Investigation of Timing Resolution and Energy Resolution for SiPM/PET Detectors Using the Silicon Flexible Optical Material

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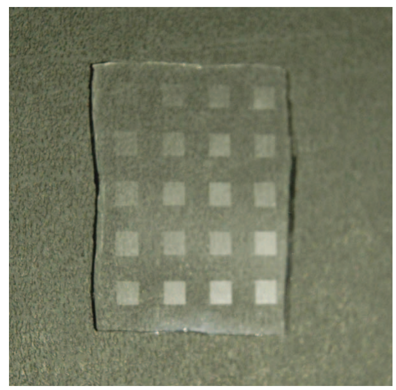
***Abstract*—Silicon photomultipliers (SiPMs) attract extensive attentions for detecting optical photons in high energy physics and medical imaging due to its high gain, high photon detection efficiency (PDE), low operation voltage and fast timing response. We use a binary optical element (BOE) made of the silicon flexible optical material to transform the incident light intensity expressed as Gaussian distribution into uniform in space, making the incident photons be detected by the SiPM evenly. In this way, we can make full use of all cells of the SiPM, and more cells operating means more photons being detected for a certain pulse, which can increase the count rate of the incident photons and therefore improve the detection efficiency of the SiPM. Also, by comparing the outputs of the SiPM in different light intensity inputs, we can obtain the best light intensity fit for the SiPM along with the suitable scintillator and surface treatment for the positron emission tomography (PET) imaging based on the SiPM. In our experiments, we use the laser pulse as the SiPM input, whose light intensity can be expressed as Gaussian distribution in space, and then compare the readouts of the SiPM with and without the BOE. As expected, by using the BOE, the timing resolution and energy resolution of the SiPM are better than those without using it for some certain light intensity.**

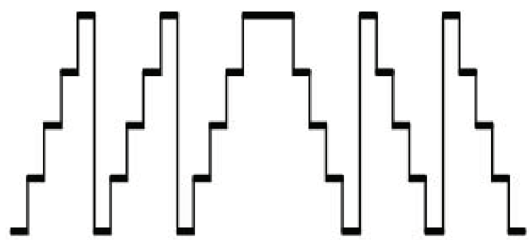
***Index Terms*—SiPM, PET, Timing Resolution, Energy Resolution, BOE.**

I. Introduction

Silicon photomultipliers (SiPMs) are novel, solid-state devices for detecting optical photons, and are considered as the most promising alternative to photomultiplier tubes (PMTs) in high energy physics and medical imaging [1]. An SiPM consists of an array of small independent Geiger-mode cells, operating at 40-70 volts. All cells are combined on the same substrate (from 100 to 4000 cells/mm^2), and connected to a same readout. Depending on the structure of the diode, an electron can accelerate across the high-field region with a gain range of 10^5-10^6 when a single optical photon is detected, and the SiPM gets a fast timing response [2]. As compact silicon devices, SiPMs are insensitive to magnetic fields, and may be manufactured at a low cost in a mass production. All these characteristics lead SiPMs fit for the positron emission tomography (PET) imaging[3].



(a) The picture of a BOE



(b) A binary phase representation of a binary optical element

Fig. 1. The silicon flexible optical material - a binary optical element

SiPMs have high quantum efficiency to detect the optical photons. However, the photon detection efficiency (PDE) of SiPMs (25%-65%) is relatively low for the limitation of the geometrical efficiency (the ratio of the sensitive surface to the total surface) and the probability to initiate a Geiger discharge [2]. In practice, because the SiPM is a binary photoelectric conversion element, if the incident light focuses on only a part of the sensitive area of SiPMs, it will lead to the saturation of cells in this area, and they won't respond to the upcoming incident photons in a short time once again. Meanwhile, other cells may receive fewer or even no optical photons, making the photons count rate of SiPMs fall, thus the photon detection efficiency of SiPMs may decrease badly.

A binary optical element (BOE) is a new type of optical component which can be made of the silicon flexible optical material by Very Large Scale Integration technics (VLSI), using computer design pattern generation, mask making and ion/electron-beam microlithography [4-6]. It can be made in micro-array or as an integrated device, as shown in Fig.1. The great advantage of the BOE is its ability to generate an arbitrary needed wavefront. Through the computation and simulation based on the G-S algorithm, we have designed and produced a BOE which can transform the input light intensity expressed as Gaussian distribution into uniform in space, and make more incident photons be detected by the SiPM evenly. Consequently, placing the BOE between the incident light and the SiPM will make full use of all cells. More cells operating means more photons being detected for a certain pulse, which can increase the photons count rate of the SiPM and improve the detection efficiency and other performance of the SiPM detection, such as the timing resolution and energy resolution. Besides, by analyzing the results of the SiPM output in different light intensity, we can find out the best light intensity fit for the SiPM and the suitable crystal type and surface treatment for SiPM/PET detectors.

