Inverted-conical light guide for crosstalk reduction in tightly-packed scintillator matrix and MAPMT assembly

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ABSTRACT

In this paper we present the Inverted-Conical light guide designed for optical crosstalk reduction in the scintillator-MAPMT assemblies. The research was motivated by the 30% crosstalk observed in UFFO X-ray telescope, UBAT, during the preliminary calibration with MAPMTs of 64 2 × 88 mm2 pixels and identically gridded YSO crystal matrices. We began the study with the energy and crosstalk calibrations of the detector, then we constructed a GEANT4 simulation with the customized metallic film model as the MAPMT photocathode. The simulation reproduced more than 70% of the crosstalk and explained it as a consequence of the total reflection produced by the photocathode. The result indicated that the crosstalk mechanism could be a common case in most of the contact-assembled scintillation detectors. The concept of the Inverted-Conical light guide was to suppress the total reflection by contracting the incident angle of the scintillation. We optimized the design in the simulation and fabricated a test sample. The test sample reduced 52% crosstalk with a loss of 6% signal yield. The idea of the Inverted-Conical light guide can be adapted by scintillation detectors multi-pixel, imaging-purpose scintillation detectors such as the ultra-fast GRB observatory UFFO-UBAT, whose performances are sensitive to responding time, image resolution, and geometrical modifications.

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1. Introduction

1.1. UFFO project

Ultra-Fast Flash Observatory (UFFO) is a space-borne observatory aiming to detect the early emission of the Gamma-ray bursts (GRBs) [2]. It will be installed on-board Moscow State University satellite Lomonosov schedule for launch in 2015. With its ultra-fast slewing
capability, UFFO can start its follow-up UV–optical observation 1–2 s after the X-ray prompt triggers. Even in other fast GRB observatories, e.g. Swift, GRB UV–optical (afterglow) data is mostly taken 50–100 s after the prompt triggers. UFFO is hopefully the first space observatory delivering the sub-minute afterglow data [1,2].

Many exciting physics topics are waiting to be discussed for the first time with the sub-minute afterglow. Some are seen with salient hints and are urgently needing the confirmation with even earlier light curves, e.g. Panaitescu et al. [3] suggests that Supernovae (SNe) may serve as the new “recalibratable standard candles” based on the early afterglow obtained by the Swift; Page et al. [4] points out, according to a few peculiarly bright events like GRB 080810 observed with the prompt-emission-like structure in the rather early afterglow light curves, the internal–external shock unification model may be tested with the data of the earlier mixing phase of the prompt emission and the afterglow, which in principle exists in all early light curves. Others are simply hypothetical but lack supporting data, e.g. the (non-)existence of the short-hard burst (SHB) afterglows, which quickly decay into dimness before any former experiment starts its optical observation, the progenitor modeling of the SHBs, the (non-)existence, origination or even classification of the dark bursts. And most of all, completion to the long anticipated “blind time” data lays between the end of the prompt emission and the start of the former optical-UV observations [2,5–7].

1.2. Design of UFFO-p and UBAT

Ultra-Fast Flash Observatory, as it is named, is built to be the fastest ever UV-optical observatory that triggers on the transient X-ray sources, and UFFO pathfinder (UFFO-p) is the first attempt in UFFO. It is composed of two major telescopes: UFFO Burst Alert and Trigger Telescope (UBAT) and Slewing Mirror Telescope (SMT). They coordinate the full operation of UFFO-p. Fig. 2 is the schematics of UFFO-p.

UBAT is equipped with a wide field of view (FOV) and serves as the primary trigger telescope responsible for 10–150 keV prompt X-ray observation. UBAT operates under the coded mask aperture camera scheme similar to Swift-BAT (Fig. 1) [9,10]. Once a GRB occurs in UBAT FOV, the coded mask pattern is projected on to the focal surface (FS) of UBAT. Through recognizing the location of the mask’s projection, the event directions may be discerned. Note that as the incident angle rises, the legible fraction of the mask’s projection decreases [11]. (For interpretation of the references to color in this figure caption, the reader is referred to the web version of this article.)
an instant. The innovation improves the 100 s limitation of Swift to 1 s [2,8,9]. Fig. 3 illustrates the concept of SMT.

