Design and Experiments of Photon Counting Imaging Test Platform

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Abstract—**The photon counting avalanche photodiode (APD) imaging test platform is put up according to the semi-classical theory of photoelectric detection which the classical statistical fluctuation of the light field is combined with the fluctuation of the interaction between light and matter. A mathematical model between APD photon counting frequency's expectation and input gray levels is set up. With changes of scene gray, the photon number of reflective radiation is bigger; photon counting frequency expectation of the corresponding sampling points will be greater. A black white stripe image is scanned at 10^{-3}lx low light level (LLL) illumination. In accordance with the established mathematical model and the scanning mechanism, the photon counting output appearing as one-dimensional time-domain will be represented as two-dimensional image information.**

Keywords-photon counting imaging;avalanche photodiode;low light level;statistical optics

I. INTRODUCTION

Beam is a flux composed of a large number of photon. When the optical power gradually diminishes, photon will be more and more isolated. When the optical power decreases to a certain degree, the photon will appear as a discrete random distribution. If the optical signal is continued to weaken, a single photon will be generated. The single-photon energy with different wavelength is only $1.9865 \times 10^{-19} / \lambda$ [1].

Photon counting method is usually used to detect such weak signal, namely to utilize the characteristics that the output signal of photon detector is naturally discrete under the low-light irradiation, and use pulse discrimination technology and counting technology to identify and extract extremely weak signal. The traditional photon counting method is to use photomultiplier tube (PMT) for detection. With technology development, there are a lot of new photon counting detection techniques and devices. Typical devices such as, microchannel plate (MCP) [2], electron bombarded charge-coupled device (EBCCD) [3] and multi-anode microchannel array (MAMA) [4]. The above all devices are bulky and frangible vacuum devices and needed to be equipped with kilovolt high voltage power supply and extra cooling equipment during working. In 2001, Andor Technology Ltd first used electron-multiplying CCD (EMCCD) [5] for iXon series on high-end super-high-sensitivity camera. EMCCD is small, and the gain may be up to more than 1,000 times, but EMCCD will also enlarge the dark current noise while the signal is amplified. The dark current noise has greatly impacted on detection sensitivity and signal-to-noise ratio.

In order to realize high sensitivity imaging detection, APD based photon counting imaging research is introduced. Lincoln Laboratory developed three-dimensional (3D) imaging laser radars with Geiger (photon counting) mode APD array [6]. All images were obtained by active illumination of the scene by a laser. A camera prototype based on the APD array image sensor was built by Ecole Polytechnique Fédérale de Lausanne in Switzerland [7]. At home, there are tentative studies on APD device recent years [8, 9]; to the best of our knowledge, the researches on imaging system based APD have been in blank state. We launched a study on the passive photon counting system based on a single APD. It is different from Lincoln lab's active system and EPFL's APD array system. The constituents and imaging process of the passive imaging test platform are mainly expounded in this paper.

II. SINGLE-PHOTON DETECTION PRINCIPLE

Avalanche photodiode for single-photon detection, is based on the theory of strong field impact ionization. When the APD is working in the "Geiger" mode, that is, when the device's reverse bias voltage is higher than breakdown voltage. If a photon which energy is greater than the bandgap energy is injected in the depletion region, its energy will be absorbed by lattice atoms, and the valence electron will be stimulated for the transition to the conduction band, at the same time, leaving a hole in the valence band. The initial electron hole pair is formed. Under the influence of strong electric field, during drift, the electron and hole will collide with other lattice atoms to generate a new secondary electron - hole pair, the result of this chain effect is that APD is triggered and generate the order of milliampere self-sustaining avalanche current. So, APD realizes single-photon order incident signal detection.

III. PHOTON COUNTING IMAGING DETECTION PROCESS

The avalanche photodiode manufacturing by standard semiconductor technique has all-solid-state structure and low power consumption with working voltage less than 35 volts. Especially APD in the Geiger mode has the impact ionization mechanism under negative bias, which may provide the initial carrier with rapid multiplication so as to obtain the internal current gain. The noise associated with this gain is obviously

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smaller than the noise level of the method that is to use photoelectric converter and electronic amplifier for getting the same gain. The system based APD has a higher signal-to-noise ratio.

