



An approach to overcome the resolution–efficiency trade-off in X-ray scintillator imaging

Hong-Quan Zhou^{1,2} · Yan-Qing Wu^{1,3} · Lu Wang^{1,2} · Hao Shi³ · Cheng-Qiang Zhao⁴ · You He³ · Jia-Li Long³ · Yong Wang³ · Zhi Guo³ · Ren-Zhong Tai^{1,3}

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Abstract

To address the well-known “resolution–photon efficiency” trade-off, we developed a lens-coupled X-ray tube-based indirect imaging system that incorporated a thick scintillator plate and lens with a large numerical aperture. This configuration provided sufficient photon flux while maintaining a theoretically high spatial resolution, thereby reducing the core challenge of resolving the defocusing issue induced by a thick scintillator and approaching the theoretical resolution limit. Two key techniques were developed: (1) generalized point spread function (PSF) restoration, which extended the single PSF recovery method to geometrically magnified X-ray imaging systems, demonstrating its suitability for large-NA configurations, and (2) truncated PSF correction, which eliminated the imaging artifacts caused by severe fabrication defects in ultrathin scintillators through PSF truncation, followed by resolution restoration using experimentally measured PSFs. The experimental results showed that in the high-frequency range, the power spectral density was improved by up to 8.45 times for an image on a thick scintillator. High image quality and photon efficiency were achieved simultaneously, demonstrating the feasibility of this integrated strategy. These results provide a critical pathway for overcoming the long-standing resolution–efficiency dilemma in indirect X-ray imaging using an X-ray tube source or synchrotron radiation facility.

Keywords Scintillator · X-ray imaging · Indirect imaging

1 Introduction

Both direct and indirect imaging techniques are used for high-resolution X-ray detection [1]. Direct imaging uses semiconductor materials such as CdZnTe to generate electrical signals via ionization effects, offering high sensitivity [2]. However, the high cost of CdZnTe crystal growth and manufacturing [3] limits its large-scale applications. Using current micro-/nanofabrication processes, the pixel size of direct imaging can be reduced to 20 μm , which is still larger than the 6.5 μm pixel size of the standard sCMOS cameras used in high-resolution indirect imaging systems. Despite challenges such as light scattering [4], secondary electron scattering, and fluorescence field depths exceeding the depth of field (DOF) of the optical system, the resolution of indirect X-ray imaging remains higher than that of direct imaging systems. Therefore, high-resolution indirect imaging systems are still widely used in synchrotron radiation imaging stations and in

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✉ Yan-Qing Wu
wuyanqing@sari.ac.cn

✉ Cheng-Qiang Zhao
chqzhao@siom.ac.cn

✉ Ren-Zhong Tai
tairz@sari.ac.cn

¹ Shanghai Institute of Applied Physics, Chinese Academy of Sciences, Shanghai 201800, China

² University of Chinese Academy of Sciences, Beijing 100049, China

³ Shanghai Synchrotron Radiation Facility, Shanghai Advanced Research Institute, Chinese Academy of Science, Shanghai 201204, China

⁴ Shanghai Institute of Optics and Fine Mechanics, Chinese Academy of Sciences, Shanghai 201800, China

industrial and biomedical fields because of their high stability and low cost [5].

In the last decade, micrometer/submicrometer lens-coupled X-ray indirect imaging technology has advanced significantly. (1) Detector performance has been enhanced by optimizing the materials and thickness of scintillator screens, with new scintillators such as LuAG:Ce and GAGG:Ce boosting the light output and resolution [6, 7]. ZnO:In nanorod arrays suppress optical crosstalk via a pixelated design, combining a subnanosecond decay time and high light yield ($> 1 \times 10^4$ photons/MeV), and simultaneously enhancing the temporal and spatial resolutions [8, 9]. Perovskites are excellent indirect imaging detectors because of their high carrier mobility and flexible processability. The CsPbI₂Br/CsPbBr₂ film developed at Zhejiang University achieved a dark current of < 1 nA/cm² and sensitivity of 2.6×10^4 μ C Gy⁻¹ cm⁻² [10]. The flexible Cs₄PbI₆ detector of NUAA demonstrated a sensitivity of 256.20 μ C Gy⁻¹ cm⁻² with 60-day stability, surpassing rigid detector limits [11]. The structured CsI scintillation screen was further optimized, and its comprehensive performance was significantly improved [12]. (2) Image recorders have evolved from CCD to CMOS and sCMOS types, which have greatly improved the sensitivity, dynamic range, and imaging speed. (3) Optical lens systems have also been developed. The ZEISS Xradia series employs a two-stage magnification architecture, achieving submicrometer resolution (RaaD technology), while maintaining a large working distance (> 10 mm). Optical lens structures have also been developed with designs such as large numerical aperture (NA) and long working distance lenses [13, 14], increasing the light-coupling efficiency and resolution. This technology has broad applications in X-ray micro-computed tomography (CT) imaging, materials science, and medical imaging. When combined with synchrotron radiation sources, 3D micro-/nanostructural reconstruction and dynamic observations can be performed.

The Shanghai Synchrotron Radiation Facility (SSRF) was instrumental in this technological progress. Its high-performance beamlines provide high-brightness, highly collimated X-rays for various X-ray imaging methods [15–19] and their applications [20, 21], particularly indirect micrometer/submicrometer-resolution X-ray imaging. Over the past decade, the hard X-ray imaging beamline at the SSRF has achieved breakthroughs in indirect imaging technologies, with micro-CT serving as the core technique (supporting $> 70\%$ of the experiments). By integrating absorption, phase contrast, and fluorescence imaging with rapid algorithms, high-precision 3D reconstructions can be realized [22, 23]. Furthermore, multimodal approaches, such as fluorescence/dynamic/diffraction CT, have been implemented, with dynamic CT

capturing real-time images of microscopic evolution in living insects [24].

Deep learning is widely used in optical imaging. In recent years, it has also been introduced in direct-coupled indirect X-ray imaging fields to eliminate the influence of optical blurring under various conditions [25, 26]. For lens-coupled systems, we developed deep neural network-assisted high spatial frequency enhancement and reconstruction (DA-HSFER), which is an information optics-based innovation that addresses high-frequency information loss in X-ray microscopic imaging [27–30]. This technique combines an optical encoder on the scintillator surface with a deep-learning decoding module that converts X-ray-induced high-frequency fluorescence signals into low-frequency signals transmitted through the scintillator–air interface. The deep-learning model reconstructs high-frequency details from the low-frequency data. Through encoder–decoder synergy, DA-HSFER recovers lost information, overcomes traditional physical limitations, and significantly enhances the imaging performance.