II. Methods and Results

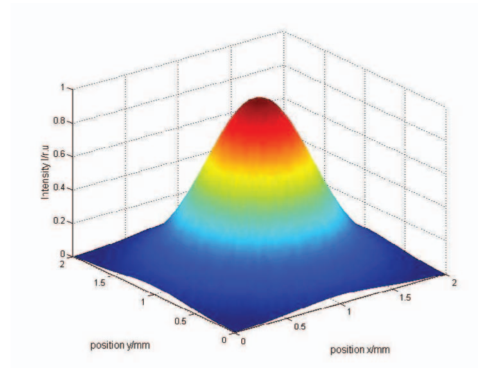
The intensity of the laser pulse is not evenly distributed and it can be expressed as Gaussian distribution spatially. By applying a BOE, we can transform the incident laser pulses into evenly distributed photon pulse signals and then they reach the sensitive surface of the SiPM. By comparing the laser pulses with and without the BOE, we can study the influence from the photon distribution towards the energy resolution and timing resolution of SiPMs.

A. Laser simulation

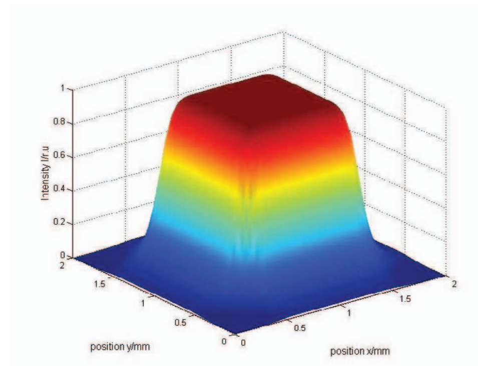
The principle of a binary optical element is similar to the phase recovery principle in an optical transform system, i.e. based on the output light intensity which is modulated through an imaging system, the final expected image can be obtained precisely.

In the simulation, we adopt the G-S algorithm to simulate the functions of the binary optical element. The G-S algorithm is a widely used phase recovery optimal algorithm, and in each of its repetitions three steps are involved: (1) Do the Fourier transform based on the initial phase and the swing distribution of the input light field; (2) Introduce the constraints from the output light field, i.e. substitute the required swing for the original swing, but keep the light phase fixed; (3) Do the inverse Fourier transform with the constraints from the input light field, i.e. substitute the original input light field swing for the required swing, but keep the light phase fixed. The repetitions can continue until a satisfied result is achieved [7].

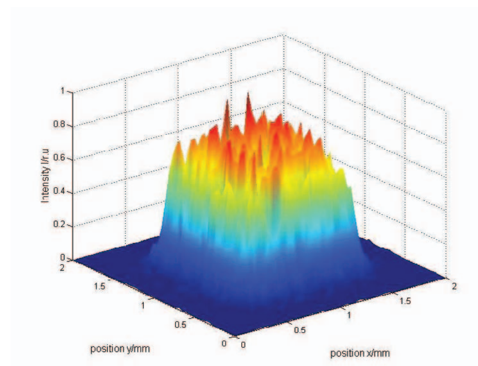
To study the transform effect of the BOE, we use the laser intensity with the standard Gaussian distribution spatially in our simulation. The input laser wave length is 409nm, and the radius of the beam waist is 1mm. The beam intensity distribution is shown in Fig.2(a). The size of the binary optical element is 3mm∗3mm, and we hope to get an evenly distributed input beam as shown in Fig.2(b). The output pulses through the simulation based on the G-S algorithm is shown in Fig.2(c).



(a) The intensity distribution of the input beam



(b) The expected ideal intensity distribution of the output beam



(c) The intensity distribution of the output beam through the simulation

Fig. 2. The results of the laser simulation

According to the simulation result, we can know that by designing a BOE which can transform the Gaussian distributed input laser into an evenly distributed beam, the efficiency of the cells in the SiPM can be improved in theory.