In order to increase the success rate of the narrow-FOV aiming of UV–optical observation in SMT, it is crucial UBAT determines the precise GRB locations from the X-ray coded mask image fast and accurate. To that end, UBAT must obtain a clearly resolved coded mask image, i.e. clearly discriminates the γ-hit/non-hit signals on FS.

This paper is organized as follows: we first present the calibration of UBAT focal surface (FS) in Section 2, where the signal yield and the situation of the high signal crosstalk among pixels is reported. This work was motivated by the ~30% crosstalk signal height found in the pixels surrounding the X-ray-photon-illuminated pixel. The purpose of this study was to search for possible solutions to reduce the crosstalk-to-signal ratio for better mask pattern recognition with possible enhancement to the absolute signal yield. To resolve the causes of the crosstalk, we built the simulation of UBAT FS, which is discussed in Section 3. Once we understood the mechanism of the crosstalk, we were able to propose the Inverted-Conical light guide. In Section 4, we introduce the concept and optimization of Inverted-Conical light guide. It was specialized to cope with the reflection-caused crosstalk, which could be a common problem in touching-assembled scintillation detectors. We then fabricated the test sample to put the idea to a further validation. The result is reported in Section 5. Inverted-Conical light guide was proven to reduce the crosstalk and potentially enhance the signal yield. The conclusion is provided in Section 6.

1.3. UBAT focal surface components

In this paper we utilized the FS detection units1 of UBAT as our X-ray scintillation detector. UBAT FS is composed of 36 assemblies of Yttrium Oxythosilicate (YSO) scintillator arrays and the multi-anode photomultiplier tubes (MAPMTs) (Fig. 4). The detection units connect to the electronics underneath in a 6 × 6 matrix. The total sensitive area is 13.82 × 13.82 cm², i.e. 191.1 cm².

The scintillator array is an 8 × 8 integration of 64 2.68 × 2.68 × 3 mm³ Cesium-doped YSO (Y₂SiO₅·0.2% Ce) crystal cubes. To enhance the collectivity of the scintillation photons and improve the imaging quality, 200 μm dielectric mirror reflector films are attached between the crystal cubes. A 70 μm reflector covers the entire non-MAPMT-coupling surface. The scintillator is designed to match the pixel geometry of the MAPMT, and each YSO crystal cube aligns its corresponding MAPMT pixel at the center while coupled. Table 1 lists the characteristics of the YSO crystal.2 UBAT utilizes Hamamatsu R11265-03-M64 MAPMT which is specialized for the imaging purposes in space scientific missions.

![Fig. 3. An illustration to the concept of SMT. The UV/optical signals are redirected into the stationary telescope by the slewing mirror [8].](image)

The UFFO collaboration has demonstrated that UFFO-p, including the delicate MAPMTs and other optical components, can survive the launch and the space environment with a series of space-mimic tests [2]. Table 2 lists the parameters of UBAT MAPMT. It has two special features: First, UBAT MAPMT does not implement any insensitive gaps between the photocathode pixels. This modification from its predecessor not only enlarges the packing factor of the sensitive region by about 30%, but also enhances the evenness of detection efficiency and imaging quality on the surface. Second, UBAT MAPMT equips the newly developed photocathode compound. The Quantum Efficiency (QE) of the old material was ~25% at the YSO scintillation peak, and it is ~35% of the new compound.

1.4. Review on light guide design

Fig. 5 is an example of a traditional design of light guides (LGs). It intuitively matches the sizes of the scintillator and the photon detector at two ends and serves as a funnel that collects photons through internal reflection. By recovering the photons that would have been lost, the size-coupling design may enhance the signal significantly. But the design generally suffers from a signal drawback as the length grows [24]. However, it is usually impractical to implement too short a size-coupling LG, e.g. shallower than the crystal size, when the optical-caused crosstalk is to be concerned. A shorter LG implies a sharper-sloped funnel shape, which redirects the scintillation light with larger incident angles and a wider area of illumination. An example of the possible solution is also presented in Fig. 5. By absorbing the redirected light at large angle, the signal uniformity can be regained to some level. But the signal yield is again compromised [25].

