

An Approach to break 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 incorporating a thick scintillator plate and a large numerical aperture (NA) lens. This configuration provides sufficient photon flux while maintaining theoretical high spatial resolution, thereby reducing the core challenge to resolving the defocusing issue induced by the thick scintillator and approaching the theoretical resolution limit. Two key techniques were developed: (1) Generalized PSF restoration: Extending the single PSF recovery method to geometrically magnified X-ray imaging systems, demonstrating its particular suitability for large NA configurations. (2) Truncated PSF correction: Eliminating imaging artifacts caused by severe fabrication defects in ultra-thin scintillators through PSF truncation, followed by resolution restoration using experimentally measured PSFs. The experimental results show that in the high frequency range, power spectral density is improved by up to one order of magnitude for the image on the thick scintillator. High resolution and high 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 X-ray indirect imaging based on X-ray tube source or synchrotron radiation facility.

Full Text

Preamble

An Approach to Break the Resolution-Efficiency Trade-off in X-Ray Scintillator Imaging

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To address the well-known “resolution-photon efficiency” trade-off, we developed a lens-coupled X-ray tube-based indirect imaging system incorporating a thick scintillator plate and a large numerical aperture (NA) lens. This configuration provides sufficient photon flux while maintaining theoretical high spatial resolution, thereby reducing the core challenge to resolving the defocusing issue induced by the thick scintillator and approaching the theoretical resolution limit. Two key techniques were developed: (1) **Generalized PSF restoration**: Extending the single PSF recovery method to geometrically magnified X-ray imaging systems, demonstrating its particular suitability for large NA configurations. (2) **Truncated PSF correction**: Eliminating imaging artifacts caused by severe fabrication defects in ultra-thin scintillators through PSF truncation, followed by resolution restoration using experimentally measured PSFs. The experimental results show that in the high frequency range, power spectral density is improved by up to 8.45 times for the image on the thick scintillator. High image quality and high 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 X-ray indirect imaging based on X-ray tube sources or synchrotron radiation facilities.

Keywords: Scintillator, X-ray imaging, indirect imaging

Introduction

High-resolution X-ray detection includes direct and indirect imaging techniques [?]. Direct imaging uses 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 application. Using current micro-nano fabrication processes, direct imaging’s pixel size can be reduced to 20 μm , yet it’s still larger than the 6.5 μm pixels of standard sCMOS cameras in high-resolution indirect imaging systems. Despite challenges such as light scattering [?], secondary electron scattering, and fluorescence field depths exceeding the optical system’s depth of field (DOF), the resolution of X-ray indirect imaging is still higher than that of direct imaging systems. Therefore, high-resolution indirect imaging systems are still widely

used in synchrotron radiation imaging stations, industrial, and biomedical fields, also due to their high stability and low cost [?].

In the last decade, micrometer/submicrometer lens-coupled X-ray indirect imaging technology has advanced significantly: (1) Detector performance has been enhanced by optimizing scintillator screen materials and thickness, with new scintillators like LuAG:Ce and GAGG:Ce boosting light output and resolution [?, ?]. The ZnO:In nanorod arrays suppress optical crosstalk via pixelated design, combining sub-nanosecond decay time and high light yield ($>1 \times 10^4$ photons/MeV), achieving simultaneous enhancement of both temporal and spatial resolution [?, ?]. Perovskites excel in indirect imaging detectors due to high carrier mobility and flexible processability. Zhejiang University's CsPbI₂Br/CsPbIBr₂ film achieves dark current <1 nA/cm² and sensitivity of 2.6×10^4 pC · Gy⁻¹ · cm⁻² [?]. NUAA's flexible Cs₄PbI₆ detector demonstrates 256.20 pC · Gy⁻¹ · cm⁻² sensitivity with 60-day stability, surpassing rigid detector limits [?]. The structured CsI scintillation screen was further optimized and the comprehensive performance has been significantly improved [?]. (2) Image recorders have evolved from CCD to CMOS and sCMOS types, greatly improving sensitivity, dynamic range, and imaging speed. (3) Optical lens systems have also been developed. ZEISS Xradia series employs a two-stage magnification architecture, achieving submicron resolution (RaaD technology) while maintaining a large working distance (>10 mm). Optical lens structures have also been innovated, with designs like large-NA and long-working-distance lenses [?, ?], increasing light coupling efficiency and resolution. This technology now has broad applications in X-ray micro-CT imaging, materials science, and medical imaging. When combined with synchrotron radiation sources, it can perform 3D micro-nano structural reconstruction and dynamic observation.