Specifically, the optical encoder employs specialized micro-/nanostructural patterning on the scintillator surface to modulate the visible light generated by X-ray excitation, encoding high-frequency details that are typically lost during conventional imaging processes. Subsequently, deep-learning algorithms decode and reconstruct the encoded image data, leveraging large-scale training datasets and optimized neural network architectures (e.g., hybrid convolutional neural network (CNN) transformer models) to accurately restore high-frequency information, which significantly enhances the image detail fidelity. This technology overcomes the limitations of traditional indirect X-ray imaging, where the high refractive index of the scintillator restricts the bandwidth of the optical system and degrades the image resolution.

However, in practical applications and further research and development, we must prioritize resolving the fundamental optical bottleneck arising from the contradiction between the imaging depth and DOF of an optical system, which causes defocus blurring and surpasses the impact of high-order aberrations and high-frequency information loss induced by internal reflections in scintillators. The imaging depth refers to the longitudinal distribution of fluorescence patterns generated by X-ray penetration within a scintillator, which is typically on the scale of hundreds of micrometers or more. This often leads to blurred features in sample regions distant from the focal plane in high-NA optical systems designed for high resolution, thereby compromising the overall imaging quality. This challenge remains a critical unresolved issue in many scenarios, particularly in biomedical applications such as imaging thick tissue sections or 3D cell cultures, as well as in industrial inspections of multilayered electronic

components, where defocus blurring significantly degrades the imaging accuracy and detection precision.

Experimental data show that as the CsI:Tl thickness increases from 100 to 500 μm , the absorption rate of 200 keV X-rays increases from 38% to 92% [31], while the modulation transfer function value at half maximum (MTF50) decreases from 4.2 to 1.8 lp/mm [32]. This contrasting thickness–performance relationship stems from two factors. First, the light yield (LY) increases with the X-ray excitation depth in the scintillator. Second, the longitudinal distribution of fluorescence points caused by X-ray penetration broadens the full width at half maximum (FWHM) of the point spread function (PSF). However, although traditional thinning methods (e.g., laser cutting to 50 μm) improve the spatial resolution, they also introduce high costs, instability, machining defects, and a low photon yield in thin scintillators, creating an “efficiency–quality–reliability” trilemma. The present study overcame this optical bottleneck through the synergistic integration of optimized optical structural designs and novel image restoration methods, thereby advancing the development and application of micron/submicron-scale indirect X-ray imaging technologies.

Wavefront coding has been employed for general optical imaging DOF issues [33], where phase masks modulate the wavefronts to maintain consistent PSFs across the entire DOF, followed by PSF deconvolution for image recovery. However, the phase plate in this technology is wavelength-sensitive and introduces design, manufacturing, or computational complexities when applied to broad-spectrum light sources [34]. Studies on synchrotron-based indirect X-ray imaging [35] have indicated that a pure-PSF method can be used to restore images under parallel light conditions because the fluorescence point distributions at different depths in the scintillator are sufficiently uniform. Reference [35] employed a generalized PSF function from the simulation, which was overly idealized.

Our study theoretically extended this method to the non-parallel geometric magnification configurations commonly used in systems based on X-ray tubes and often employed in imaging stations at synchrotron radiation facilities, especially those with large NAs. Crucially, prior simulations [35] ignored some non-ideal factors, such as crystal lattice deformation, which may lead to deviations in images. To address this problem, we developed a PSF-based image restoration method. Taking a Ce^{3+} -doped yttrium aluminum garnet (YAG) crystal as an example, we used a 20 μm -thin YAG crystal film, with a depth close to the DOF of the optical system, as the control group. By deconvolving the 200- μm -thick YAG imaging results with the control group, we extracted the actual PSF and restored the high-resolution image. In indirect X-ray imaging, the direct measurement of the PSF for image restoration has

long faced significant challenges because of limitations in experimental setups and material properties [36–38]. In this study, the challenges included severe defects that severely degraded the reliability of the measured PSF, along with low photon efficiency in the thin YAG, which required a long exposure time to induce sample drift. We utilized these defects as alignment markers and exploited the differences in defect correlations between thick and thin scintillators to eliminate the effects of the defects entirely. By combining this method with large-NA optics, a microfocus X-ray imaging system was developed, in which both high photon flux and high-definition imaging were achieved.

2 Imaging principle

2.1 An extended PSF-based restoration method for addressing depth-related challenges in fluorescent pattern imaging

All of the studies were conducted using a microscope-coupled high-resolution indirect X-ray imaging system. A tungsten target X-ray source was employed and operated at an accelerating voltage of 50 kV, producing X-ray photons with energies predominantly in the range of 10 keV to 30 keV, as shown in Fig. 1.

The penetration depth of these photons in a yttrium aluminum garnet (YAG) crystal varied with photon energy, ranging from 100 to 200 μm . To ensure the maximum absorption of X-ray photons, a 200- μm -thick YAG: Ce^{3+} scintillator was utilized for indirect X-ray imaging.