B. Scintillator simulation

When the Gamma photons subside within the scintillator and emit a large number of visible light photons, some of the visible light photons are distributed in the Gaussian form. This phenomenon is especially distinct where the subsiding process occurs close to the coupling interface between the scintillator and the SiPM. Through the simulation software tool - GATE, the distribution of the photons from within the scintillator is simulated. In the simulation, a LYSO crystal with the size of 2∗2∗15mm is adopted, and the bottom surface of 2∗2mm is coupled with the SiPM while the other 5 surfaces are polished smoothly. The photon distribution achieved through the LYSO crystal is shown in Fig.3(a). We hope the photon output can be evenly distributed after passing through the BOE, as shown in Fig.3(b). The simulation result is shown in Fig.3(c).

From the above results we can know that the originally densely centralized visible photons are distributed more evenly after passing through the BOE, and this can help improve the detection efficiency of SiPMs.

C. Laser experiment

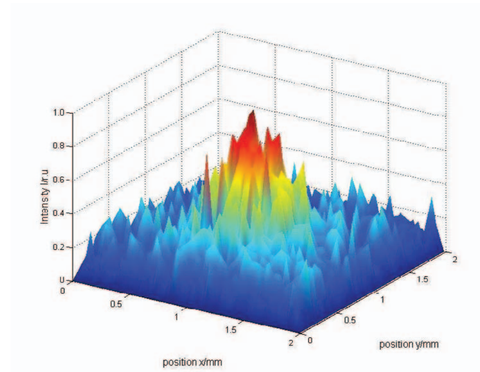
In our experiment, we adopt the SPMMicro 3035 SiPM produced by Sensl with an effective detection area of 3∗3 mm^2 with 3640 cells. We use the picosecond injection laser as the input signal to the SiPM, the distance between the laser and the SiPM is about 1m, and the binary optical element is placed in the middle of them. The wavelength of the laser output is 409nm, the beam diameter is 3mm, and the laser intensity is a standard Gaussian distribution spatially. By adjusting the laser intensity, we can compare the output signals of the SiPM with and without the binary optical element. The results are shown in Figure 4.

Based on the above results, we can draw the following conclusions:

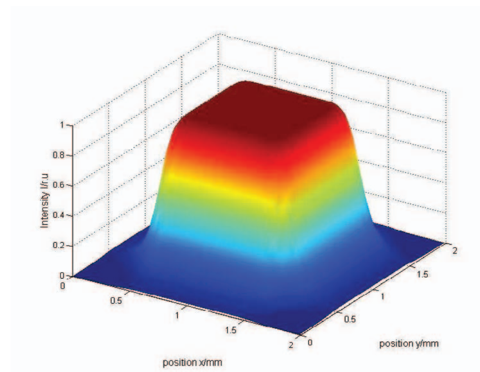
a. When the light intensity of the laser pulse is relatively high (>90%), almost all cells can receive a large number of photons and be saturated owing to the considerable number of incident photons. In this way, the SiPM can make full use of all cells. By use of the BOE, although the input photons become the uniform distribution, the number of operating cells doesn't change. Moreover, the detection efficiency and the photons count rate of the SiPM have not increased significantly as well as the signal to noise ratio (SNR). Therefore, the output intensity, the energy resolution and the timing resolution do not change distinctively.

b. When the light intensity of the laser pulse lowers to an appropriate value (20% - 90%), the majority of photons focuses on only a part of the cells, while other cells receive very few or even no incident photons. Placing the BOE before the SiPM helps all cells receive the photons equally. It can increase the photons count rate obviously, and the output signal/noise ratio can be enhanced distinctively, thus the energy resolution and the timing resolution can be improved substantially.

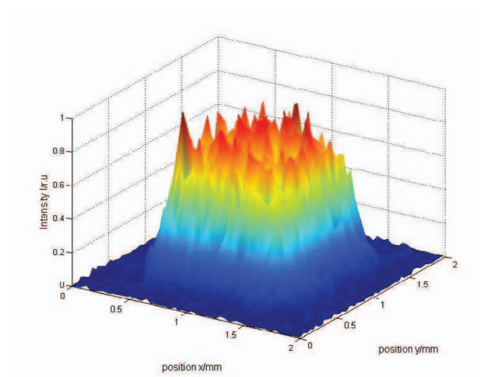
c. When the light intensity of laser pulse is too low (<20%), the small number of the incident photons worsens the uniform character of the BOE. Besides, because of the attenuation effect of the BOE to incident photons, the number of incident photons decreases and its uncertainty increases. As a consequence, the energy resolution and timing resolution get worse.