A. Photon Counting Detection Theory

The detection for natural scene is not direct operation for the nature's own state, but is to operate for this scene's optical express such as: radiation light, reflected light and transmitted light. Using light to express nature state has the statistical characteristics, which mainly because all real light waves have statistic or random property. The radiation generated by light also has the statistical property. The phenomenon of random fluctuation also exists in the process of light's reflective radiation to detector. So each stage of the imaging system is a random process. If the light field does not change, photon counting is a Poisson process. However, the light field is actually a random process, so photon counting is a double stochastic Poisson process. Under a certain light field W, the probability of m times of photoelectric events happening for the detector from time t to time t + T is

$$P(m;t,t+T\mid W)=\frac{(\alpha W)^m}{m!}\exp(-\alpha W). \qquad (1)$$

Where $\alpha=\eta/h\bar{v}$, η expresses quantum efficiency of the detector, h is Planck constant, $\bar{v}$ is the average frequency of the radiation.

Considering the light field's integral intensity distribution Pw (W), the expectation of m is

$$\begin{aligned}\bar{m}&=\sum_m mP(m;T)\\&=\int_0^\infty P_w(W)\Big(\sum_m m\frac{(\alpha W)^m}{m!}\exp^{-\alpha W}\Big)dW\\&=\int_0^\infty P_w(W)\alpha W dW\\&=\alpha\overline{W}.\end{aligned} \qquad (2)$$

This formula reflects the relationship between photon counting expectation, detector and light field. This is the theoretical basis for photon counting imaging detection. The expectation of photoelectric events happening for the detector is equal to the expectation of light field multiplied by a coefficient α related the photoelectric conversion device.

B. APD Imaging Detection Process

The information flow of photon counting APD imaging detection is shown in Fig.1. The temporal and spatial distribution information from a certain band of the scene may image on the photosensitive surface of APD detector by objective lens through the attenuation of the atmosphere. After photoelectric conversion for targets by APD, APD will output discrete photon counting values formed by photon incidents.

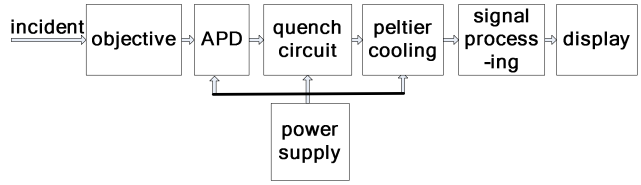

Figure 1. APD-based single photon imaging system information flow.

The photon counting values will be supplied to the signal processing circuit for displaying the image that reflects the scene after the treatment. In order to protect the APD and prevent the continual increase of self-sustaining avalanche current resulting in the permanent breakdown for the device, quench circuit is used to reduce APD's reverse bias working voltage to below the breakdown voltage, and effectively inhibits the avalanche effect in APD. The quenching circuit shall reset the APD to above the breakdown voltage to prepare for the next photon detection after outputting the avalanche signal. Because the avalanche diode is very sensitive to temperature change, tunneling noise and thermal noise will enlarge along with the temperature increase, the test platform uses thermoelectric cooling of semiconductor Peltier effect to guarantee APD has a minimum dark current and improve APD's working stability.

IV. EXPERIMENT TEST PLATFORM FOR PHOTON COUNTING IMAGE DETECTION

Experiment test platform for photon counting APD imaging detection consists of dark-box, single-photon counter, objective lens, computer, micro-light illuminance meter, light source, two-dimensional guide pair and connection cables.