The Shanghai Synchrotron Radiation Facility (SSRF) has been instrumental in this technological progress. High-performance beamlines provide high-brightness, highly collimated X-rays for various X-ray imaging methods [?] and their applications [?, ?], especially for micrometer/submicrometer-resolution X-ray indirect imaging. Over the past decade, the hard X-ray imaging beamline at 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/fluorescence imaging with rapid algorithms, high-precision 3D reconstruction has been realized [?, ?]. Furthermore, multimodal approaches such as fluorescence/dynamic/diffraction CT have been implemented, with dynamic CT capturing real-time microscopic evolution in living insects [?].

Deep learning has been widely used in the optical imaging field. In recent years, it has also been introduced into direct-coupled X-ray indirect imaging field, such as eliminating the influence of optical blurring under various conditions [?, ?]. For lens-coupled systems we developed DA-HSFER (Deep Neural Network-Assisted High Spatial Frequency Enhancement and Reconstruction), an information optics-based innovation addressing 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: the encoder converts X-ray-induced high-frequency fluorescence signals into low-frequency signals transmittable through the scintillator-air interface, while the deep learning model reconstructs high-frequency details from 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-nano structural patterning on the scintillator surface to modulate 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 CNN-Transformer models) to accurately restore high-frequency information, resulting in significantly enhanced image detail fidelity. This technology overcomes the limitations of traditional indirect X-ray imaging, where the high refractive index of scintillators restricts the optical system's bandwidth 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 the depth of field (DOF) of optical systems, which causes defocus blur and has surpassed the impact of high-order aberrations and high-frequency information loss induced by internal reflections in scintillators. Imaging depth, referring to the longitudinal distribution of fluorescence patterns generated by X-ray penetration within scintillators (typically on the scale of hundreds of micrometers or more), often leads to blurred features in regions of samples distant from the focal plane in high-numerical-aperture (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, and in industrial inspections of multilayered electronic components, where defocus blur significantly degrades imaging accuracy and detection precision.

Experimental data shows that as CsI:Tl thickness increases from 100 μm to 500 μm , the absorption rate of 200 keV X-ray rises 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 contrary thickness-performance relationship stems from two factors: firstly, the light yield (LY) increases with the X-ray excitation depth in the scintillator; secondly, 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, traditional thinning methods (e.g., laser cutting to 50 μm), though improving spatial resolution, introduce high costs, instability, machining defects, and low photon yield in thin scintillators, creating an “efficiency-quality-reliability” trilemma. Consequently, this study will overcome the optical bottleneck through the synergistic integra-

tion of optimized optical structural designs and novel image restoration methods, thereby advancing the development and application of micron/submicron-scale X-ray indirect imaging technologies.

For general optical imaging DOF issues, wavefront coding has been employed [?], in which phase masks modulate wavefronts to maintain consistent PSFs across the whole DOF, followed by PSF deconvolution for image recovery. However, the phase plate in this technology is wavelength-sensitive, which introduces design, manufacturing, or computational complexities when applied to broad-spectrum light sources [?]. Further study on synchrotron-based X-ray indirect imaging [?] indicates that by a pure-PSF-method images can be restored under parallel light conditions because fluorescence point distributions at different depths in the scintillator are sufficiently uniform. In Ref. [?] a generalized PSF function from simulation was employed, which is overly idealized.