(a) The distribution of the beam intensity from within the scintillator, achieved through the GATE simulation



(b) The expected ideal distribution of the output beam intensity

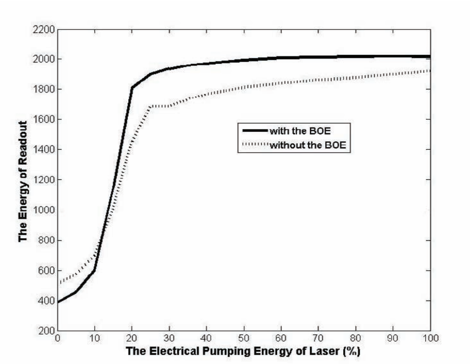


(c) The distribution of the output beam intensity after passing through the BOE in the simulation

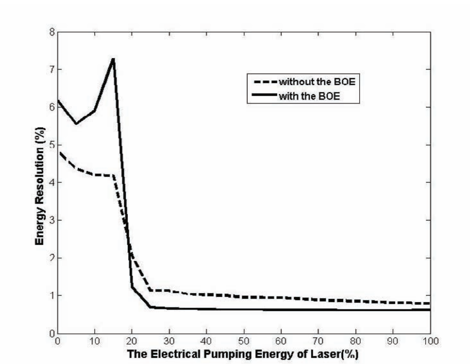
Fig. 3. The results of the scintillator simulation

III. Conclusion

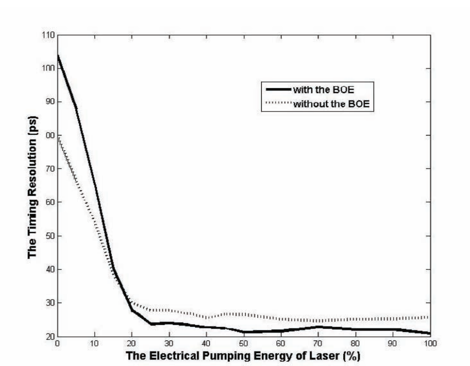
From the results and analysis above, we can know that the laser pulse can be transformed into the uniform distribution spatially with the application of the BOE, and the incident photons reach the sensitive area evenly. It can increase the



(a) The output signals of the SiPM under different laser intensity



(b) The energy resolutions under different laser intensity



(c) The timing resolutions under different laser intensity

Fig. 4. The results of the Laser experiment

photons count rate obviously, and improve the performance of the SiPM detection, such as the timing resolution and energy resolution, when the input light intensity is suitable.

To improve the performance of SiPM detectors further, we can choose a high light output scintillator like LaBr3:Ce (~60000 photons/MeV) and apply the ground surface treatment to make the incident photons evenly distributed. Also, for low light output scintillators, the discovery of a new material as an optical film to the surface of the scintillator, which can make all distribution uniform spatially and has almost no attenuation effect to incident photons, can achieve the same performance. In either case, the energy resolution and timing resolution can be improved effectively.

Considering the difference between the laser output and the scintillation pulse, in our future work, we will design and make a BOE for scintillators and apply the BOE to SiPM/PET detectors, and use a new type of scintillator processed by the ground surface treatment, and then evaluate the effect on the timing resolution and energy resolution in PET imaging.

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References

[1] R. Pestotnik, R. Dolenec, S. Korpar, P. Krizan, and A. Petelin, *Silicon photomultiplier as a position sensitive detector of cherenkov photons*, Nuclear Instruments and Methods in Physics Research Section A:Accelerators, Spectrometers, Detectors and Associated Equipment. vol.581, pp. 457-460, Oct 2007.

[2] Popova. E, *Silicon photomultiplier: application for high-granularity scintillator calorimeters*, Nuclear Science Symposium Conference Record, 2004, IEEE. vol.1, pp. 102-106, Oct 2004.

[3] David P. McElroy, Valeri Saveliev, Alla Reznik, and John A. Rowlands, *Evaluation of silicon photomultipliers*: *A promising new detector for mr compatible pet*, Nuclear Instruments and Methods in Physics Research Section A: Accelerators, Spectrometers, Detectors and Associated Equipment. vol. 571, pp. 106-109, Feb 2007.

[4] Guofan Jin, Qiaofeng Tan, *Binary optics*, Technology and Information in Optoelectronics. vol.14, no.5, pp.1-10, 2001.

[5] Wenjie Nong, Ning Jin, *Technic parameter calculation in binary optics*,Infrared Technology. vol.24, no.6, pp.13-16, 2004.

[6] Zhongwei Fan, *Binary optical elements in optical systems*,Optical Precise Engineering. vol.3, no.2, pp.1-10, 1995.

[7] Manping Xu, Jie Zhou, *Application of MATLAB in the design of binary optical elements*,Journal of Anhui Normal University (Natural science edition). vol.28. no.1, pp.35-37, 2005.