic images across numerous object and image points. In planar arrays, where multiple camera modules are arranged in rows or grids, each module can be specialized to capture specific light colors or achieve varying diagonal image angles. Spatial arrays, on the other hand, involve grouping multiple modules into configurations such as spheres or regular polyhedrons. This setup facilitates omnidirectional image capture, utilizing sub- bodies within spheres or polyhedrons to generate 360° panoramic images through layered or segmented bodies.

A core innovation within this camera module is the implementation of Single-Photon Avalanche Diodes (SPADs) as the sensor technology. SPADs are highly sensitive detectors capable of capturing individual photons, operating in Geiger mode above their breakdown voltage. This sensitivity allows for exceptional low-light performance and precise real-time motion detection. The incorporation of SPAD technology enhances the module's capability to capture extremely detailed images, even in challenging lighting conditions, making it suitable for various high-performance imaging applications. The integration of SPADs with advanced microchannel technology ensures optimal light collimation and efficient photon detection, significantly reducing noise and improving signal quality. This combination of SPAD technology and sophisticated optical design positions the quantum camera module as a cutting-edge solution for modern imaging challenges [1-4].

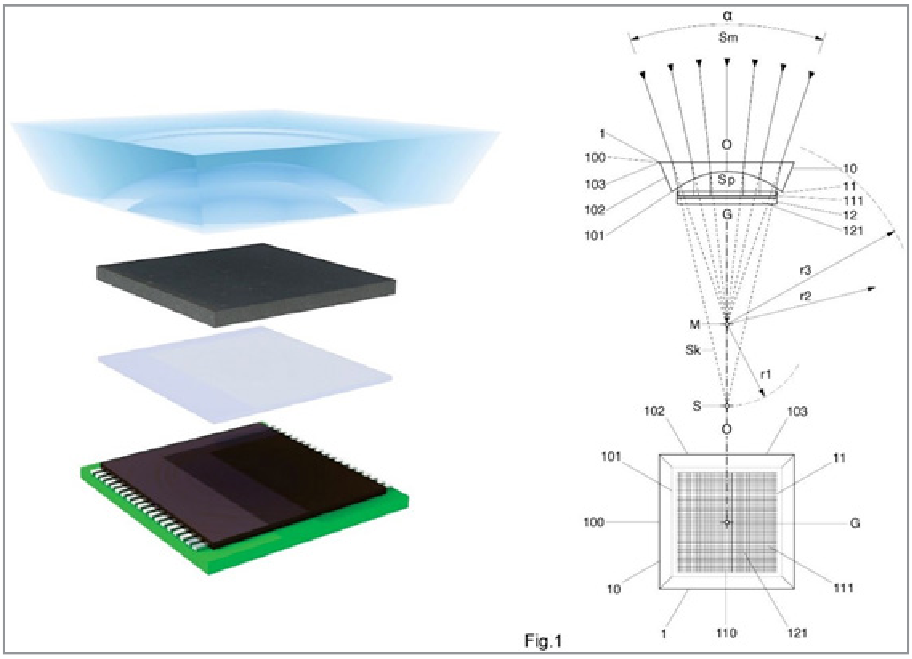

Figure: 2

State of the Art

The genesis of cameras traces back to the pinhole camera, a dark chamber with a minute aperture on one side and a screen on the other to capture inverted images from object points through converging rays. Inserting a converging lens into the pinhole enhanced image brightness and sharpness, laying the foundation for modern camera designs. Contemporary cameras typically employ complex objective lenses composed of multiple elements to project inverted images onto an image plane.

However, challenges persist, such as aperture control, exposure adjustments, and lens adaptation for varying distances, limiting real-time image capture capabilities.

Drawing inspiration from natural optics, the human eye operates similarly to a camera. Its crystalline lens adjusts via ciliary muscles to focus light onto the retina, which serves as a light-sensitive surface akin to a camera sensor. Insects, with their compound eyes, achieve infinite depth of field and real- time image processing by employing multiple ommatidia—individual optical units that independently capture and combine visual information into a cohesive image. For instance, a dragonfly's compound eye can comprise up to 30,000 ommatidia, highlighting nature's efficiency in vision systems.