Our work theoretically extends this method to non-parallel geometric magnification configurations commonly used in systems based on X-ray tubes, and often employed in imaging stations on synchrotron radiation facilities, especially with large numerical aperture (NA). Crucially, prior simulations [?] ignore some non-ideal factors, e.g. crystal lattice deformation, which may lead to deviations in images. To address this, we established a measured PSF-based image restoration method. Taking Ce^{3+} doped Yttrium Aluminum Garnet (YAG) crystal as an example, we used 20 μm -thin YAG crystal film, with depth close to the optical system's DOF, as a control group. By deconvolving 200 μm -thick YAG imaging results with the control group, we extracted the actual PSF and restored high-resolution imaging.

In X-ray indirect imaging, direct measurement of the PSF for image restoration has long faced significant challenges due to limitations in experimental setups and material properties [?]. In this study the challenges included severe defects, severely degrading the measured PSF's reliability, and low photon efficiency in the thin YAG, requiring long exposure time that induced sample drift. We utilized these defects as alignment markers and exploited differences in defect correlations between thick and thin scintillators to entirely eliminate the effect of the defects.

Combining this method with large NA optics, a micro-focus X-ray imaging system has been developed, in which both high-photon-flux and high-definition imaging were achieved. The image spot of the fluorescent object point at the absorption depth (Δ) in the scintillator is $s = 2\Delta \tan \theta$. When $\text{NA} = 0.4$ and $\Delta = 100 \mu\text{m}$, $s = 86 \mu\text{m}$. Assuming s is one pixel size, $6.5 \mu\text{m}$, then $s/\Delta = 13$ times. This means that the PSF function for the fluorescent points varies greatly with the depth z in the scintillator, which is much greater than the variation of the overall light intensity distribution on the imaging surface (Fig. 2a [Figure 2: see original paper]), so the image distribution can be looked as with different depth in scintillator in this study.

Imaging Principle

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

All the study was conducted on a microscope-coupled high-resolution indirect X-ray imaging system. A tungsten-target X-ray source is employed, operated at an accelerating voltage of 50 kV, producing X-ray photons with energies predominantly in the 10 keV to 30 keV range as shown in Fig. 1 [Figure 1: see original paper].

The penetration depth of these photons in a YAG (yttrium aluminum garnet) crystal varies with photon energy, ranging from 100 μm to 200 μm . To ensure maximum absorption of X-ray photons, a 200-micrometer-thick Ce:YAG scintillator is utilized for indirect X-ray imaging.

The error analysis of the optical imaging system is shown in Fig. 2, where optical magnification $M=5$, Numerical aperture $NA = \sin \theta = 0.4$, Absorption length $\Delta = 100 \mu\text{m}$, and $d_1 = 10 \text{ cm}$, $d_2 = 10 \text{ cm}$, $r = 1 \times 10^3 \mu\text{m}$. Then we obtain $\delta_1/r = \Delta/d_1$, $\delta_2 = r - x$, $x/r = d_2/(d_2 + \Delta)$. Therefore the image point shifts $M \cdot \delta_1 = 2.5 \mu\text{m}$ due to X-ray geometric magnification and the other shift $M \cdot \delta_2 = 7.5 \mu\text{m}$ due to the thickness of the scintillator. The edge parts of the image shift 7.5 μm , about 1 pixel (6.5 μm), for a 2 mm field of view (Fig. 2a). This error can be ignored in the present stage of research. In Fig. 2b, the numerical aperture $NA = \sin \theta$, where s is the imaging point size of the fluorescent object at the front surface of the scintillator. s represents the size of the defocused image spot of the fluorescent object point at absorption depth Δ in the scintillator.

