High-spatial-resolution X-ray imaging detector equipped with photodiffusion-free transparent scintillator DIFRAS

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DIFRAS detector

photo**DI**ffusion-**F**ree t**RA**nsparent **S**cintillator (**DIFRAS**)

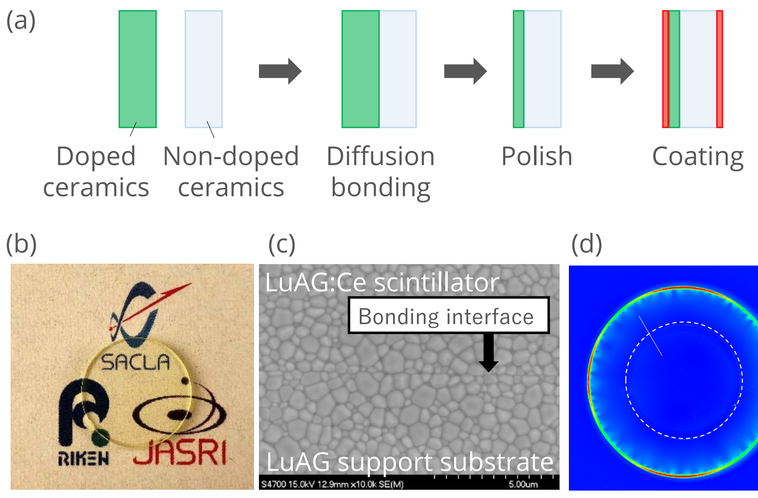


Fig. 1 (a) Fabrication process of thin-film transparent ceramic scintillators
(b) 5 μm-thick LuAG:Ce scintillator formed on the 1mm-thick non-doped LuAG
(c) SEM image of LuAG:Ce/zLuAG composite at region of the bonding interface
(d) Distortion map of 5-μm-thick LuAG:Ce scintillator

- Identical host
- Fully-densified polycrystalline structure
- sub-nm grain boundary

▶ Quasi-homogenious refractive index & low distortion enables photodiffusion-free image transfer

Optical design of DIFRAS detector

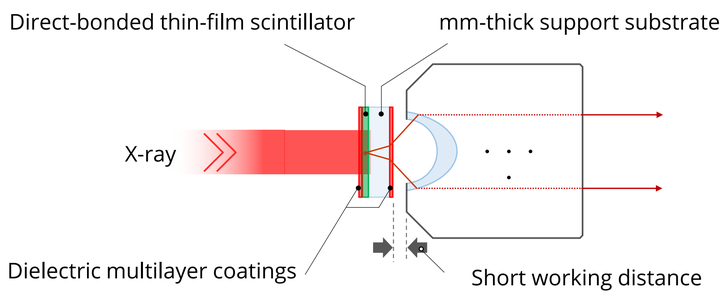


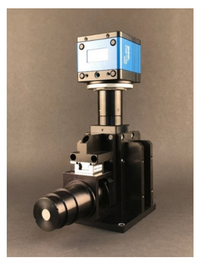
Fig. 2 Schematic of DIFRAS optical system

▶ Quasi-diffraction-limited resolution & damage-free operation

X-ray imaging unit specifications

Unit type	Full-range 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

Full-range 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

*1Typical 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 photodiffusioon-free transparent scintillator by using direct-bonding of transparent ceramics. Direct-boned a scintillator-film and a substrate has quasi-homogenious refractive index and low distortion. This enables photodiffusion-free image transfer. The mm-thick non-doped LuAG substrate attenuates X-ray intensity down to ~10^{-40} at 10 keV and suppresses lens browning in the imaging unit. These features provide quasi-diffraction-limited spatial resolution and damage-free operation. Two variants of X-ray imaging units equipped with DIFRAS are deployed. A full-range unit offers a wide-range magnification (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 evacuating optical components. A short depth geometric design can insert detection plane in 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