Another example of image modulator is the micro-lens array (MLA) (Fig. 6) [26–28]. It is basically an array of identical lenses. Through advanced engineering, the lenses can be made 10–100 μm in sizes with customized concave or convex curves. There are several advantages of MLA. First, it may possess the identical optical functionality of the one-piece lens, e.g. focusing or diverting the light, but be much thinner in thickness. Second, if the photon detector used is multi-pixel, the arrangement of lens array may be customized to be one-pixel-to-one(several)-lens. The major problem of MLA is it is obviously delicate and cost-unfriendly. Considering the drawback, MLA seems impractical for space missions such as UFFO.

2. Focal surface calibration

2.1. Method

All the experiments performed in this paper were conducted in the laboratory environment under normal atmospheric pressure,

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1 We will frequently address one scintillator matrix-MAPMT assembly as a detection unit.

2 Items without the references mentioned are provided by the manufacture.
C. Every contact interface between the optical components, e.g. MAPMT, scintillator and light guide, was coupled by Dow/C0 Corning Q2-3067 optical couplant. A 25/25/180 cm³ light-tight aluminum cabinet was prepared for the experiments. The interior and the fixtures inside were covered by the black flannel blanket to eliminate reflections. The calibration sources, e.g. LED and radioactive sources, were situated 80–160 cm away from the detection unit. Regarding the calibration sources point-like, the divergent angles of the illuminations were ±0.4°–±0.7° on the frontal surface of the detection unit.

We used the data acquisition (DAQ) system developed by NuTel experiment as the MAPMT DAQ [14–17]. The DAQ system was capable of simultaneously taking data from 512 MAPMT channels in the range of 0–1000 photocathode-emitted photoelectrons (PEs) up to 1500 Hz. We calibrated the signal gain of each channel separately and designated 0.33 PE to be the trigger threshold. We applied a collimator on the detection unit, so the calibrating X-ray photons could only illuminate one of the central pixels (Figs. 7 and 8). The collimator was a Lead plate 3 mm in thickness with a ϕ1.0 mm pin hole at the center of Ch. 27. The triggers from all the non-collimated channels were disabled, so the signals in 64 channels were only recorded when the collimated channel observed significant signals. Table 3 lists the radioactive calibration sources used in this paper. Am²⁴¹ decays and emitted photons spontaneously, the others were stimulated and emitted X-ray by Am²⁴¹ radioactivity. We placed the sources along the collimation line about 1 m apart from the scintillator. The distance were adjusted to obtain the trigger rates at ~100 Hz [18,19].

Table 1
The specification of UBAT YSO crystal.

<p>| | |</p>
<table>
<thead>
<tr>
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<tbody>
<tr>
<td>Density (g/mm³)</td>
<td>4.45</td>
</tr>
<tr>
<td>Peak scintillation (nm)</td>
<td>400</td>
</tr>
<tr>
<td>Index of refraction (at 400 nm)</td>
<td>1.8</td>
</tr>
<tr>
<td>Scintillation time constants (ns)</td>
<td>35 [12]</td>
</tr>
<tr>
<td>Photon yield (γ/keV)</td>
<td>9.2 [13]</td>
</tr>
</tbody>
</table>

Fig. 4. The photos of the complete construction of UBAT FS and the electronic box (top), the MAPMT and the detection unit (middle), and the front and the back side of the YSO scintillator array (bottom). The dimensions may be inferred from the reference shown in the photos.

23 °C. Every contact interface between the optical components, e.g. MAPMT, scintillator and light guide, was coupled by Dow – Corning® Q2-3067 optical couplant. A 25 × 25 × 180 cm² light-tight aluminum cabinet was prepared for the experiments. The interior and the fixtures inside were covered by the black flannel blanket to eliminate reflections. The calibration sources, e.g. LED and radioactive sources, were situated 80–160 cm away from the detection unit. Regarding the calibration sources point-like, the divergent angles of the illuminations were ±0.4°–±0.7° on the frontal surface of the detection unit.