The results of an error analysis of the optical imaging system are shown in Fig. 2, where optical magnification $M = 5$,

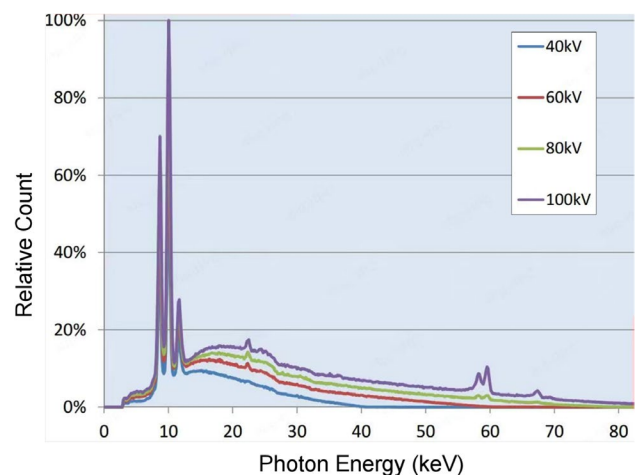
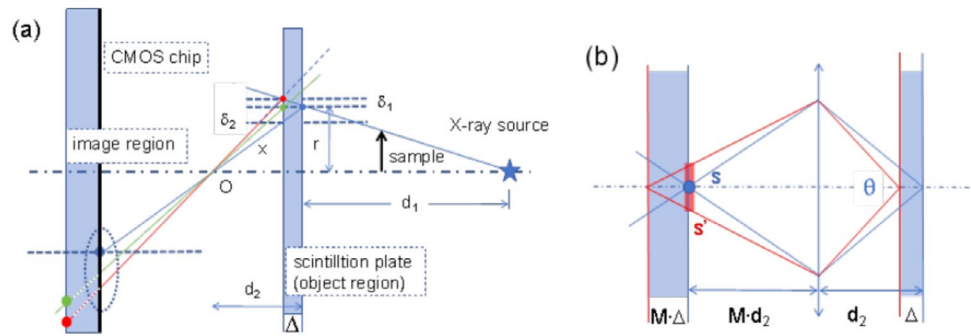


Fig. 1 (Color online) Energy spectrum of X-ray source (Hamamatsu L10101) with tungsten target at different accelerating voltages

Fig. 2 (Color online) Error analysis results for the optical imaging system: **a** the image field distribution error caused by the thickness of the scintillator and X-ray geometric magnification was one pixel; **b** the point spread of the image was caused by the depth of the fluorescent object scene, which was at most 13 times



numerical aperture $NA = \sin \theta = 0.4$, absorption length $\Delta = 100 \mu\text{m}$, $d_1 \sim 10 \text{ cm}$, $d_2 \sim 10 \text{ cm}$, and $r \sim 1 \times 10^3 \mu\text{m}$. Then, we obtained $\delta_1/r = \Delta/d_1$, $\delta_2 = r - x$, $x/r = d_2/(d_2 + \Delta)$. Therefore, image point shifts $M \cdot \delta_1 = 2.5 \mu\text{m}$ owing to the X-ray geometric magnification, and the other shifts $M \cdot \delta_2 = 7.5 \mu\text{m}$ because of the thickness of the scintillator. The edge parts of the image shifted by $7.5 \mu\text{m}$, or by approximately one pixel ($6.5 \mu\text{m}$), for a 2 mm field of view (Fig. 2a). This error can be ignored in the present stage of research. In Fig. 2b, $NA = \sin \theta$, where s is the imaging point size of the fluorescent object on the front surface of the scintillator. Here, s' represents the size of the defocused image spot of the fluorescent object at the absorption depth (Δ) of the scintillator, $s' = 2\Delta \tan \theta$. When $NA = 0.4$ and $\Delta = 100 \mu\text{m}$, $s' = 86 \mu\text{m}$. Assuming s is the size of one pixel, $6.5 \mu\text{m}$, then $s'/s = 13$. This means that the PSF function for the fluorescent points varies greatly with depth z in the scintillator. This variation is much greater than the variation in the overall light intensity distribution on the imaging surface (Fig. 2a). The image distribution could be viewed as having different depths in the scintillator in this study.

Under the above estimation, fluorescent patterns at different depths along the optical axis (z direction) exhibited geometrically similar spatial distributions, and the finite thickness (Δz) of the scintillator led to multifocal superposition (defocusing) and considerable X-scattering from the z -planes downstream. The imaging process was then modeled as shown in Eq. (1):

$$I_i = \int_0^{\Delta z} k(z) I_g(\alpha \cdot (z + z_0) \cdot x, \alpha \cdot (z + z_0) \cdot y) * PSF(x, y, z) dz, \quad (1)$$

where $*$ denotes the convolution, z_0 is the distance from the anterior surface of the scintillator to the X-ray source, $k(z)$ is the depth-dependent intensity-weighting function, I_g is the ideal image under parallel light, and $\alpha \cdot (z + z_0)$ is the geometric magnification. The PSF combines internal photon diffusion (PSF_{internal}) and optical system effects (PSF_{optical}). PSF_{internal} is caused by X-ray scattering, while PSF_{optical} is the result of the pattern at z not being in the center of the DOF.

When the field coverage angle for the X-ray source is much smaller than the angular acceptance of the optical system downstream, which is usually satisfied by a high-NA system, I_g varies much less than PSF in the integral above. In our system, the two angles were approximately 1.8° and 31° . Thus, we obtain Eq. (2).

$$I_i(x, y) = I_g(\alpha z_0 \cdot x, \alpha z_0 \cdot y) * \int_0^{\Delta z} k(z) \cdot PSF(x, y, z) dz \\ = I_g(\alpha z_0 \cdot x, \alpha z_0 \cdot y) * PSF_{\text{all}}(x, y) \quad (2)$$

Therefore, a single PSF -based convolution is sufficient, even under geometric magnification in our system.

Imaging by a $20 \mu\text{m}$ -depth YAG crystal was chosen as the standard for the experimental PSF measurement. By analyzing the modulation transfer function (MTF) for $20 \mu\text{m}$ and $200 \mu\text{m}$ scintillators, we derived Eq. (3).

$$\frac{\mathcal{F}\{I_{i,200}\}}{\mathcal{F}\{I_{i,20}\}} = \frac{\mathcal{F}\{I_g\} \cdot \mathcal{F}\{PSF_{\text{all},200}\}}{\mathcal{F}\{I_g\} \cdot \mathcal{F}\{PSF_{\text{all},20}\}} = \frac{\mathcal{F}\{PSF_{\text{all},200}\}}{\mathcal{F}\{PSF_{\text{all},20}\}} \quad (3)$$

Based on this analysis, we further defined the deconvolution kernel, PSF_{20-200} , using Eq. (4).

$$\mathcal{F}\{PSF_{20-200}\} = \frac{\mathcal{F}\{PSF_{\text{all},200}\}}{\mathcal{F}\{PSF_{\text{all},20}\}} \quad (4)$$

Applying PSF_{20-200} to $200\text{-}\mu\text{m}$ -thick YAG imaging restored the high-frequency details while retaining the high photon efficiency. As shown below, the defects in the thin and thick YAG layers were uncorrelated and could be suppressed via PSF truncation.

