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

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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.

Full Text

Preamble

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 a lens with a large numerical aperture. This configuration provided sufficient photon flux while maintaining 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 and demonstrated its suitability for large-NA configurations; and (2) truncated PSF correction, which eliminated imaging artifacts caused by severe fabrication defects in ultrathin scintillators through PSF truncation, followed by resolution restoration using experimentally measured PSFs. 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

Introduction

Both direct and indirect imaging techniques are used for high-resolution X-ray detection. Direct imaging employs semiconductor materials such as CdZnTe to generate electrical signals via ionization effects, offering high sensitivity. However, the high cost of CdZnTe crystal growth and manufacturing limits its large-scale applications. Using current micro-nano fabrication 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 standard sCMOS cameras used in high-resolution indirect imaging systems. Despite challenges such as light scattering, 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 industrial and biomedical fields because of their high stability and low cost.

In the last decade, micrometer/submicrometer lens-coupled X-ray indirect imaging technology has advanced significantly. First, 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 light output and resolution. ZnO:In nanorod arrays suppress optical crosstalk via a pixelated design, combining sub-nanosecond decay time and high light yield ($>1 \times 10^4$ photons/MeV) to simultaneously enhance temporal and spatial resolution. Perovskites are excellent indirect imaging detectors because of their high carrier mobility and flexible processability. The $CsPbI_2Br/CsPbIBr_2$ film developed at Zhejiang University achieved a dark current of <1 nA/cm^2 and sensitivity of 2.6×10^4 $\mu C \cdot Gy^{-1} \cdot cm^{-2}$. The flexible Cs_4PbI_6 detector of NUAA demonstrated a sensitivity of 256.20 $\mu C \cdot Gy^{-1} \cdot cm^{-2}$ with 60-day stability, surpassing rigid detector limits. The structured CsI scintillation screen was further optimized, and its comprehensive performance was significantly improved. Second, image recorders have evolved from CCD to CMOS and sCMOS types, greatly improving sensitivity, dynamic range, and imaging speed. Third, 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, increasing 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 and their applications, 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 experiments). By integrating absorption, phase contrast, and fluorescence imaging with rapid algorithms, high-precision 3D reconstructions can be realized. 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.

Deep learning is widely used in optical imaging and has recently been introduced in direct-coupled indirect X-ray imaging fields to eliminate the influence of optical blurring under various conditions. For lens-coupled systems, we developed deep neural network-assisted high-spatial-frequency enhancement and reconstruction (DA-HSFER), an information optics-based innovation that addresses high-frequency information loss in X-ray microscopic imaging. 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 imaging performance. Specifically, the optical encoder employs specialized micro/nanostructural patterning on the scintillator surface to modulate visible light generated by X-ray excitation, encoding high-frequency details typically lost during conventional imaging. 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, significantly enhancing 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 image resolution.

However, in practical applications and further research and development, we must prioritize resolving the fundamental optical bottleneck arising from the contradiction between 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, 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 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 imaging accuracy and detection precision.

Experimental data show that as the CsI:Tl thickness increases from 100 μm to 500 μm, the absorption rate of 200 keV X-rays increases from 38% to 92%, while the modulation transfer function value at half maximum (MTF50) decreases from 4.2 lp/mm to 1.8 lp/mm. This contrasting thickness-performance relationship stems from two factors. First, the light yield increases with 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. However, although traditional thinning methods (e.g., laser cutting to 50 μm) improve spatial resolution, they also introduce high costs, instability, machining defects, and 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, where phase masks modulate 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. Studies on synchrotron-based indirect X-ray imaging have indicated that a pure-PSF method can restore images under parallel light conditions because fluorescence point distributions at different depths in the scintillator are sufficiently uniform. Reference [35] employed a generalized PSF function from 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 ignored some non-ideal factors such as crystal lattice deformation, which may lead to image deviations. To address this problem, we developed a PSF-based image restoration method. Using a Ce^{3+}-doped yttrium aluminum garnet (YAG) crystal as an example, we employed 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, direct measurement of the PSF for image restoration has long faced significant challenges because of limitations in experimental setups and material properties. In this study, the challenges included severe defects that degraded the reliability of the measured PSF, along with low photon efficiency in the thin YAG, which required long exposure times and induced sample drift. We utilized these defects as alignment markers and exploited differences in defect correlations between thick and thin scintillators to eliminate defect effects entirely. By combining this method with large-NA optics, we developed a microfocus X-ray imaging system in which both high-photon-flux and high-definition imaging were achieved.

