Diffraction-limited resolution scintillator detector

Takashi Kameshima and Takaki Hatsui
SACLA
E-mail: kameshima@spring8.or.jp

Diffraction-limited resolution scintillator detector

LuAG:Ce transparent ceramic scintillator

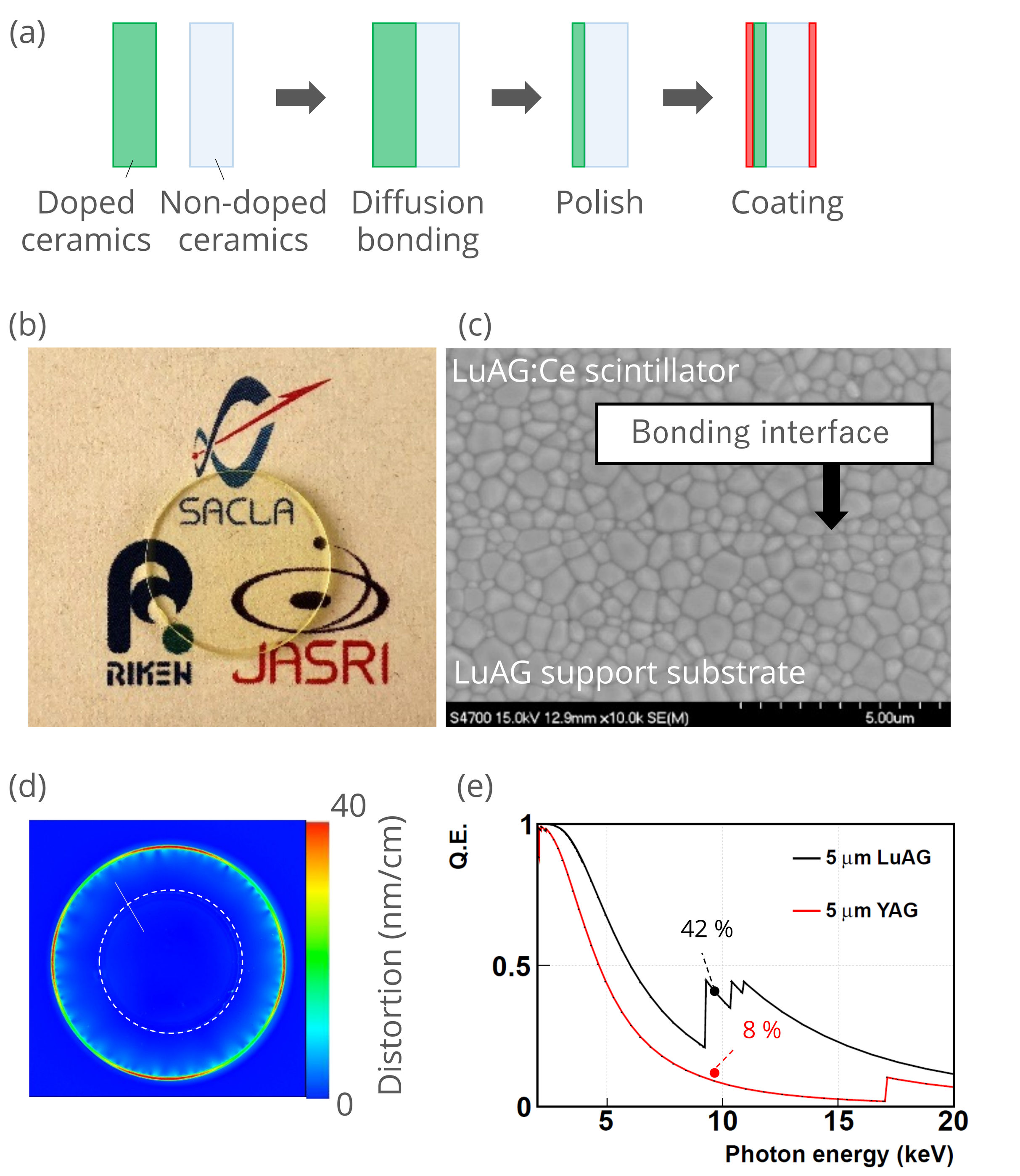


Fig. 1 (a) Fabrication process of thin-film transparent ceramic scintillators
(b) 5 μm-thick LuAG:Ce scintillator formed on the 1mm-thick non-doped LuAG
(c) SEM image of LuAG:Ce/LuAG composite at region of the bonding interface
(d) Distortion map of 5-μm-thick LuAG:Ce scintillator
(e) Quantum efficiencies of LuAG and YAG