2.2 Optical system design for high-resolution imaging with thick scintillator and high-NA lens

In the microscope there were two lenses with optical magnifications of $5\times$ and $10\times$ and NAs of 0.4 and 0.9 , respectively. The camera pixel size was $6.5 \mu\text{m}$. As previously mentioned, we employed a thick scintillator to convert the X-ray patterns into visible light. A high-NA optical microscope lens was utilized to capture more photon flux and achieve high diffraction-limited resolution. The

depth of field of the optical system was not particularly restricted, allowing for the reduction of various aberrations under the conditions of a high NA, thick scintillator, and suitable working distance. To resolve depth-dependent fluorescence field distortions in the thick scintillator, a PSF-based restoration method was adopted using thin scintillator-derived high-resolution images as reference standards. Therefore, images with both a high photon efficiency and high definition were obtained.

X-rays can degrade optical lenses over time, thereby reducing their optical efficiency. A conventional solution involves installing a lead glass filter at the front of the lens to protect subsequent optics. However, conventional high-NA microscope lenses, particularly those with $NA = 0.9$, have short working distances (typically, approximately 0.5 mm). Although Nikon offers an $NA = 0.9$ lens with a working distance of up to 2 mm, installing a lead glass filter directly would significantly affect axial aberrations, such as spherical and chromatic aberrations, because of not considering the thickness of the filter during commercial lens design, thereby reducing the imaging resolution. Hence, there is a need to develop dedicated, long working distance, and high-NA microscope lenses that can accommodate lead glass.

To meet these requirements, we designed and developed two long working distance microscope lenses with 5× and 10× magnifications, which had a conjugate distance of 500 mm and NA values of 0.4 and 0.9, respectively. Both lenses exceeded the 40% MTF values at 384 lp/mm and 769 lp/mm, corresponding to a camera pixel size of 6.5 μm . A replaceable 2-mm-thick ZF7 lead glass filter with a lead equivalence of 0.66 mm Pb (0.33 mm Pb per millimeter of ZF7 glass) was installed between the lens and scintillator. In addition, the effects of different scintillator thicknesses on high-NA lens aberrations cannot be overlooked. Therefore, during the lens design, aberration optimization was performed for a commonly used 50- μm -thick scintillator. Simulations showed that with an MTF decrease to 30% as the criterion, the 5× lens could accommodate scintillator thicknesses ranging from 0 to 210 μm without adjusting the back-focal distance, whereas the 10× lens could only accommodate 45 to 55 μm . With an adjustable back-focal distance, the range for the 5× lens was extended to 0 to 300 μm , and that for the 10× lens was extended to 0 to 100 μm . Figure 3a, b shows the optical layouts of the two lenses and their corresponding MTF curves.

To further protect the CCD/sCMOS camera, a mirror was added between the lens and camera to redirect the overall optical path by 90°. These designs ensured a high photon collection efficiency while effectively blocking X-rays from damaging the optical components and CCD camera, thereby extending the lifespan of the equipment. The high NA enabled the system to theoretically achieve pixel-level resolution, but at the cost of a shorter DOF.

As shown in Fig. 3e, for a 5× lens at a spatial frequency of 384 lp/mm (corresponding to two imaging pixels, $2 \times 1.3 \mu\text{m}$), the contrast decreased to zero when the defocus distance was $\pm 5.5 \mu\text{m}$ (Fig. 3e), which provided a DOF of approximately 11 μm . Similarly, the DOF for the 10× system was approximately 3.5 μm for a spatial frequency of 384 lp/mm (Fig. 3f).

The thinnest scintillator foil obtained had a thickness of 20 μm . The fluorescence images within the top 11 μm had an actual resolution exceeding the pixel resolution of the camera (384 lp/mm, 2-pixel criterion), whereas in the deeper region, it fell below this threshold. Images on the 20 μm thick YAG foils were employed as standard images for the PSF-based recovery method. Using the high-NA lenses, a new recovery method was investigated in this study that overcame the DOF and scintillator thickness contradiction to achieve high-resolution and high-definition imaging.

The optical DOF, X-rays, and electron scattering may all degrade the imaging resolution. In a YAG crystal, electron scattering has a mean free path of $\sim 100 \text{ nm}$ for secondary electrons, which is too small to induce significant image blur. Therefore, the degradation of the image resolution is mainly caused by optical defocusing and X-ray scattering. Under the X-ray photon energy range and DOF of the optical system employed in this study, X-ray scattering was not the primary factor affecting the resolution (as discussed later).

3 Experiments, results, and analysis

3.1 Experiments

The experimental setup is shown in Fig. 4. It consisted of an X-ray-tube-based source, a scintillator conversion layer, and a high-NA visible-light microscope.

For high-definition images, a microfocus X-ray source (Hamamatsu L10101, tungsten target) was employed. It had an adjustable accelerating voltage range of 40 kV to 100 kV, with a maximum output power of 20 W. At an output power of 4 W, the source spot size was 5 μm . The X-ray source was operated at an accelerating voltage of 50 kV to achieve a small source spot size. In future studies, higher accelerating voltages will be utilized for imaging with thick scintillators to achieve a higher photon flux. Using a 5× lens and an sCMOS camera with a pixel size of 6.5 μm , a pixel resolution of 1.3 μm was obtained. YAG:Ce³⁺ crystal films were used to convert X-rays into visible light with high luminous efficiency in the 500–600 nm wavelength range.