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2.2. Result

Figs. 9 and 11 present the energy spectra observed in the collimated channel. When the spontaneous radioactivity of YSO crystal (mainly Yttrium) was observed, the 2 keV scintillation PE yield appeared to be linear. However, since the PE yield was only 1.4 PE, the detection unit could hardly distinguish the spectral detail shown in the reference. When the radioactive sources were applied, the fitted PE yield was linear and was in consistent with which given by the YSO self-scintillation, 0.72 PE/keV. But in addition to the scintillation peaks, a source-induced pedestal was observed covering below 18 keV, and the peaks were all elevated by 7.9 keV (5.7 PE).
In parallel with the calibration of the energy scale, by comparing the signals observed in different channels under the collimated trigger scheme, the signal crosstalk was also quantified. We defined the crosstalk ratio $\text{(CR)}$:

$$\text{CR} = \frac{\text{Pulse height in the channel of discussion}}{\text{Pulse height in the collimated trigger channel}}$$

(1)

Averagely $38.27 \pm 3.25$, $11.22 \pm 0.99$ and $3.13 \pm 0.26$ PEs were observed in the collimated, alongside and diagonal channels, respectively (Fig. 12). So the CRs were

$$\text{CR}_{\text{alongside}} = \frac{11.22 \pm 0.99}{38.27 \pm 3.25} = 0.29 \pm 0.04$$

(2)

### Table 3

<table>
<thead>
<tr>
<th>X-ray source</th>
<th>$K_\alpha$ (KeV)</th>
<th>$K_\beta$ (KeV)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Am$^{241}$</td>
<td>59.5$^a$</td>
<td></td>
</tr>
<tr>
<td>Tb</td>
<td>44.23</td>
<td>50.65</td>
</tr>
<tr>
<td>Ba</td>
<td>32.06</td>
<td>36.55</td>
</tr>
<tr>
<td>Ag</td>
<td>22.10</td>
<td>24.99</td>
</tr>
</tbody>
</table>

*Note that there is only one energy listed for Am$^{241}$ because we utilized its spontaneous nuclear $\gamma$-decay emission, while others were used with their simulated X-ray emissions.*
It was obvious that a significant fraction of the scintillation budget was shared by the non-illuminated channels. If the crosstalk in the remotest channels was omitted, one could conclude that the leakage of the scintillation was about 60%, e.g.

\[
\text{crosstalk} + \text{trigger} = \frac{(0.08 + 0.29) \times 4 \text{ ch.}}{1.0 + (0.08 + 0.29) \times 4 \text{ ch.}} = 0.60 \pm 0.09
\]

(4)

The result indicated that crosstalk led to not only a serious drawback of the detection efficiency, but even crucial, a smearing of the coded mask image. Fig. 10 shows a comparison of the simulated coded mask image considering the crosstalk to the perfectly distinguished one. It was immediately understood it would be unrealistic for UBAT to discriminate the X-ray-illuminated and non-illuminated channels of a factor-15 dynamic range, e.g. 10–150 keV, under a simple rate trigger scheme.

3. Simulation

To further resolve the crosstalk issue and search for the possible solutions, we have constructed the simulation package...
of the UBAT FS with GEANT4 [20]. All the components noted in Fig. 7 were constructed in the simulation. Fig. 14 is an example of the screen shot of the simulation. We were able to reproduce the crosstalk in the simulation and interpreted the back-scattering occurred at the photocathode as the key source contributed to at least 70% of the crosstalk. Because the inner space of MAPMT behind the glass window was a vacuum, when the photons traveled from the glass window to the inner space, i.e. penetrating the photocathode, total reflection frequently occurred. And the photons being totally reflected were likely to be observed in the nearby channels as the crosstalk (Fig. 13).

In order to model the response of the photocathode accurately, we had to consider a better model independent from any of the optical surfaces prepared in the GEANT4 library. It was proven in published studies that the photocathode could be modeled nicely by a thin metallic film. The thickness of the film was comparable with the incident wavelength, and its EM wave response was governed by classical electrodynamics. The real and imaginary parts of the refractive index of the photocathode material could be subsequently fitted from the experimental data [21–23]. We explicitly constructed the metallic film model in GEANT4 to simulate the photocathode. Only when the metallic film model was implemented could we simulate the trigger PE yield and the amount of the crosstalk accurately, and stabilized CR within 1%. On the contrary, if the dielectric–metal model prepared by GEANT4 was used, the simulation revealed a trivially small amount of crosstalk.