Tab. 1 Comparison between LuAG:Ce and YAG:Ce

	LuAG:Ce	YAG:Ce
Quantum efficiency for 10 keV	**42 %**	8 %
X-ray attenuation in 1-mm-thick LuAG for 10 keV	**$\sim 10^{-40}$**	$\sim 10^{-7}$
Light yield (photons/MeV)	16,000	20,000

X-ray imaging unit specifications

Unit type	Standard unit	Off-axis unit
Scintillator	LuAG:Ce/LuAG transparent ceramic composite with dielectric multilayer coatings YAG:Ce/YAG transparent ceramic composite with dielectric multilayer coatings	
Scintillator size	Φ10, 5 μm-thick Φ10, 15 μm-thick	
Support substrate size	Φ12.5, 1 mm-thick	
Emission wavelength	450 ~ 700 nm (520 nm peak)	
decay time	~ 40 ns	
Image circle	Φ21.4	
Camera mount	C-mount	
Objective	2x, 5x, 10x, 20x, 20xHR, 50x, 100x	2x, 5x, 10x, 20x
X-ray quantum efficiency	5 μm-thick LuAG:Ce scintillator 36 % for 10 keV 11 % for 20 keV 4 % for 30 keV	15 μm-thick LuAG:Ce scintillator 74 % for 10 keV 30 % for 20 keV 12 % for 30 keV
Optics protection from X-ray	Attenuation in the support substrate 10^{-40} for 10 keV, 10^{-11} for 20 keV, 10^{-4} for 30 keV	Optical system to evacuate all lenses from X-ray optical axis

Standard unit optical configuration

Magnification	100x	50x	20xHR	20x	10x	5x	2x
NA	0.85	0.7	0.7	0.45	0.3	0.15	0.06
FOV	Φ0.214	Φ0.428	Φ1.07	Φ1.07	Φ2.14	Φ4.28	Φ10.7
Conversion*1	15 photons	10 photons	10 photons	4 photons	1.7 photons	0.4 photons	0.07 photons
Scintillator	5 μm	5 μm	5 μm	5 μm	15 μm	15 μm	15 μm

Off-axis unit optical configuration

Magnification	20x	10x	5x	2x
NA	0.45	0.3	0.14	0.055
FOV	Φ1.07	Φ2.14	Φ4.28	Φ10.7
Conversion*1	4 photons	1.7 photons	0.4 photons	0.07 photons
Scintillator	5 μm	15 μm	15 μm	15 μm

*1 Typical conversion & transfer efficiency for single X-ray photon with 10 keV. X-ray quantum efficiency in the scintillator and quantum efficiency of the image sensor are not included.

To achieve diffraction-limited resolution, we have developed a thin-film transparent scintillator fabricated by solid-state diffusion bonding of ceramics. The scintillator film directly bonded on the support substrate has quasi-homogenious refractive index and low distortion. The mm-thick support substrate formed by non-doped LuAG layer strongly attenuates X-ray intensity down to $\sim 10^{-40}$ at 10 keV and suppresses lens browning in the imaging unit. These features enable quasi-diffraction-limited spatial resolution and non-damage imaging optics operation. Two variants of X-ray imaging units equipped with the developed thin-film scintillators are deployed. A standard unit provides full-range magnification configuration (100x ~ 2x). The maximum NA configuration of 0.85 can achieve a resolving power of 200 nm L&S visualization. Off-axis unit is designed for high energy X-ray measurement (>30 keV) by keeping objective lens off an X-ray optical axis and for detection plane insertion to narrow space (depth size of 27 mm) . The magnifications of 2x ~ 20x are available.