A fixed visible-light imaging system was used in the experiment, and the scintillator plate position was finely adjusted for focusing. To accurately determine the optimal focus positions for the two YAG scintillators with different thicknesses, we used a displacement stage with a step size

Fig. 3 (Color online) Optical design of the imaging system: **a**, **b** the optical layouts of the 5× and 10× lenses, respectively; **c**, **d** MTFs for 5× and 10× lenses, respectively. MTF simulation results for lenses with defocus: **e** 5× lens with 5.5 μm defocus and **f** 10× lens with 1.7 μm defocus. The colored lines indicate the contrast of line pairs (lp) at different positions on the image plane, while the black line represents the value corresponding to the optical diffraction limit. Here, “T” and “S” represent tangential and sagittal, respectively, and 0.0000 mm, 6.6500 mm, and 9.4000 mm are the distances between the test positions on the lens and its center

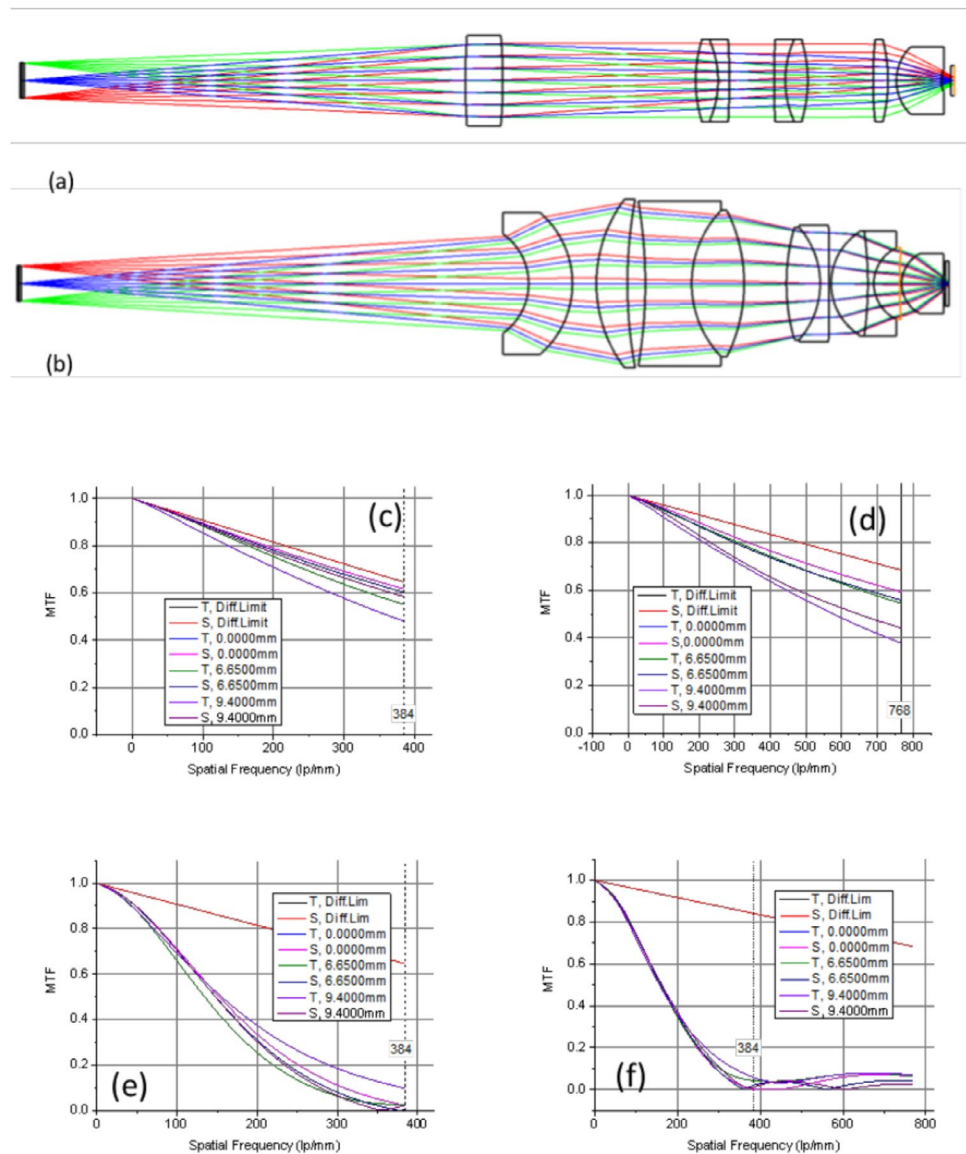
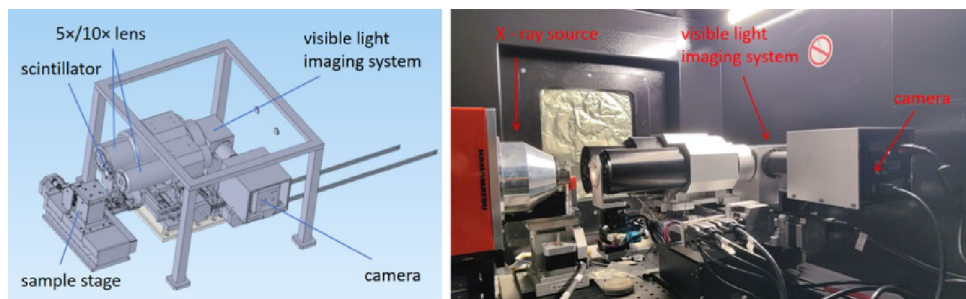


Fig. 4 (Color online) Schematic and photograph of the developed X-ray indirect imaging system



of 1 μm to scan the samples axially. This process required precise mechanical adjustments and repeated verification of the focal position to ensure the optimal imaging quality. After locating the best focal plane, each sample and its corresponding background were imaged ten times to

enhance the data reliability and stability. LabVIEW software controlled the CCD for synchronized data acquisition and storage. The raw data were then imported into MATLAB for averaging, to reduce the noise and highlight the true features of the samples. Background subtraction was also performed

to eliminate interference from YAG surface defects and system noise, thus clarifying the details of the samples. These rigorous experimental steps and data-processing methods ensured the acquisition of high-quality image data for subsequent analyses.

The image on the 20- μm -thick YAG scintillator film had a high resolution but weak signal, requiring an exposure time of 10 s, whereas 1 s was needed for the 200- μm -thick YAG scintillator film. Accurate alignment of the sample and background images was crucial to avoid information bias and ensure a reliable analysis.

As shown in Fig. 5a, b, the scale-invariant feature transform (SIFT) algorithm was used, which is known for its noise resistance in image feature matching. SIFT is widely used for image registration because of its stability and reliability. It identifies feature points by recognizing distinct image features. In this study, the unique contours, positions, and higher intensities of the defect features rendered them suitable reference points for registration. Weaker image information was treated as “noise” and ignored. Image alignment was performed using SIFT feature point matching, and some obviously incorrect matches were manually excluded, which eventually eliminated the influence of image drift.