Recent advancements in camera technology emulate insect vision, leveraging micro and nanotechnologies to create intricate optical structures on nano and micro scales. Techniques like additive laser printing enable the fabrication of transparent and opaque polymer optical elements, while subtractive methods like laser ablation allow precise manipulation of nanomaterials like carbon nanotubes. Gas phase deposition techniques further expand possibilities by constructing 3D structures from various materials with unprecedented miniaturization potential, surpassing natural optical systems in complexity and compactness. Spherical cameras represent another evolutionary leap, employing concentrically arranged lenses to converge light rays onto an imaging plane for comprehensive image capture. The development of the Bayer filter by Bryce E. Bayer in 1976 revolutionized color imaging by dividing sensor surfaces into fields with varying light transmittance— 50% for green and 25% each for red and blue—enabling color reproduction through sensor photocells.

Various patents and publications have contributed significantly to camera module innovation. For instance, technologies like optoelectronic cameras with integrated image intensifiers and microchannel plates enhance light sensitivity and resolution. Wafer-scale manufacturing techniques enable the production of planar camera arrays with precise optical components and aperture control, facilitating compact and versatile imaging solutions for diverse applications. Spatial arrays, such as cube configurations integrating multiple camera modules, enable omnidirectional imaging capabilities, further expanding the scope of visual capture in complex environments.

Structural Design and Innovation

Building upon the advancements outlined in the State of the Art, the invention aims to revolutionize camera module design by providing a structurally simplified yet highly efficient system for capturing static and dynamic images in both black and white and color formats, adaptable for integration with various devices. Central to the invention is the emulation of digital imaging techniques inspired by the compound eyes of insects, ensuring robust performance across diverse applications. Each camera module serves as a fundamental building block within an optical architecture, facilitating the formation of either planar or spatial arrays of multiple modules.

The primary objective is to establish a direct optical link between object points in Euclidean space and individual photocells of a sensor, utilizing a centered light bundle collimated by specially designed lenses and microchannel arrays. This approach not only enhances the reliability and precision of image capture but also reduces the overall construction height of the camera module, a critical aspect for applications requiring compact designs without compromising functionality.

Innovations within the invention include uniform size ratios between dispersion lenses, filter apertures, and sensors to optimize optical performance and image quality. The lenses themselves are crafted either from monolithic polymer materials or combinations of crown and flint glasses, offering achromatic or apochromatic corrections to mitigate chromatic aberrations. Multilayered constructions enhance optical performance, ensuring precise light manipulation from outer surfaces to sensor photocells.

The invention supports a wide range of imaging capabilities, from macroscopic photography with converging lenses to telephoto and wide-angle shots using dispersion lenses. Microchannel arrays integrated into the lenses effectively manage stray light, maintaining clear and precise image capture under varying lighting conditions. Advanced optical structures, including micro honeycomb structures and micro perforated plates, optimize light distribution and intensity across sensor photocells, further enhancing image fidelity.

For color photography, the invention incorporates Bayer filters and planar arrays of multiple plastic lenses, each dedicated to capturing specific wavelengths, thereby facilitating high-fidelity color reproduction. The design flexibility extends to spatial arrays, which enable omnidirectional image capture suitable for applications such as surveillance and panoramic photography. Omnidirectional motion detection capabilities are enhanced through spatial arrays equipped with micro converging lenses, ensuring comprehensive coverage and real-time monitoring.

Manufacturing processes are optimized for efficiency and scalability, leveraging materials like polymethyl methacrylate, polycarbonate, and polystyrene for durability and performance. Injection molding techniques are employed to produce plastic lenses in planar and segmented polyhedral configurations, supporting diverse imaging needs across industries.

Lens Technologies

The invention distinguishes between dispersion lenses positioned on the object side and converging lenses situated on the image side. When the camera module's center is on the image side, a dispersion lens collimates the centered light bundle, capturing an image angle ranging from 5 to 72 degrees. This configuration allows for omnidirectional image capture when multiple camera modules share a central point in a spatial array. Conversely, if the center of the camera module is on the object side, a converging lens is employed to collimate the light bundle, with aperture angles ranging from 5 to 30 degrees for plano-convex lenses and 5 to 50 degrees for bi-convex lenses. In a single module, the object of interest lies within the sector defined by the converging lens's aperture angle, while in a spatial array, the object is centered, enabling comprehensive macro imaging.

Manufactured either as monolithic lenses from polymer materials or as combinations of crown and flint glass for achromatic or apochromatic correction, these lenses address chromatic aberration effectively. Multilayer constructions are utilized for both dispersion lenses (convex-concave, plano- concave, or bi-concave) and converging lenses (plano-convex or bi-convex), ensuring optimal light transmission and correction across varying wavelengths. For applications requiring lightweight design, lenses can be fabricated as Fresnel lenses, facilitating integration with movable platforms such as robotic arms.