A. Objective Lens

The main function of objective lens is to image the observed scene on the photosensitive surface of APD detector. In accordance with the principles of geometrical optics, a point on the scene must be imaged to another corresponding point of photosensitive surface after focusing by objective lens. The scene will be formed on the focal plane to an image field distribution. According to the statistical rule of fluctuation of light quantum under low illumination, low-illumination resolution of low-light-level imaging system shall be directly proportional to the square root of objective lens effective aperture and optical transmittance. Objective lens shall have a large effective optical aperture and high-pass optical transmittance. At the same time objective lens shall have an appropriate focal length to ensure that the imaging system has a higher spatial resolution under low-light-level illumination, but the enlargement of aperture and the increase of focal length are two factors to be mutual conflict and binding to each other. To compromise as the actual situation, the platform selects the lens of the variable focal length, the scope of a variable focal length is: 8.3mm to 49.8mm, the relative aperture is D / f = 1:1.4.

B. APD Photon Counter

In the platform, the photoelectric detection uses photon counting module produced by Ireland SensL. Several advantages of this module structure over competing systems include increased sensitivity to blue-red wavelength photons, increased response time (low timing jitter < 200ps) to fast optical signals. The module can provide single-photon-counting capability with a low-operating voltage less than 35 volts, which greatly decreases power consumption. APD is manufactured using standard complementary metal–oxide–semiconductor substrates and fabrication steps [10]. The responsivity of the detectors is found to peak at 540nm with a quantum efficiency of 18.34% at 5 V above the breakdown voltage. The low dark count of the detector is about 4 Hz.

C. Light Source

In the design of photon counting imaging experiment, the design of light source is very important. Stable and continuous illumination source can furthest ensure the accuracy of the experiment, and be favorable to the analysis of the experimental results and the error calculation. In a variety of devices, the diode source has the features such as long emitted light wavelength, small error, and simple luminous intensity control, which is suitable for single-photon source. The change rule for diode luminescence intensity I and voltage V is as follows,

$$I = A\exp(eV/KT). \tag{3}$$

Where A and K are constants, T is temperature.

The relationship between current flow I_f through diode and the voltage V supplied to the two ends of diode is as follows,

$$I_f = A'\exp(eV/nKT). \tag{4}$$

In the formula, A' is constant, 1<n<2. The relationship between diode's luminescence intensity I and the flowing current I_f is educed as follows,

$$\ln I = n\ln I_f + c. \tag{5}$$

C is a constant in the formula. It can be seen that there is linear relationship between the current flowing through diodes and the diode's luminescence intensity. The current flowing through diodes can be adjusted to control diode's luminescence intensity. On this basis, the single-photon source which has stable frequency and photon number can be obtained by using narrow-band filter and attenuator for light filtering and attenuation.

V. EXPERIMENTAL METHODS

A. Mathematical Model of Photon Counting Frequency Expectation and Ggray Levels

Experimental setup is put in 10^{-3}lx which is in the range of low light level (LLL) environment. A gray level test pattern is scanned from left to right as shown in Fig.2.

Figure 2. Gray levels test pattern.

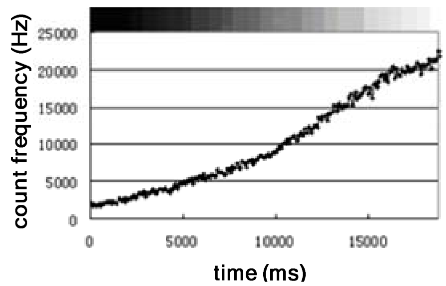

Figure 3. Count frequencies scanning gray levels test pattern.

The test pattern's gray level changes cause the difference of photon number of the reflective radiation of the pattern. So, the pattern is converted different outputs of photon counting frequency by APD. The output photon counting frequency is recorded into the data acquisition software developed by VC + + language. Transforming the photon frequency values into the form of a chart is shown in Fig.3 which can be intuitive to analyze the situation that the frequencies of photon counting vary with different image gray levels. The change of pattern gray levels is directly proportional to the pattern's photon radiation level in a certain range [11]. It indicates that the more photon number of reflective radiation, the greater counting frequency value of corresponding pixel.

Under very weak light, because photon's particle property appears and the light field fluctuates in time and space, the photon density distribution is actually the expectation of photon density distribution. The expectation of photon distribution is proportional to the gray of corresponding region of gray image [12]. Thus the curve of time-domain in Fig.3 is converted to the relation between gray levels of spatial domain and photon counting frequencies is shown in Fig. 4.