Background subtraction, which involves subtracting a background image from a sample image, is feasible because of the rich frequency components of the resolution target

image. These components help achieve high contrast and sharp line edges, allowing the background-subtracted image to retain more detail. As shown in Fig. 5c, d, when comparing the images of the 20- μm -thick YAG film with those of the 200- μm -thick YAG sample, the former still shows significant defect impacts. This indicates that while background subtraction can effectively enhance the image quality, the inherent defects in thinner YAG scintillator films may still interfere with the imaging results. These defects likely stem from the material properties or unavoidable factors in the fabrication process.

3.2 Data analysis

As shown in Fig. 6a, b, PSF_{20-200} was obtained by deconvolving the resolution target image (Fig. 5d) on 200- μm -thick YAG with that (Fig. 5c) on 20- μm -thick YAG. The Lucy–Richardson algorithm was employed, and the number of iterations was limited to eight. The entire structure, Gaussian-like peaks, and some adjacent structures can be found in the central region. PSF truncation was employed to remove the influence of defects on a 20- μm -thick YAG plate used as a standard sample (Fig. 5c), but these were not completely removed during background removal. The imaging process in the frequency domain is described in Eqs. (5) and (6).

Fig. 5 (Color online) Alignment of **a** image on 20 μm -depth YAG and **b** its background images, and resolution target images **c** on 20 μm -depth, **d** 200 μm -depth YAG samples

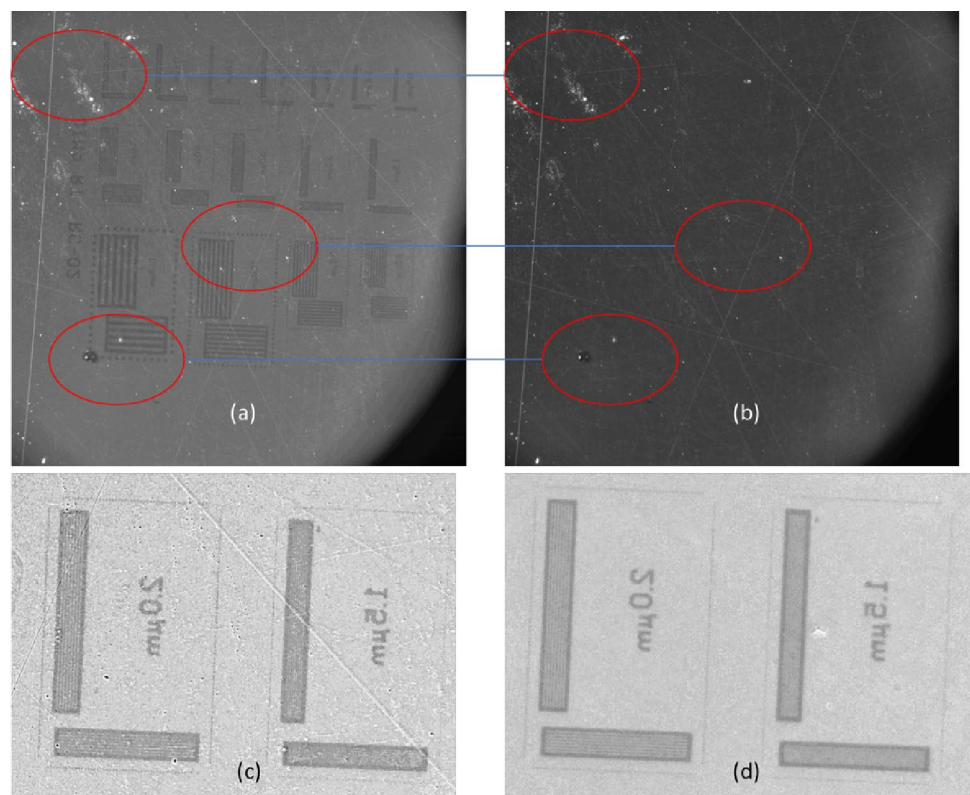
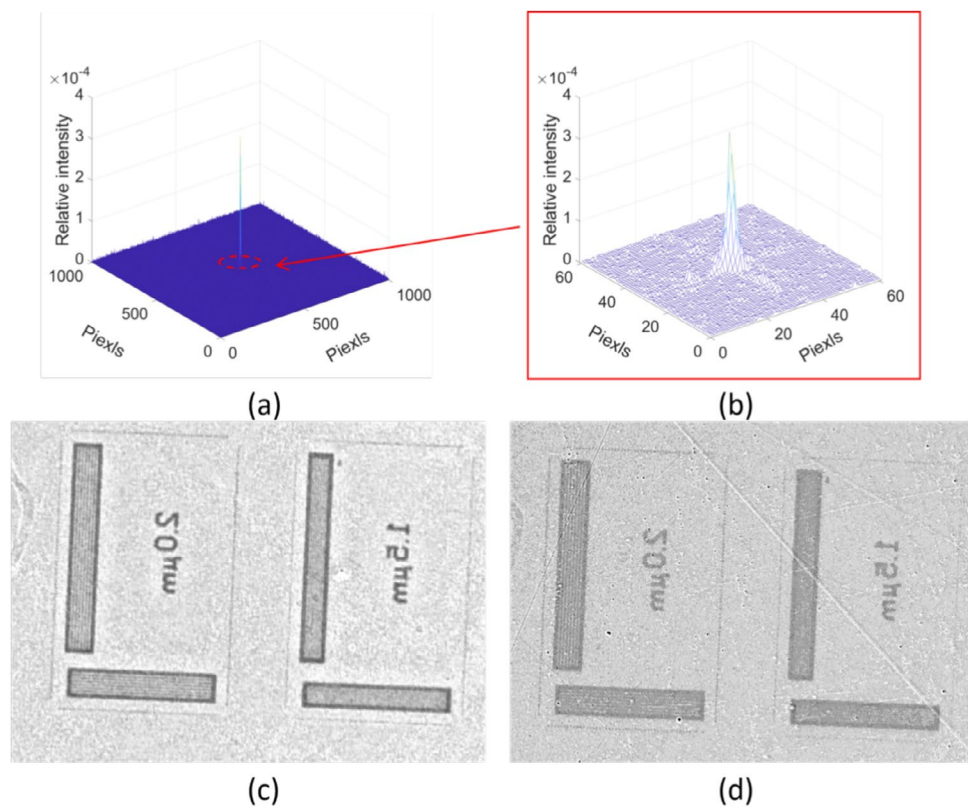