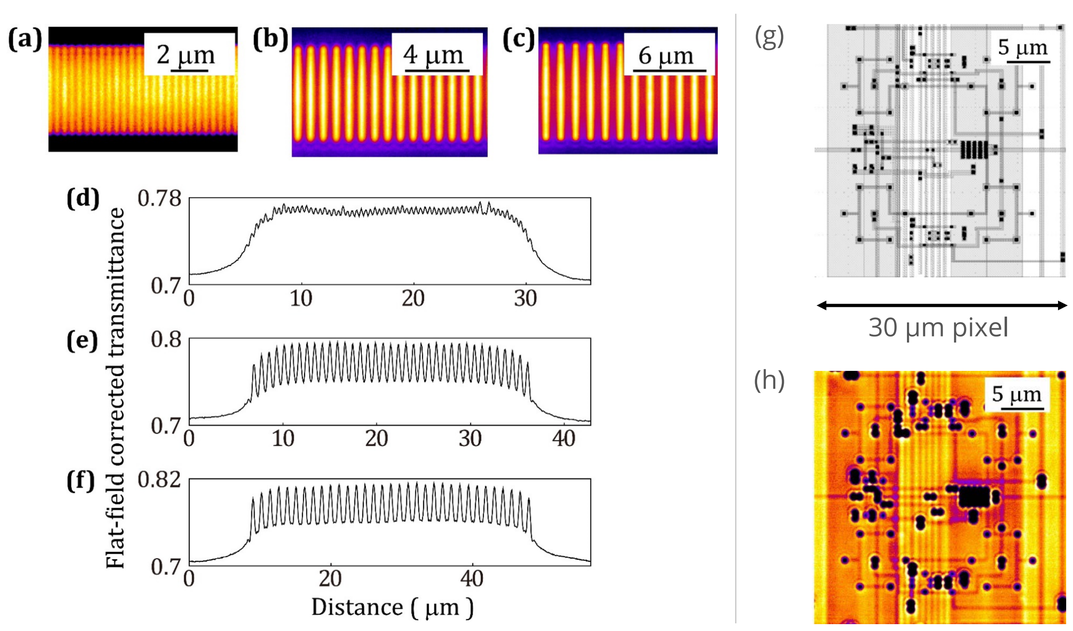


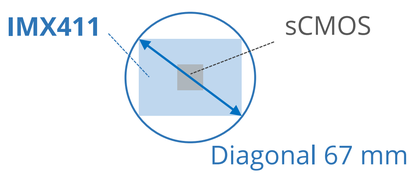
Fig. 3 (a-c) Transmitted X-ray images of 200/400/600 nm lines and spaces in the tungsten test chart
(d-f) Line profiles of (a-c)
(g) VLSI circuit design drawing
(h) Transmitted X-ray images of VLSI circuit in the area of (g)

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

T. Kameshima and T. Hatsui, J. Phys.: Conf. Ser. 2380 012094 (2022)

SONY IMX411sensor



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

		Lens A1	Lens A2	Lens A3	Lens A4	Lens A5
Lens category		Development	COTS	COTS	COTS	COTS
NA		0.85	0.35	0.27	0.159	0.083
空間分解能 (L&S)	**[μm]**	~0.2	0.45	0.6	1.0	4
実効視野	**[mm²]**	2.6 x 1.9	7.6 x 5.7	10.3 x 7.7	15.2 x 11.4	53.3x 40.0
Staus		not developped	**done**	not evaluated	**done**	**done**

Detector evalution

Lens A4 + IMX411 ■ 0.5 μm L&S resolution, 7.6 x 5.7 mm² FOV

Lens A2 + IMX411 ■ 1.2 μm L&S resolution, 15.2 x 11.4 mm² FOV

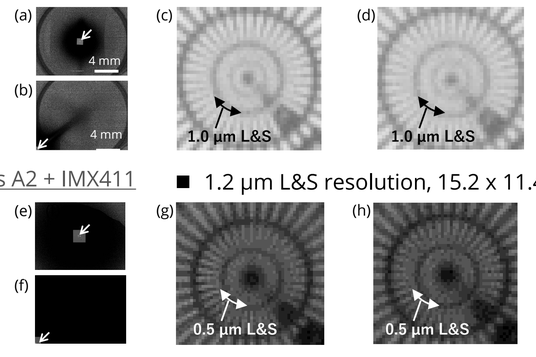


Fig. 4 (a-h) Microradiographs of a tantalum Siemens star pattern acquired by the assembled detector. (a), (b), (e) and (f) are images of the entire field of views where the Siemens star pattern is located at the position indicated by white arrows. (c) and (d) are zoomed images of (a) and (b) in the Siemens star pattern, respectively. Also, (g) and (h) are zoomed images of (e) and (f) in the Siemens star pattern, respectively.

We developed a large-format X-ray imaging detector to enhance a field of view, implementing the SONY IMX411 image sensor and a large image circle optics. The prototype unit has successfully visualized 0.5 μm L&S pattern in the center and the corner of FOV with 7.6 x 5.7 mm².