Detector performance

T. Kameshima et al., Optics Letters 44, 1403 (2019)

Test chart imaging

200 nm process VLSI imaging

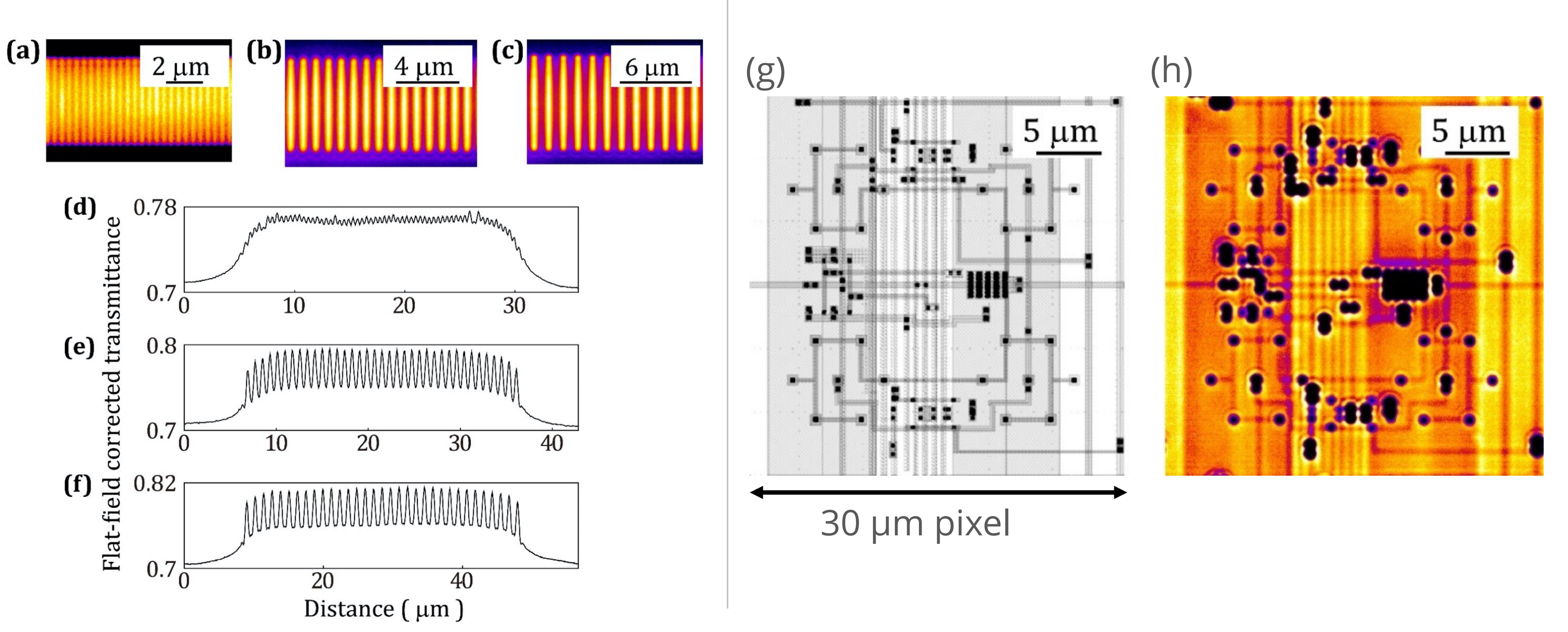
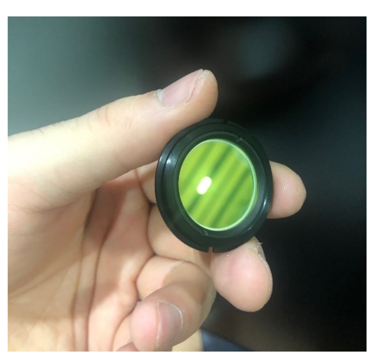


Fig. 3 (a-c) Transmitted X-ray images of 200/400/600 nm lines and spaces in the tungsten test chart
(d-f) Line profiles of (a-c)
(g) VLSI circuit design drawing
(h) Transmitted X-ray images of VLSI circuit in the area of (g)

200 nm L&S structure was successfully visualized in the configuration of a 5 μm-thick LuAG:Ce scintillator and NA0.85 objective lens. Al wiring lines with 300 nm width & 600 nm-thickness in the inner layer of VLSI circuit were successfully detected and visualized.