Under the estimation above, fluorescent patterns at different depths along the optical axis (z direction) exhibit geometrically similar spatial distributions, and the finite thickness (Δz) of the scintillator leads to multi-focal superposition (defocusing) and causes a considerable amount of X-ray scattering from the z -planes downstream. Then the imaging process is modeled as shown in Eq. (1):

$$I_i(x, y) = \int k(z) I_g(\alpha \cdot (z + z_0) \cdot x, \alpha \cdot (z + z_0) \cdot y) * PSF(x, y, z) dz$$

Here, $*$ 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; $\alpha \cdot (z + z_0)$ is the geometric magnification. The PSF combines internal photon diffusion (PSF_{internal}) and optical system effects (PSF_{optical}). PSF_{internal} is contributed by X-ray scattering; PSF_{optical} is caused by the pattern at z not being in the center of the optical system's focal plane.

When the field coverage angle for the X-ray source is much less than angular acceptance of the optical system downstream, which is usually satisfied by a

high NA system, the I_g varies much less than PSF in the integral above. In our system, the two angles are about 1.8° and 31° , respectively. Thus we can get Eq. (2):

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

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

The imaging by a 20 μm -depth YAG crystal was chosen as the standard for the experimental PSF measurement. By analyzing the modulation transfer function (MTF) for 20 μm and 200 μm scintillators, we derived Eq. (3):

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

Based on this analysis, we further define the deconvolution kernel $PSF_{\{20-200\}}$ as Eq. (4):

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

Applying $PSF_{\{20-200\}}$ to 200 μm -thick YAG imaging restores high-frequency details while retaining high photon efficiency. As shown below, the defects in thin and thick YAG are uncorrelated, and they can be suppressed via PSF truncation.

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

In the microscope there are two lenses with optical magnifications of $5\times$ and $10\times$, with numerical apertures of 0.4 and 0.9, respectively. The camera pixel size is 6.5 μm . As mentioned above, we employed a thick scintillator to convert X-ray patterns into visible light. To capture more photon flux and achieve high diffraction-limited resolution, a high numerical aperture (NA) optical microscope lens is utilized. The optical system's depth of field is not particularly restricted, allowing for the reduction of various aberrations under conditions of high NA, thick scintillator, and suitable working distance. To resolve depth-dependent fluorescence field distortions in thick scintillators, a PSF-based restoration method was adopted, using thin scintillator-derived high-resolution images as reference standards. Therefore, both high photon efficiency and high-definition image were achieved.

X-ray radiation can degrade optical lenses over time, reducing optical efficiency. A conventional solution involves installing a lead glass filter at the front of

the lens to protect the subsequent optics. However, conventional high-NA microscope lenses, especially those with $NA=0.9$, have short working distances (typically around 0.5 mm). Although Nikon offers an $NA=0.9$ lens with a working distance up to 2 mm, installing a lead glass filter directly would significantly impact axial aberrations such as spherical and chromatic aberrations due to the lack of consideration for the filter's thickness during commercial lens design, thereby reducing imaging resolution. Hence, there is a need to develop dedicated long working distance, high-NA microscope lenses that accommodate lead glass.

To meet these requirements, we have designed and developed two long working distance microscope lenses with $5\times$ and $10\times$ magnifications, both having a conjugate distance of 500 mm and NA values of 0.4 and 0.9, respectively. Both lenses exceed 40% modulation transfer function (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), is installed between the lens and the scintillator. Additionally, the impact 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 show that, with an MTF decrease to 30% as the criterion, the $5\times$ lens can accommodate scintillator thicknesses ranging from 0 to 210 μm without adjusting the back focal distance, while the $10\times$ lens can only accommodate 45 to 55 μm . With adjustable back focal distance, the range for the $5\times$ lens extends to 0 to 300 μm , and for the $10\times$ lens, it extends to 0 to 100 μm . Fig. 3a [Figure 3: see original paper],b show the optical layouts of two lenses and their corresponding MTF curves.