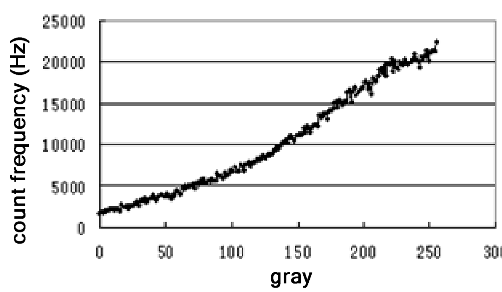

Figure 4. Count frequencies vs. gray levels

The starting point in the process of acquisition is influenced by gray test pattern background and photon fluctuation. So in 300 collected photon counting values, the gray value of the smallest data 1706.908 is set as 0, the biggest data 22,445.71 corresponds to 255 of gray level.

In the actual test, the photon counting frequency values are known for the scanned gray test pattern, the photon counting frequencies are regarded as the independent variable x, gray levels are dependent variable y. In order to simplify the calculation and to ensure the identity of the processing, the photon counting frequencies are normalized to be a scalar. By looking for the relationship between the normalized photon counting frequencies and image gray levels, a mathematical model between both is set up. Since the fitting curve of arbitrary function relation may be carried out through the polynomial. A scatter diagram may be obtained by these Three hundred measured data points (x1, y1), (x2, y2) ..., (x300, y300) at the plane identified x, y. According to the basic principle of least square method, the curve s (xi) is fit to satisfy the smallest sum of squares of the distance between known points and s (xi). That is, the sum of square of the error $\sum_{i=1}^{300} \delta_i^{\,2}$, $\delta_i = s(x_i) - y_i$, $i = 1,2,\cdots,300$ is the smallest. The calculation by Matlab is used to get the relation between image gray levels and photon counting frequencies. The model of photon counting APD between photon counting frequencies and gray levels is obtained,

$$\begin{aligned} y &= s(x) \\ &= 453.8x^3 - 854.6x^2 + 719.06x - 51.924 . \end{aligned} \tag{6}$$

The fitting curve is shown in Fig. 5.

B. Image Restoration

A black and white image that is shown in Fig. 6 is averagely divided into 16 lines, and then this image is progressively scanned in accordance with the mode in the figure from top to bottom from left to right. The each line's photon counting frequencies are recorded in data acquisition software. The established model between photon counting frequency and the gray levels is used to restore the image of stripes. The result of restoration is shown in Fig. 7.

It may be seen that photon counting image can reflect the gray change in black and white stripes. It is a better correlation between photon counting frequency expectation and image gray level, but being affected by the reflective radiation of adjacent stripe edge, photon's wave-particle duality and light field intensity fluctuation, it results in the acquiring image with

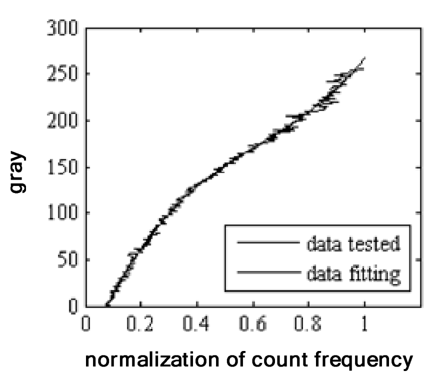

Figure 5. Curve fitting between gray and count frequency

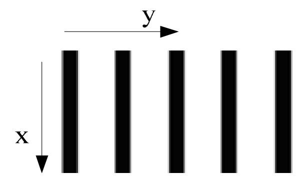

Figure 6. Scanning manner of the original daylight image.