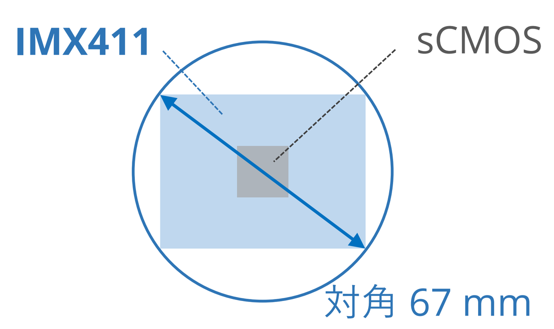
Development of large-format X-ray imaging detector

50 μm-thick, Φ22 LuAG:Ce



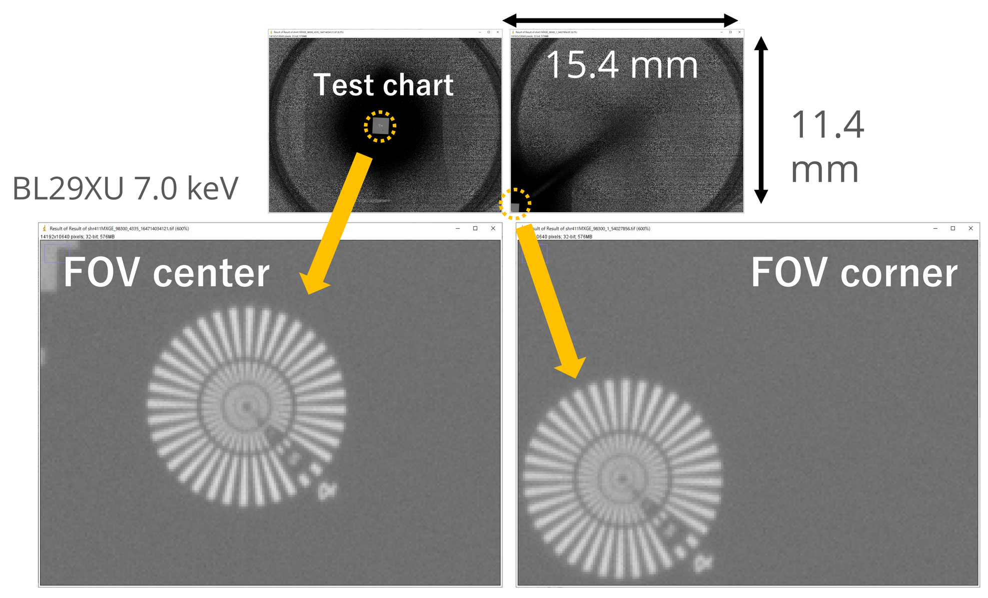
SONY IMX411sensor

https://www.sony-semicon.co.jp/e/products/IS/camera/product.html



- 14,192 x 10,640, 3.76 μm pixels
- 53.3 x 40 mm² chip
- Back illumination
- 16 bit depth

X-ray imaging result



We are planning to develop a large-format X-ray imaging detector to enhance a field of view, implementing the SONY IMX411 image sensor. The prototype imaging unit has successfully visualized 1.2 μm L&S pattern in the center and the corner of FOV with 15.4 x 11.4 mm².

Summary

Quasi-diffraction-limited spatial resolution is achieved by the transparent thin-film LuAG:Ce scintillator development. The 200 nm line-and-space structure was successfully visualized. The indirect imaging detectors equipped with this scintillators are deployed to SACLA experiments and high resolution beam monitors. Various optical configuration are selectable for the resolution range of 0.2 ~ 2.6 μm L&S. For the upgrade plans, the field of view is ~ 20 times enhanced by implementing the large format image sensor. The prototype imaging unit show the performance to resolve 1.2 μm L&S patterns in the center and the corner of FOV with 15.4 x 11.4 mm².