To further protect the CCD/sCMOS camera, a mirror is added between the lens and the camera, redirecting the overall optical path by 90 degrees. These designs ensure high photon collection efficiency while effectively blocking X-rays from damaging optical components and the CCD camera, thereby extending the equipment's lifespan. The high numerical aperture enables the system to theoretically achieve pixel-level resolution; however, this comes at the cost of a shorter depth of field (DOF).

As shown in Fig. 3e, for the $5\times$ lens, at a spatial frequency of 384 lp/mm (corresponding to 2 imaging pixels, $2\times 1.3\text{ }\mu\text{m}$), the contrast drops to 0 when the defocus distance is $\pm 5.5\text{ m}$ (Fig. 3e), giving a DOF of about 11 m. Similarly, the DOF for the $10\times$ system is approximately 3.5 μm for the spatial frequency of 384 lp/mm (Fig. 3f).

The thinnest scintillator foil currently obtained measures 20 μm in thickness. This means that fluorescence images within the top 11 μm depth exhibit actual resolution exceeding the camera's pixel resolution (384 lp/mm, 2-pixel criterion), while images from deeper regions fall below this threshold. Nevertheless, the images on the YAG foils with 20 μm thickness were employed as standard images for the PSF-based recovery method. In cooperation with the high-NA

lenses, a new recovery method was proposed in this paper to overcome the DOF and scintillator thickness contradiction and achieve high resolution and high-definition imaging.

Optical DOF, X-ray and electron scattering may all degrade imaging resolution. In YAG crystals, electron scattering has a mean free path of 100 nm for secondary electrons, too small to induce considerable image blur. Therefore, the degradation of image resolution is mainly caused by optical defocusing, and all the scattering above can be ignored to a certain degree.

III. Experiments, Results, and Analysis

A. Experiments

The experimental setup, shown in Fig. 4 [Figure 4: see original paper], consists of an X-ray tube-based source, a scintillator conversion layer, and a high-NA visible-light microscope.

For high-definition imaging, a micro-focus X-ray source (Hamamatsu L10101, tungsten target) was employed. It has 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 is 5 μm . Here the X-ray source was operated at 50 kV accelerating voltage to achieve a small source spot size. In future work, higher accelerating voltages will be utilized for imaging with thick scintillators for higher photon flux. With a $5\times$ lens and a sCMOS camera with a pixel size of 6.5 μm , a pixel resolution of 1.3 μm can be obtained. YAG:Ce³⁺ crystal films were used as the material to convert X-rays into visible light, with high luminous efficiency in the 500-600 nm wavelength range.

In the experiment, a fixed visible light imaging system is used, and the scintillator plate position can be finely adjusted for focusing. To accurately determine the optimal focus positions for the two YAG scintillators of different thicknesses, we used a displacement stage to scan the samples axially with a step size of 1 μm . This process required precise mechanical adjustments and repeated verification of the focus position to ensure optimal imaging quality. After locating the best focal plane, each sample and its corresponding background were imaged 10 times to enhance 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 noise and highlight the samples' true features. Background subtraction was also performed to eliminate interference from YAG surface defects and system noise, making the samples' details clearer. These rigorous experimental steps and data processing methods ensured the acquisition of high-quality image data for subsequent analysis.

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

As shown in Fig. 5a [Figure 5: see original paper] and 5b, the SIFT (Scale-Invariant Feature Transform) algorithm, known for its noise-resistance in image feature matching, was used. SIFT, widely used for image registration due to its stability and reliability, identifies feature points by recognizing distinct image features. In this study, the unique contours, positions, and higher intensity of defect features made them suitable reference points for registration. Weaker image information was treated as noise and ignored. Image alignment is performed by SIFT feature point matching and some obviously incorrect matches are manually excluded, which eventually eliminates the influence of image drift on the imaging.