Fig. 6 (Color online) Convolution function PSF_{20-200} . **a** The entire area, **b** central area, **c** image obtained by deconvolving the resolution target image on 200- μm -thick YAG (Fig. 5d) with the truncated PSF, and **d** image from Fig. 5c



$$F_{20} = F \cdot M_{20} + G_{20} \quad (5)$$

$$F_{200} = F \cdot M_{200} + G_{200} \quad (6)$$

Here, F , F_{20} , F_{200} , M_{20} , M_{200} , G_{20} , and G_{200} represent ideal imaging, imaging on 20- μm and 200- μm -thick scintillators, and the corresponding modulation transfer functions and point-like defects on 20- μm and 200- μm -thick scintillators, respectively. G_{200} is much smaller than G_{20} and thus can be ignored. The measured MTF was obtained using Eq. (7).

$$M = \frac{F_{200}}{F_{20}} \approx \frac{M_{200}}{M_{20} \cdot \left(1 + \frac{G_{20}}{F \cdot M_{20}}\right)} \approx \frac{M_{200}}{M_{20}} \cdot \left(1 - \frac{G_{20}}{F \cdot M_{20}}\right) \quad (7)$$

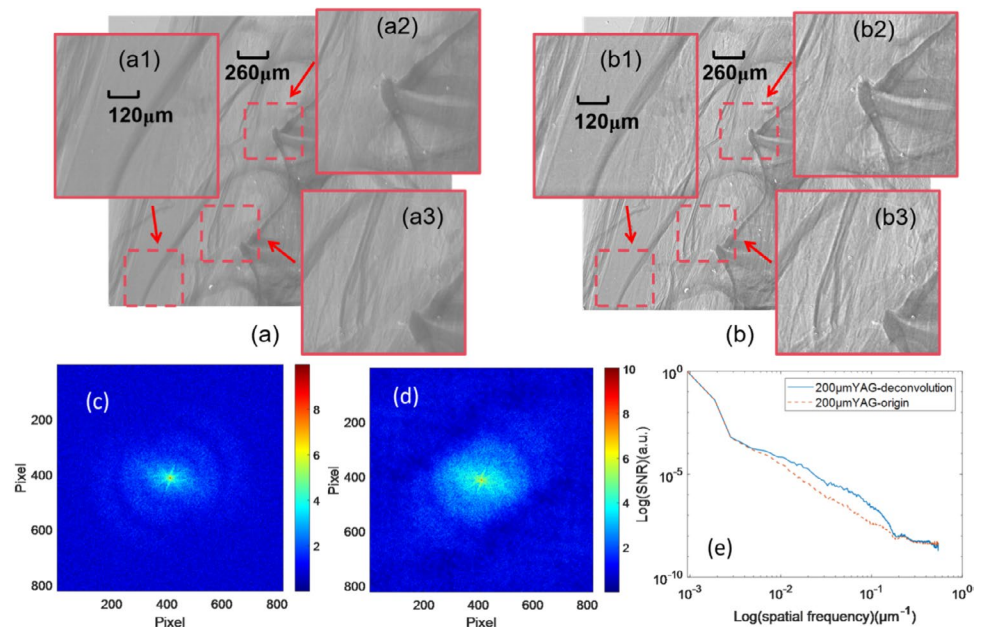
In the spatial domain, the second item, $\frac{G_{20}}{F \cdot M_{20}}$, corresponds to $\frac{1}{psf'}$, where psf' is the pseudo-impulse response contributed by the point-like defects attached to the real-image PSF. This additional $\frac{1}{psf'}$ has a small total power, wide distribution, and small amplitude in the central region, which is relatively large in the outer range. Therefore, in principle, PSF truncation can remove the influence of defects in a standard image (on a 20- μm -thick YAG plate). Furthermore, the blurred image spot on the 200- μm -thick YAG was approximately 13 pixels; thus, the truncation boundary had to be significantly larger than 13 pixels. However, to reduce

the frequency domain pollution caused by PSF truncation, the truncation boundary needed to be far from the center. Therefore, a central region (60 pixels $\times$ 60 pixels) containing almost all these characteristics was finally selected.

Compared to the image (Fig. 6d) on the 20- μm -thick YAG film, the image (Fig. 6c) deconvolved from the resolution target image on the 200- μm -thick YAG using the above-mentioned truncated PSF was much better. The details were clearer and sharper; the edges were more distinct; the overall image quality was significantly improved; and the influence of defects was fully eliminated. This showed that the truncated PSF method used in this study is effective in removing the influence of these sparsely distributed sharp defects, while keeping the image details intact.

Figure 7a, b presents the deconvolution results from zebrafish images captured using a 200 μm YAG indirect imaging system utilizing the extracted central PSF region. Figure 7a shows the original zebrafish image after the background subtraction. The basic outline and shape of the zebrafish are discernible, but the details are obscured by background noise, resulting in a blurry image. Figure 7b presents the deconvolved image. Visually, the processed images showed remarkable improvements, with enhanced clarity and sharper details for the scales and fins of the zebrafish. This indicated that deconvolution effectively reduced blurring and boosted the image contrast and resolution.

Fig. 7 (Color online) Zebrafish imaging: **a** three $0.65\text{ mm} \times 0.65\text{ mm}$ areas showing details from the original image on 200- μm -thick YAG, **b** the corresponding deconvolved results, **c** 2D PSD of the raw image, **d** 2D PSD of the deconvolved image and **e** 1D PSD comparison of raw and deconvolved results



It is important to note that while the 200 μm YAG substrate has inherent defects, such as surface impurities, processing flaws, and minor crystal structure inconsistencies, these defects are less impactful. The greater imaging depth and photon count associated with thicker scintillators indicate that these defects do not significantly interfere with the key imaging features. By contrast, defects such as surface scratches and internal bubbles in the 20 μm YAG control group are theoretically more detrimental. However, after PSF function truncation, their impact was effectively controlled and high-frequency information enhancement remained largely unaffected.