Color photography is facilitated by a Bayer filter positioned in front of the sensor's photocells. Alternatively, a planar array of plastic lenses, each dedicated to a specific light color, can produce color images by combining outputs from individual modules. Common polymer materials include polymethyl methacrylate, polycarbonate, polystyrene, or polycycloolefin-based polymers, each lens coated with dielectric and anti-reflection layers on both sides and a scratch-resistant coating on the image side. To prevent stray light, the edges of round or polygonal lenses within planar arrays are blackened.

The design of convex-concave lenses with spherical outer surfaces or plano-concave lenses with concave outer surfaces ensures minimal light dispersion, with the focal point coinciding precisely with the camera module's center. The spherical surfaces of convex-concave lenses enable the formation of spherical spatial arrays, exemplified by configurations comprising multiple modules forming a sphere, with additional space provided for conduits. Plano-concave dispersion lenses can be interconnected in spatial arrays to form regular polyhedrons, with edge configurations determined by whether the flat surface faces the object or image side. Bi-concave dispersion lenses result in polyhedrons with concave outer and inner surfaces, offering flexibility in light path and diagonal image angles.

Glass polyhedrons typically range from 10 mm to 60 mm in circumference, while spherical glass modules can reach diameters of up to 300 mm. Manufacturing spatial arrays involves interconnecting dispersion lenses at polygonal edges, often utilizing injection molding for plastic components, enabling the creation of layered or segmented structures.

SPAD Technology

The core of the camera module's sensor technology is based on the implementation of Single-Photon Avalanche Diodes (SPADs), which are highly sensitive and capable of detecting individual photons.

SPADs operate in Geiger mode, where they are biased above their breakdown voltage and can thus detect single photons with high temporal resolution. This technology allows for the capture of extremely low-light images and enables precise real-time motion detection.

High Sensitivity and Precise Timing

SPAD technology explores the high sensitivity and precise timing capabilities of SPADs, enabling the detection of single photons—a critical feature for applications in quantum optics, cryptography, and high-speed imaging. The high sensitivity of SPADs allows the camera module to capture images in extremely low-light conditions, making it ideal for environments where traditional imaging sensors would struggle. The precise timing capabilities of SPADs, which can measure the arrival time of individual photons with picosecond accuracy, are crucial for high-speed imaging applications, allowing the capture of fast-moving objects and scenes with exceptional clarity and detail.

Microchannel Integration

The integration of SPADs with microchannels is crucial for enhancing the module's performance. Microchannels, arranged in a grid, ensure that light entering the module is collimated and directed precisely towards the SPAD sensors. The microchannels serve a dual purpose: they filter out unwanted stray light and guide parallel light beams towards the sensors, thereby enhancing the accuracy and clarity of the captured images. This design reduces noise and improves the signal-to- noise ratio, making it easier to capture clear images even in challenging lighting conditions.

Advanced Microchannel Design

At the image-side termination of microchannels, micro-collecting lenses focus the light onto the SPAD photocells, ensuring optimal capture efficiency. This is achieved by employing a lens matrix with varying sizes of dispersion and converging lenses, ensuring uniform light intensity distribution across the image. The manufacturing of these microchannels and lenses involves advanced 3D printing techniques, where materials such as carbon nanotubes are used to create precise and efficient microstructures. This ensures that the lenses are accurately aligned with the microchannels, resulting in a highly efficient light collection system.

Color and Motion Detection

A Bayer filter in front of the SPAD photocells enables the differentiation of light into primary colors, facilitating color imaging. The high temporal resolution of SPADs allows for the detection of motion in real time, making the camera module capable of capturing fast movements with exceptional clarity. This is particularly useful for applications in security, surveillance, and sports, where precise motion detection is crucial.

Manufacturing Techniques

The construction of microchannels and the integration of SPADs involve advanced manufacturing techniques. Methods such as 3D laser printing and the use of carbon nanotubes allow for the precise fabrication of microchannels. These channels are arranged in grids on microhole plates, with diameters ranging from 3 to 8 mm. The plates are created using ablative methods, resulting in cylindrical or conical microchannels that efficiently transmit light.

Computational Image Processing

The invention incorporates sophisticated computational image processing techniques to correct image distortions. This is essential for ensuring accurate image reproduction, particularly when capturing images through complex lens arrangements and microchannels. Dedicated algorithms process the captured data to correct for aberrations and enhance image quality, ensuring that the final images are clear and detailed. These techniques are integrated into the module’s hardware, enabling real-time image correction and processing, which is crucial for applications requiring immediate image analysis and interpretation.