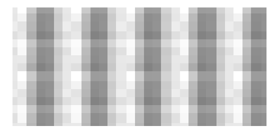

Figure 7. Photon counting image (image obtained in low light level environment)

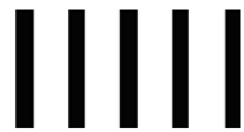

Figure 8. Restored LLL image

a certain photon noise and edge blur. Comparing with the day original image (Fig.6), the contrast of restored low-light-level image has decreased significantly. In the histogram, the range of gray levels is narrow, the maximum gray level is 255, and the minimum is 131. Obviously, the contrast range of the photon counting image is reduced. The de-noising is made for photon counting image by the signal processing circuit, the noise of image is removed after processing (Fig. 8), but black stripe width is expanded by 3% over the original image because the sampling resolution is only 16 × 42.

VI. CONCLUSION

In this paper, because the original image is discretized as 16 × 42 sampling points under low light circumstance, and the passive imaging mode is used, the image resolution declines slightly. In order to get a good restored image, the sampling resolution needs to further improve and strengthen the post-processing of restored image, simultaneously also enhance APD's reverse bias voltage in the scope of 5v in order to improve the quantum efficiency of APD.

According to the theory of statistical optics, APD low-light imaging system is set up based on photon counting. The present experiment proves that this platform can achieve the object imaging detection under the circumstance of 10^{-3}lx. The test confirms the correctness of system design idea, and has great guiding significance for the future work. In addition, the experimental system uses the APD with all-solid-state structure, using its strong field impact ionization mechanism may simplify the circuit design and improve system's signal-to-noise ratio and time resolution. Because the system has been supplied by only 35 volts voltage, it makes the system small size and low power consumption which provide conditions for system's miniaturization development.

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REFERENCES

[1] J.X. Zhang, Y.D. Li, and W.Q. Jin, Imaging technique of low light level and infrared, Beijing institute of technology press, Beijing, 1995.

[2] R.W. Airey, TJ. Norton, B.L. Morgan, J.L.A. Fordham, D.A. Bone, and J.R. Powell, "DQE enhancement of MCP intensifiers for astronomy results of the MIC II program", Proc. SPIE, 1990, Vol. 1235, pp. 338-346.

[3] G.M. Williams, A.L. Reinheinmer, and et al., "Back-illuminated and electron-bombarded CCD low light level imaging system performance", Proc. SPIE, 1995, Vol. 2551, pp. 208-223.

[4] D.B. Kasle, and J.S. Morgan, "High resolution decoding of multianode microchannel array detector", Proc. SPIE, 1991, Vol.1549, pp.52-58.

[5] D.J. Denvir, and E. Conroy, "Electron Multiplying CCD Technology: The new ICCD", Proc. SPIE, 2002, Vol. 4796, pp.164-174.

[6] M.A. Albota, B.F. Aull, D.G. Fouche, et al. "Three-dimensional imaging laser radars with Geiger-mode avalanche photodiode arrays", Lincoln Laboratory Journal, 2002, 13 (2), pp. 351-370.

[7] Niclass C., Sergio M., Charbon E., "A single photon avalanche diode array fabricated in deep-submicron CMOS technology", Proc. of the Conference on Design, Automation and test in Europe, 2006, pp. 81-86.

[8] S.f. L i, Y.Y. Xiong, H. Wang , S.M. Zeng, and C.J. L iao, "Temperature Characteristic for InGaAs / InP Single-photon Detector at Infrared Communication Wavelengths", Acta Sinica Quantum Optica, 2008,Vol.14 (3), pp.327-332.

[9] W. Lei, F.M. Guo, D.P. Hu, Z.Q. Zhu, and J.H. Chu,"Simulation and Optimizing for Heterostructure of InGaAs/ In P Avalanche Photo-detectors", LASER & INFRARED, 2008,Vol. 38, No. 10, pp.1000-1003.

[10] J.C. Jackson, P.K. Hurley, B. Lane, and A. Mathewson, "Comparing leakage currents and dark count rates in Geiger-mode avalanche photodiodes", Appl. Phys. Lett, 2002, Vol. 80, pp.4100-4102.

[11] G.R. Cao, X. Yu, and X.Q. Hu, "Photon counting image acquisition technique and its applications", Proc. SPIE 1994, Vol. 2513, pp.566-572.

[12] B.R. Frieden, Probability, Statistical Optics, and Data Testing, Berlin, Springer-Verlag, 1983.