Imaging Principle

An Extended PSF-Based Restoration Method for Addressing Depth-Related Challenges in Fluorescent Pattern Imaging

All 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 [Figure 1: see original paper]. The penetration depth of these photons in a yttrium aluminum garnet (YAG) crystal varied with photon energy, ranging from 100 µm to 200 µm. To ensure 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 [Figure 2: see original paper], where optical magnification $M = 5$, numerical aperture $NA = \sin \quad = 0.4$, absorption length $\Delta = 100$ µm, $d_1 \quad 10$ cm, d_2 10 cm, and $r \quad 1 \times 10^3$ µm. From these parameters, we obtained $\delta_1/r = \Delta/d_1$ and $\delta_2 = r - x$, where $x/r = d_2/(d_2 + \Delta)$. Therefore, image point shift $M \cdot \delta_1 = 2.5$ µm occurs due to X-ray geometric magnification, while another shift $M \cdot \delta_2 = 7.5$ µm results from the scintillator thickness. The edge portions of the image shift by 7.5 µm, or approximately one pixel (6.5 µm), for a 2 mm field of view (Fig. 2a). This error can be ignored at the present stage of research. In Fig. 2b, $NA = \sin \quad$, 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, with $s \quad = 2\Delta \tan \quad$. When $NA = 0.4$ and $\Delta = 100$ µm, $s \quad = 86$ µm. Assuming s is the size of one pixel (6.5 µm), then $s \quad /s = 13$. This means the PSF for fluorescent points varies greatly with depth z in the scintillator, a variation much greater than the variation in 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 downstream z-planes. The imaging process was modeled as shown in Eq. (1):

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

where * denotes 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 α • (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} results from the pattern at z not being in the center of the optical system.

When the field coverage angle for the X-ray source is much smaller than the angular acceptance of the optical system downstream—a condition usually satisfied by high-NA systems—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):

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

Therefore, a single PSF-based convolution is sufficient even under geometric magnification in our system. Imaging by a 20 µm-depth YAG crystal was chosen as the standard for experimental PSF measurement. By analyzing the modulation transfer function (MTF) for 20 µm and 200 µm scintillators, we derived Eq. (3):

$$\mathcal{F}\{PSF_{20}\} = \mathcal{F}\{PSF_{200}\} \cdot \frac{\mathcal{F}\{PSF_{20}\}}{\mathcal{F}\{PSF_{200}\}}.$$

Based on this analysis, we further defined the deconvolution kernel, PSF$_{20\ 200}$, using Eq. (4):

$$\mathcal{F}\{PSF_{20-200}\} = \frac{\mathcal{F}\{PSF_{Ii,20}\}}{\mathcal{F}\{PSF_{Ii,200}\}}.$$

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

Optical System Design for High-Resolution Imaging with Thick Scintillator and High-NA Lens

The microscope contained two lenses with optical magnifications of 5× and 10× and NAs of 0.4 and 0.9, respectively. The camera pixel size was 6.5 µm. As previously mentioned, we employed a thick scintillator to convert 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 reduction of various aberrations under conditions of 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, thereby obtaining images with both high photon efficiency and high definition.

X-rays can degrade optical lenses over time, 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 the filter thickness is not considered during commercial lens design, thereby reducing imaging resolution. Hence, there is a need to develop dedicated, long working distance, 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 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 mmpb (0.33 mmpb 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 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 extended to 0 to 300 µm, and that for the 10× lens extended to 0 to

100 µm. Figures 3a and 3b show 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 high photon collection efficiency while effectively blocking X-rays from damaging optical components and the CCD camera, thereby extending equipment lifespan. 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 [Figure 3: see original paper], for a 5× lens at a spatial frequency of 384 lp/mm (corresponding to two imaging pixels, 2 × 1.3 µm), contrast decreased to zero when the defocus distance was $\$\pm 5.5m(Fig.3e),providingaDOFofapproximately11m.Similarly,theDOFforthe10\times\$$ 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. Fluorescence images within the top 11 µm had actual resolution exceeding the pixel resolution of the camera (384 lp/mm, 2-pixel criterion), whereas in deeper regions, resolution 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. Optical DOF, X-rays, and electron scattering may all degrade imaging resolution. In a YAG crystal, electron scattering has a mean free path of 100 nm for secondary electrons, which is too small to induce significant image blur. Therefore, image resolution degradation 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 resolution (as discussed later).

Experiments, Results, and Analysis

Experiments

The experimental setup is shown in Fig. 4 [Figure 4: see original paper], consisting 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) with a 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 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:Ce^{3+} 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 optimal focus positions for the two YAG scintillators with different thicknesses, we used a displacement stage with a step size of 1 µm to scan samples axially. This process required precise mechanical adjustments and repeated verification of the focal position to ensure optimal imaging quality. After locating the best focal plane, each sample and its corresponding background were imaged ten times to enhance data reliability and stability. LabVIEW software controlled the CCD for synchronized data acquisition and storage. Raw data were then imported into MATLAB for averaging to reduce noise and highlight true sample features. Background subtraction was also performed to eliminate interference from YAG surface defects and system noise, clarifying sample details. These rigorous experimental steps and data processing methods ensured acquisition of high-quality image data for subsequent analyses.