Background subtraction, which involves subtracting the background image from the sample image, is feasible due to 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 details. As shown in Fig. 5c and 5d, 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 image quality, the inherent defects in thinner YAG scintillator films may still interfere with imaging results. These defects likely stem from the material's properties or unavoidable factors in the fabrication process.

B. Data Analysis

As shown in Fig. 6a [Figure 6: see original paper], $\text{PSF}_{20\ 200}$ was yielded 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, with the number of iterations limited to 8. The whole structure, a Gaussian-like peak 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) that were not completely removed during the background removal process. The description of the imaging process in the frequency domain is like Eq. (5) and Eq. (6):

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

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

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

$$M_{200} \approx M_{200} \cdot \left(1 - \frac{G_{20}}{F \cdot M_{20}}\right) \cdot \left(1 + \frac{G_{20}}{F \cdot M_{20}}\right)$$

In the spatial domain, the second item G_{20} corresponds to psf^* , where the psf^* is the pseudo-impulse response contributed by the point-like defects, attached to the real image PSF. This additional psf^* has a small total power, a wide distribution and a small amplitude in the central region, relatively larger in the outer range. Therefore, in principle PSF truncation can remove the influence of defects on standard image (on the 20 μm -thick YAG plate). Furthermore, the blurred image spot on the 200 μm -thick YAG is about 13 pixels, thus the truncation boundary must be chosen much larger than 13 pixels. On the other hand, to reduce the frequency-domain pollution brought by PSF truncation, the truncation boundary should be far from the center. Therefore, the central region (60-pixel $\times$ 60-pixel) containing almost all these characteristics was finally selected.

Compared with the image (Fig. 6c2) on the 20 μm thick YAG film, the image (Fig. 6c1) deconvolved from the resolution target image on the 200 μm -thick YAG using the above-mentioned truncated PSF is much better. The details are clearer and sharper, edges are more distinct, and the overall image quality is significantly improved, and the influence of defects has been fully eliminated. This shows that the truncated PSF method used in this work is good at removing the influence of these sparsely distributed sharp defects while keeping image details intact.

Fig. 7 Figure 7: see original paper presents deconvolution results from zebrafish specimen images captured using a 200 μm YAG indirect imaging system, utilizing the extracted central PSF region. Fig. 7(a) shows the original zebrafish image after background subtraction. The zebrafish's basic outline and shape are discernible, but details are obscured by background noise, resulting in a blurry image. Fig. 7(b) reveals the deconvolved image. Visually, the processed image shows remarkable improvements, with enhanced clarity and sharper details in the zebrafish's scales and fins. This indicates that deconvolution effectively reduces blur and boosts image contrast and resolution.

It's 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 higher photon count associated with thicker scintillators mean that these defects do not significantly interfere with key imaging features. In contrast, defects like surface scratches and internal bubbles in the 20 μm YAG control group are theoretically more detrimental. However, after PSF function truncation, their impact is effectively controlled, and high-frequency information enhancement remains largely unaffected.

Regarding specimens with complex details, low intrinsic contrast, and weak visible-light signals (e.g., zebrafish specimens), we used division-based back-

ground subtraction. Unlike traditional subtraction methods, this approach removes the background by dividing the image pixel values by the estimated background signal values. In zebrafish specimen images, this method preserves crucial details like fine surface textures and weak internal fluorescence signals that might be lost with traditional subtraction. It prevents issues like excessive contrast and detail loss during background correction, providing richer and more accurate visual information for subsequent image analysis and facilitating a deeper understanding of specimen structures and properties.

PSD analysis (Fig. 7c1,c2) clearly shows that deconvolution significantly boosts image high-frequency detail recovery. The 1D PSD (Fig. 7d) indicates a significant SNR improvement in the high-frequency range (up to 8.45 times), with no low-frequency information loss. This confirms the effectiveness of the deconvolution method based on a generalized PSF function in improving image quality. However, the SNR in the high-frequency region didn't improve as expected. This is likely because the 20 μm -thick ultra-thin scintillator used exceeded the imaging lens' s depth of field (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 the low transmitted beam intensity from the 4W X-ray source results in severely degraded image contrast. This makes 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, owing to the real PSF measured, the PIQE (Perception based Image Quality Evaluator) method is adopted to judge the image fidelity. A lower score in the PIQE method implies better fidelity. The results are given below.