4. Inverted-conical light guide

4.1. Concept

Considering the 29% CR reported in the previous section, if a simple rate trigger scheme is utilized and the 15 keV lower bound of energy is to be maintained, UBAT will only be able to discriminate the coded mask pattern of events up to 15/0.29/52 keV, which is only 1/3 of the designed energy upper bound. Also learned from the calibration, the expectable signal yield, so as the resolution, are halved by the crosstalk. To cope with the crosstalk issue, we propose the concept of Inverted-Conical LG (IC-LG).

The IC-LG utilizes the orientation inverse to the traditional LG, i.e. with its wide eyelet of the conical channel facing the scintillator. From the simulation, we learned that the crosstalk was mainly caused by the total reflections occurred at the photocathode. To suppress the total reflection, IC-LG is designed to contract the large-angle incidents to be small-angle. It can be seen from Fig. 15, through the internal reflection on the inverted conical channel, IC-LG is capable to redirect all the scintillations to have smaller incident angles. So not just the crosstalk is reduced, we also expect a good fraction of the crosstalk photons are recovered to be the signal.

A simulation comparison of the situations without LG, with an IC-LG and with a NIC-LG is shown in Fig. 13. It is clear the emission from IC-LG exhibits smaller open angle and the illumination area on the photocathode plane. The reflections travel into the neighboring crystals are also less. Another advantage shown in Fig. 15 is that IC-LG can be made much thinner than the scintillation array or the

3 The traditional orientation is addressed as non-inverted conical (NIC) in the following content.
Index (CI) was also used as an indicator to the optimization:

\[ CI = \frac{\sum_{\text{ch. separation}} \times \text{local signal yield}}{\sum_{\text{ch. separation}} \times \text{collimated ch. signal yield}} \]  

Eq. (5) summed over all the channels in the same row and the column of the collimated channel, e.g. ch. 27 was the collimated channel, the equation summed up ch. 4, 11, 20, 36, 43, 52 and ch. 24, 25, 26, 28, 30, 31. The corresponding channel separations were 1 for ch. 20, 26, 28; 2 for ch. 11, 25, 29, 43; 3 for ch. 4, 24, 30, 52; 4 for ch. 59. CI was regarded as the weighted indicator to the overall condition of the crosstalk among the FS.

Fig. 17 presents the optimization of the crosstalk to \( \theta \). When \( \theta < 0 \), CR was enlarged compared to which when \( \theta > 0 \). The result coincided with the expectation IC-LG could reduce the crosstalk while NIC-LG might enlarge it. CR and CI posed similar trends and minimums appeared at \( \theta = 13.50^\circ \) and \( \theta = 15.67^\circ \), respectively. The result could be interpreted as the steeper angle suppressed more crosstalk, when the crosstalk in the further channels was taken into consideration, a larger angle was favored. Nevertheless, the \( \sim 2^\circ \) difference was actually trivial for the minimal regions were about 4 across.

Fig. 18 presents the optimization of the signal yield. The IC-LG enhanced the signal yield by at most 25% when \( T < 12 \, \text{mm} \). The signal yield decreased by \( \sim 3\% \) for every 0.1 mm increase in \( T \). It was also demonstrated in the simulation NIC-LG suppressed the signal yield and the suppression was severer with steeper NIC angle. The optimal angle of 108.9% signal yield appeared at 9.67\( \, \text{mm} \). The result indicated IC-LG had the capability of focusing the photons and enhancing the signal yield identical to MLA.

Because the primary motivation of the LG study was the crosstalk reduction, \((\theta, T) = (13^\circ, 0.6 \, \text{mm})\) was regarded as the optical solution, for it gave the least CR while also enhanced the signal yield. According to the simulation, the optimized IC-LG would enhance the signal yield by 7.2% and reduce CR to 15.8%, i.e. 45% CR reduction from the calibrated CR of the detection unit.

