Development of $Cs_3Cu_2I_5$:Tl Optical-Guiding Crystal Scintillators and Geant4-Based Analysis of Micron-Scale Core Miniaturization

Y. Nakata[1,2], K. Kamada[2,3,4], M. Yoshino[2], T. Kudo[4], Y. Yokota[2], R. Murakami[2], S. Ishizawa[2], A. Yoshikawa[2,3,4]

[1]*Tohoku University, Graduation School of Engineering, Sendai, Miyagi, Japan*
[2]*Tohoku University, Institute for Materials Research, Sendai, Miyagi, Japan*
[3]*Tohoku University, New Industry Creation Hatchery Center, Sendai, Miyag, Japan*
[4]*C&A corporation, Sendai, Miyagi, Japan*
Corresponding Author Email: nakata.yuhei.q4@dc.tohoku.ac.jp

High-resolution X-ray imaging demands detectors that balance spatial resolution with sensitivity, enabling low-dose, rapid acquisition. Conventional scintillators face inherent limitations: increasing thickness to boost X-ray absorption inevitably degrades spatial resolution through lateral light diffusion. We have developed Optical-guiding Crystal Scintillators (OCS) to overcome this limitation—a novel architecture comprising high-refractive-index scintillator cores in a low-refractive-index glass matrix [1]. This architecture exploits total internal reflection to suppress light spread, maintaining high resolution even at large thicknesses. While theory predicts improved optical confinement through miniaturization, realistic interface properties and radiation transport effects may impose fundamental performance limits. We fabricated OCS with Tl-doped $Cs_3Cu_2I_5$ cores of 1 μm and 4 μm diameter and investigated miniaturization effects through experimental and computational approaches.

OCS samples were grown via the Bridgman-Stockbarger method, enabling simultaneous melt-filling and single-crystal growth of $Cs_3Cu_2I_5$:Tl melt within fine glass capillaries. Spatial resolution was quantified through Contrast Transfer Function (CTF) analysis using microfocus X-ray imaging. A Monte Carlo simulation based on the Geant4 toolkit [2] was developed to model X-ray interaction, electron transport, and scintillation light propagation. Interface scattering was modeled using the Unified Model with parameters including surface roughness.

The fabricated OCS demonstrated superior resolution at thicknesses where commercial columnar CsI exhibited severe degradation. However, CTF improvement through miniaturization from 4 μm to 1 μm was not observed. Simulations (Figure 1) revealed that 1 μm cores exhibit a substantially increased number of photon reflections, making them more susceptible to interface scattering. Even minimal roughness degraded spatial resolution by approximately a factor of 12 relative to ideal interfaces. These findings demonstrate that miniaturization does not inherently guarantee performance improvement, revealing fundamental trade-offs between core size and physical scattering. We present fabrication methods, imaging results, and discuss implications for future OCS design.

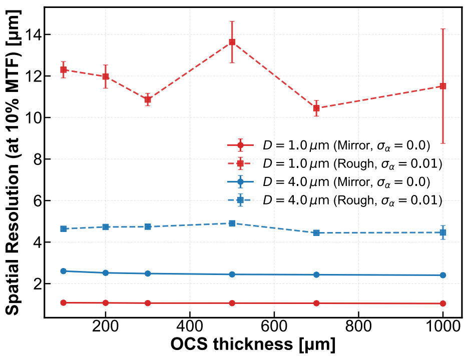

Fig 1. *Simulated spatial resolution (at 10% MTF) vs. OCS thickness for different core diameters: ideal (solid) and slightly rough (dashed) interfaces.*

1. R. Yajima, A. Yoshikawa, *et al.*, "Prototype fabrication of optical-guiding Tl:CsI crystal scintillators and investigation of the crystallization process", *Jpn. J. Appl. Phys.*, **62**, SC1064 (2023).
2. S. Agostinelli, *et al.*, "Geant4—a simulation toolkit", *Nucl. Instrum. Methods Phys. Res. A*, **506**, 250 (2003).