The image on the 20 µm-thick YAG scintillator film had 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 sample and background images was crucial to avoid information bias and ensure reliable analysis. As shown in Figs. 5a and 5b, 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 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, eventually eliminating 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 Figs. 5c and 5d, when comparing 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 image quality, inherent defects in thinner YAG scintillator films may still interfere with imaging results. These defects likely stem from material properties or unavoidable factors in the fabrication process.

Data Analysis

As shown in Figs. 6a and 6b, $\mathrm{PSF}_{20\ 200}$ 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 the 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):

$$F_{20} = F \cdot M_{20} + G_{20},$$

$$F_{200} = F \cdot M_{200} + G_{200}.$$

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):

$$MTF_{measured} = MTF_{real} \cdot \left(1 - \frac{G_{20}}{F \cdot M_{20}}\right) = MTF_{real} \cdot \left(1 + \frac{G_{20}}{F \cdot M_{20}}\right)^{-1}.$$

In the spatial domain, the second term, $G_{20}/(F \cdot M_{20})$, corresponds to psf , where psf is the pseudo-impulse response contributed by point-like defects attached to the real-image PSF. This additional psf has 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 frequency-domain pollution caused by PSF truncation, the truncation boundary needed to be far from the center. Therefore, a central region (60 pixels × 60 pixels) containing almost all 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 truncated PSF was much better. Details were clearer and sharper, edges were more distinct, overall image quality was significantly improved, and defect influence was fully eliminated. This showed that the truncated PSF method used in this study effectively removes the influence of sparsely distributed sharp defects while keeping image details intact.

Figs. 7a and 7b present deconvolution results from zebrafish images captured using a 200 μm YAG indirect imaging system with the extracted central PSF region. Fig. 7a [Figure 7: see original paper] shows the original zebrafish image after background subtraction. The basic outline and shape of the zebrafish are discernible, but details are obscured by background noise, resulting in a blurry image. Fig. 7b presents the deconvolved image. Visually, 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 image contrast and resolution.

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 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 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 traditional subtraction methods, this approach removes background by dividing image pixel values by estimated background signal values. In zebrafish images, this method preserved crucial details such as fine surface textures and weak internal fluorescence signals that 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 deeper understanding of specimen structures and properties.

PSD analysis (Figs. 7c and 7d) clearly showed that deconvolution significantly boosted high-frequency detail recovery. The 1D PSD (Fig. 7e) indicated 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, 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 SNR in the highest frequency band and further optimize 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 low transmitted beam intensity from the 4W X-ray source resulted in severely degraded image contrast, making it impossible to determine the optimal focal position by adjusting focus settings based on observed image quality.

To verify the fidelity advantage of this method based on the real measured PSF, the perception-based image quality evaluator (PIQE) method was adopted to determine image fidelity. A lower PIQE score implies better fidelity. For the image of resolution targets on the 200 µm-thick YAG, the PIQE value was 63.2, while the PIQE value after deconvolution was 48.9, showing obvious improvement. The value for the 20 µm-thick YAG plate was 75.4 because of serious defects. When imaging fish samples with the 200 µm YAG, the PIQE value was 14.0, and the PIQE value after deconvolution was 9.13, proving that image fidelity had been significantly improved.

In conclusion, this approach achieved high resolution and high SNR with 200 µm-thick YAG. Notably, this method effectively circumvents the conventional "efficiency-quality" trade-off, where improvement in resolution does not result in significant decrease in detection efficiency—a common challenge in the field. The computational overhead of our deconvolution algorithm is significantly lower than that of hardware upgrades, making it a cost-effective solution for maximizing 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, as control samples to further explore the performance of this method in 10× magnification systems. This will help us better understand the potential and limitations of our approach in different experimental and imaging scenarios.

Discussion

Effect of X-Ray Scattering on Imaging

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

Material Adaptability and Scintillator Selection

Based on these research findings, relaxing defect tolerance requirements facilitates adoption of ultrathin scintillators (e.g., 4.3 µm-thick GGG:Tb), although 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 high photon efficiency. Material differences lie only in X-ray absorption rate, luminescence efficiency, and refractive index. The influence of 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 spherical aberration remains within a controllable range. The entire process can then be performed directly, regardless of material differences.

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 high-NA optics design, we developed a high-resolution, high-SNR, indirect X-ray imager using an X-ray-tube-based system. Image details suppressed by the thick scintillator could be restored using this method. Combining these two new technologies with an imaging system featuring a large-NA lens and thick scintillator plate, both high resolution and 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 acquisition difficulty. 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.

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Note: Figure translations are in progress. See original paper for figures.