5. Sample test

5.1. Fabrication

Fig. 19 presents the photos and the schematics of the sample IC-LG. The sample was made of 6061 Aluminum alloy through CNC machining with < 1 \( \mu\text{m} \) position tolerance then polished through chemical anodic brightening. The fabrication was cost-friendly yet the end product had geometric accuracy \( \sim 0.5 \, \mu\text{m} \) and the surface roughness < 100 nm. The perimetal frame was designed to support the delicate grid-like LG. The end product was as mechanically endurable as the scintillator array and the MAPMT.

5.2. Result

The signal comparison of LG-free, IC-LG and NIC-LG cases is presented in Fig. 20. Before applying the LG, CR was 0.293 \( \pm \) 0.024. The sample IC-LG reduced 38.86 \( \pm \) 3.22% crosstalk but acquired 6.376 \( \pm \) 0.053% PE yield reduction. The resulting CR with IC-LG was...
0.195 ± 0.016. As a comparison, the sample was also inserted under the NIC orientation, i.e. 180° flipped. The NIC orientation gave CR 0.244 ± 0.020 and 11.47 ± 0.95% PE yield cutback. To understand Fig. 20, the LG-free detection unit observed the largest signal, IC-LG second, and NIC-LG the last in both the collimated and the alongside channels. However, IC-LG exhibited the collimated signal peak close to the LG-free condition but the alongside signal peak close to the NIC-LG condition. The net consequence was an amelioration of reducing CR from 0.29 to 0.20.

Before the amelioration, the alongside and the diagonal CRs were 29% and 8%. With the aid of IC-LG, CRs became 20% and < 2% in the alongside and diagonal channels, respectively. The simulated coded mask images are shown in Fig. 22. We also repeated the energy calibration with IC-LG, all the procedure was identical to Section 2. The result is shown in Fig. 21. With IC-LG, UBAT FS detection unit had linear signal yield 0.69 PE/keV.

6. Conclusion

UFFO is designed to be the first GRB observatory capable of responding to the UV–visible signals of GRBs within 1 min; UBAT is the primary prompt emission trigger telescope in UFFO–p responsible for delivering the event directions. To achieve the rapid direction determination, UBAT is designed to operate under the coded mask aperture camera scheme. So it is crucial that the focal surface detection units must confidentially discriminate the coded mask pattern.

In this paper, we demonstrated the energy and the image crosstalk calibrations of the UBAT focal surface detection unit. The signal yield was 0.72 PE/keV. A serious crosstalk issue of ~29% relative signal height was identified in the pixels closing the X-ray illuminated one. A simulation of the detection unit was then constructed to resolve the issue. Through the simulation study, we pointed out more the 70% of the crosstalk was caused by the total reflections occurred at the photocathode. After identifying the source of the crosstalk, we proposed the Inverted-Conical light guide which utilized the inverted orientation of the traditional focusing LG as a possible solution. The Inverted-Conical light guide was optimized in the simulation and fabricated. The end product reduced the crosstalk and the signal yield by 39% and 6%, which resulted in the reduction of CR from 29% to 20%.

The metallic Inverted-Conical light guide was made much thinner than the components of the detection unit. Unlike many other light guides, it preserves the original geometry of the scintillation detector. As shown in the simulation, the Inverted-
Conical light guide also has the advantage over other light guides that it reduces the crosstalk and enhances the signal yield at the same time. Since the sample light guide utilized consecutive structure of the conical channels, one might think of the MLA as a similar comparison [26–28]. Indeed MLA has been demonstrated to have the ability of focusing the light and enhancing the image quality, and it has been widely applied to delicate optical products. However, MLA is obviously too fragile for space missions like UFFO, and it is much more expensive and less customizable. IC-LG preserves the advantages of MLA but also largely improves its disadvantage of fragileness.

UFFO-pathfinder is scheduled to launch in 2015. Since the flight model of UFFO-p was completed and has been integrated to the...
platform of Lomonosov, Inverted-conical light guide was not implemented in UBAT. However, we are still looking forward to the future utilization of Inverted-Conical light guide to future UFFO-100.

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