For the image of the pair resolution target on the 200 μm -thick YAG, the PIQE value is 63.2, and the PIQE value 48.9 for the image after deconvolution, which shows obvious improvement. And the value 75.4 for that on the 20 μm -thick YAG plate because of the serious defects. For the imaging results of fish samples with 200 μm YAG, the PIQE value was 14.0, and the PIQE value after deconvolution was 9.13, which proves that the image fidelity has been significantly improved.

In conclusion, this approach achieves high resolution and high SNR with 200 μm -thick YAG. It' s worth noting that this method effectively circumvents the conventional "efficiency-quality" trade-off. In other words, the improvement in resolution does not come at the cost of a significant drop in detection efficiency, which is a common challenge in the field.

The computational overhead of our deconvolution algorithm is significantly lower than the cost of hardware upgrade. This makes it a cost-effective solution to maximize existing detector performance. 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 film, e.g., GGG:Tb film with 4.3 μm in depth [?], as control samples to further explore method performance in $10\times$ magnification systems. This will help us better understand the potential and limitations of our approach in different experimental setups and imaging scenarios.

IV. Discussion

A. Effect of X-Ray Scattering on Imaging

X-ray and electron scattering, depth of field of optical amplification systems may all degrade imaging resolution. X-ray scattering contains Rayleigh scattering and Compton scattering. In YAG, X-ray Rayleigh scattering occurs within a small angle range, which reduces imaging resolution; Compton scattering scatters X photons with a large angular distribution and then forms a background, which does not directly affect image resolution. In the range of 10 keV to 50 keV, the Rayleigh scattering probability is very small, and Compton scattering has a considerable proportion. For the X-ray source in the experiment, its spectrum contains a set of characteristic lines near 10 keV, and a broad continuum background radiation that extends mainly from 10 keV to 30 keV, thus X-ray scattering can be ignored. As mentioned above, electron scattering induces a very small image blur with 100 nm in size. Therefore, for the large NA optical lens, the degradation of fluorescent image resolution is mainly caused by optical defocusing and all the scattering above can be ignored to a certain degree.

B. Material Adaptability and Scintillator Selection

Based on the research findings, relaxing defect tolerance requirements facilitates the adoption of ultrathin scintillators (e.g., 4.3 μm -thick GGG:Tb in Ref. [?]), though material diversity remains constrained. To address this, we propose a hybrid strategy: standard imaging may employ process-compatible ultrathin conventional scintillators, while practical imaging could utilize scintillators with high photon efficiency. The 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 still be described by generalized PSF. The refractive index is required to be considered for the optical path changes, such that the spherical aberration remains within a controllable range. Then, the whole process can be directly performed, regardless of the material difference.

V. Conclusion

Theoretically and experimentally proved that the image recovery method using a single PSF can be applied for high-resolution X-ray scintillation imaging sys-

tem with high-NA lens. By integrating a measured-PSF-based deconvolution method with high-NA optics design, we have developed a high-resolution, high-SNR X-ray indirect imager based on an X-ray tube system. The image details, suppressed by a thick scintillator, have been restored by this method. Combined with the above two new technologies and the imaging system with large NA lens and thick scintillator plate, both high resolution and high SNR have been simultaneously achieved in a X-ray tube-based system. This study shows that our method does not require a perfect surface of ultra-thin scintillator for standard imaging, greatly reducing acquisition process difficulty. These results provide a critical pathway for overcoming the long-standing resolution-efficiency dilemma in X-ray indirect imaging, based on X-ray tube sources or synchrotron radiation facilities.

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