Integration in Various Devices

Due to its compact size and high performance, the quantum camera module can be integrated into a wide range of devices. Applications include mobile phones, vehicle mirrors, and endoscopes, where the module’s small size and high-resolution capabilities enhance functionality. For example, in mobile phones, the module can provide superior image quality and low-light performance. In vehicle mirrors, it can offer enhanced rear-view imaging for improved safety.

In the realm of medicine, the quantum camera module holds immense promise as an advanced endoscopic camera. Traditional endoscopic cameras often struggle with capturing high-resolution images in the dimly lit internal environments of the human body. However, the quantum camera module’s SPAD technology addresses this challenge by allowing for superior image quality even in the darkest areas, ensuring that medical professionals can conduct more accurate diagnostics and assessments. The module’s compact design also facilitates its integration into endoscopes, enhancing maneuverability while maintaining the essential capability to capture intricate details of internal tissues and organs.

Moreover, the quantum camera module’s ability to function in extremely low-light environments makes it an ideal candidate for deep-sea exploration. Deep-sea survey cameras face the challenge of capturing clear images in the abyssal depths of the ocean, where light is minimal. The module’s advanced microchannel integration and SPAD sensors are adept at overcoming these conditions, enabling the capture of high-definition images in the darkest oceanic regions. Additionally, its structural adaptability allows for the creation of spatial arrays, facilitating 360° panoramic imaging essential for comprehensive environmental assessments and marine biodiversity studies.

Future Directions and Technological Advancements

The development of this quantum camera module opens the door for future advancements and applications. Researchers and engineers will continue to enhance the sensitivity and temporal resolution of SPADs, creating smaller and more efficient SPAD arrays with improved noise reduction techniques. This will enable the capture of detailed images in even lower light conditions and at higher speeds. The integration of SPAD technology with quantum technologies will also advance fields such as secure communication and cryptography.

Combining SPAD Technology with AI

Future developments may involve combining SPAD technology with machine learning and artificial intelligence. This integration could allow for real-time motion capture and automatic adjustments based on the captured scene, benefiting fields such as autonomous vehicles, surveillance, and augmented reality/virtual reality (AR/VR) systems. The use of SPAD-based high-resolution imaging in medical diagnostics and research will also expand, offering new tools for detailed and non-invasive examinations.

Manufacturing Innovations

Innovations in manufacturing processes will lead to more cost-effective production of SPAD sensors and camera modules. Advanced 3D printing and material science techniques will allow for custom- designed sensors and optical components, tailored to specific applications. This will drive further innovation across industries, enabling new applications and improving existing technologies [5-8].

Conclusion

The quantum camera module represents a groundbreaking advancement in digital imaging technology. By integrating the principles of quantum optics, the module achieves unprecedented imaging capabilities. The use of dispersion lenses, converging lenses, microchannels, and advanced sensor technologies, combined with sophisticated computational image processing, ensures high clarity and detail in captured images. This innovation broadens the module's applicability across diverse fields, setting new standards in imaging excellence and driving technological breakthroughs.

Reference Signs

Camera module	1	Device	2
Diverging lens	10	Centered beam	Sm
Object-side outer surface	100	Converging beam	Sk
Image-side inner surface	101	Diverging beam	Sd
Edge	102	Parallel beam	Sp
Plano-concave lens	103	Optical axis	O
Biconcave lens	104	Center	M
Convex-concave lens	105	Radius	r1
Plano-convex lens	106	Radius	r2
Biconvex lens	107	Radius	r3
Microchannel, SPAD	11	Focal point	F
Micro-collecting lens	110	Intersection	S
Lens matrix	111	Apex	G
Micro-hole plate	112	Image angle	α
Micro-honeycomb structure	113	Aperture angle	δ
Sensor	12	Height	h
Bayer filter	120	Glass pane	20
Photocell	121	Screen	200
Sensor island	122	Inner mirror	201
Strip grid	123	Outer mirror	202
Array	13	Headlight glass	203
Row	130	Windshield	204
Polyhedron	131	Rear window	205
Sphere	132	Endoscope	21
Layered body	133	Video cable	210
Segmented body	134	Light channel	211
Platonic solid	135	Tool channel	212
Archimedean solid	136	Glasses	22
Conduit channel	137	Connection cable	220

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