For specimens with complex details, low intrinsic contrast, and weak visible-light signals (e.g., zebrafish specimens), division-based background subtraction was used. Unlike the traditional subtraction methods, this approach removes the background by dividing the image pixel values by the estimated background signal values. In the zebrafish images, this method preserved crucial details such as fine surface textures and weak internal fluorescence signals, which might have been lost with traditional subtraction. This prevented issues such as excessive contrast and detail loss during background correction, provided richer and more accurate visual information for subsequent image analysis, and facilitated a deeper understanding of the specimen structures and properties.

PSD analysis (Fig. 7c, d) clearly showed that deconvolution significantly boosted high-frequency detail recovery. The 1DPSD (Fig. 7e) indicated a significant SNR improvement in the high-frequency range (up to 8.45 times), with no low-frequency information loss. This confirmed the effectiveness of the deconvolution method based on

a generalized PSF function for improving image quality. However, the SNR in the high-frequency region did not improve as expected. This was likely because the 20- μm -thick ultrathin scintillator used exceeded the imaging lens DOF (11 μm). Consequently, thinner scintillators will be used in future experiments to enhance the SNR in the highest frequency band and further optimize the image quality.

In comparison, when imaging zebrafish samples using a 20- μm -thick YAG crystal, the high X-ray absorption rate of the samples combined with the low transmitted beam intensity from the 4W X-ray source resulted in severely degraded image contrast. This made it impossible to determine the optimal focal position by adjusting the focus settings based on the observed image quality.

To verify the fidelity advantage of this method, based on the real PSF measured, the perception-based image quality evaluator (PIQE) method was adopted to determine the image fidelity. A lower score for the PIQE method implied better fidelity. The results were as follows.

For the image of the pair of resolution targets on the 200- μm -thick YAG, the PIQE value was 63.2. Thus, the PIQE value of 48.9 for the image after deconvolution showed an obvious improvement. The value for the 20- μm -thick YAG plate was 75.4 because of serious defects. When imaging the fish samples with the 200 μm YAG, the PIQE value was 14.0, and the PIQE value after deconvolution was 9.13, which proved that the image fidelity had been significantly improved.

In conclusion, this approach achieved a high resolution and high SNR with 200- μm -thick YAG. It is worth noting that this method effectively circumvents the conventional “efficiency–quality” trade-off. In other words, an

improvement in resolution does not result in a significant decrease in detection efficiency, which is a common challenge in the field. The computational overhead of our deconvolution algorithm is significantly lower than that of the hardware upgrade. Thus, it is a cost-effective solution for maximizing the performance of existing detectors. By using computational methods to enhance imaging quality, we can save substantial resources that might have been spent on upgrading hardware. In future work, we will use thinner scintillator films, such as GGG:Tb films with a depth of 4.3 μm [35], as control samples to further explore the performance of this method in 10 $\times$ magnification systems. This will help us to better understand the potential and limitations of our approach in different experimental and imaging scenarios.

4 Discussion

4.1 Effect of X-ray scattering on imaging

X-ray and electron scattering, and the DOF of optical amplification systems, may degrade the imaging resolution. X-ray scattering includes Rayleigh and Compton scattering. In YAG X-rays, Rayleigh scattering occurs within a small angle range, which reduces the imaging resolution. Compton scattering scatters X-ray photons with a large angular distribution and forms a background, which does not directly affect the image resolution. In the range of 10–50 keV, the Rayleigh scattering probability is very small, and Compton scattering accounts for a considerable proportion. The spectrum of the X-ray source used in the experiment contained a set of characteristic lines near 10 keV, as well as a broad continuum of background radiation that extended mainly from 10 to 30 keV. Thus, X-ray scattering could be ignored. As previously mentioned, electron scattering induces an extremely small image blur with a size of ~ 100 nm. Therefore, for a large-NA optical lens, the degradation of the fluorescent image resolution is mainly caused by optical defocusing, and the scattering mentioned above can be ignored to a certain degree.

4.2 Material adaptability and scintillator selection

Based on these research findings, relaxing the defect tolerance requirements facilitates the adoption of ultrathin scintillators (e.g., 4.3- μm -thick GGG:Tb in Ref. [35]), although the material diversity remains constrained. To address this, we propose a hybrid strategy: Standard imaging may employ process-compatible ultrathin conventional scintillators, whereas practical imaging can utilize scintillators with a high photon efficiency. The material differences lie only in the X-ray absorption rate,

luminescence efficiency, and refractive index. The influence of the X-ray absorption rate and luminescence efficiency of different materials is described by $k(z)$, and the entire process can be described by a generalized PSF. The refractive index must be considered for optical path changes such that the spherical aberration remains within a controllable range. The entire process can then be performed directly, regardless of material differences.

5 Conclusion

This study proved theoretically and experimentally that an image recovery method using a single PSF can be applied to a high-resolution X-ray scintillation imaging system with a high-NA lens. By integrating a measured-PSF-based deconvolution method with a high-NA optics design, we developed a high-resolution, high-SNR, indirect X-ray imager using an X-ray-tube-based system. The image details suppressed by the thick scintillator could be restored using this method. Combining the above two new technologies and an imaging system with a large-NA lens and thick scintillator plate, both high resolution and a high SNR were simultaneously achieved in the X-ray tube-based system. This study showed that our method does not require an ultrathin scintillator with a perfect surface for standard imaging, which greatly reduces the difficulty of the acquisition process. These results provide a critical pathway for overcoming the long-standing resolution–efficiency dilemma in indirect X-ray imaging based on X-ray tube sources or synchrotron radiation facilities.

Author Contributions All authors contributed to the study conception and design. Material preparation, data collection and analysis were performed by Hong-Quan Zhou, Yan-Qing Wu and Cheng-Qiang Zhao. The first draft of the manuscript was written by Hong-Quan Zhou, Yan-Qing Wu, and all authors commented on previous versions of the manuscript. All authors read and approved the final manuscript.

Data availability The data that support the findings of this study are openly available in Science Data Bank at <https://cstr.cn/31253.11.sciencedb.j00186.00804> and <https://www.doi.org/10.57760/sciencedb.j00186.00804>.

Declarations

Conflict of interest Ren-Zhong Tai is an editorial board member for Nuclear Science and Techniques and was not involved in the editorial review, or the decision to publish this article. All authors declare that there is no conflict of interest.

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