An Approach to break the Resolution-Efficiency Trade-off in Thick 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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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 sources or synchrotron radiation facilities.

Keywords: Scintillator, X-ray imaging, Indirect imaging

1. 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 remains 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 [?].

The global micron/submicron X-ray microscopy market remains highly concentrated among international manufacturers like ZEISS Group, which dominates China' s high-end market through its two-stage amplification technology, high-flux sources, and intelligent software ecosystems. While domestic players such as SanYing Precision have achieved breakthroughs in industrial inspection via proprietary algorithms (e.g., real-time 3D reconstruction) and nanometer-level motion control platforms, their core imaging technologies (e.g., resolution limits, SNR optimization) still lag behind, resulting in limited market share. In terms of hardware-software synergy, ZEISS excels in full-process automation and machine learning-driven optimization, whereas the CT system from Sanying Precision is equipped with a digital image reconstruction and analysis software, Digital-PorousMedia.

In the last decade, micrometer/submicrometer lens-coupled X-ray indirect imaging technology has advanced significantly. First, 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 (>10,000 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 $CsPbI_2Br/CsPbIBr_2$ film achieves dark current $<1\ nA \cdot cm^{-2}$ and sensitivity of $2.6 \times 10^4\ \ C \cdot Gy^{-1} \cdot cm^{-2}$ [?]. NUAA' s flexible Cs_4PbI_6 detector demonstrates $256.20\ \ C \cdot Gy^{-1} \cdot cm^{-2}$ sensitivity with 60-day stability, surpassing rigid detector limits [?]. 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 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. Its 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 [?]-[?]. The BL13W1 beamline is equipped with in-line phase contrast imaging (IL-PCI) and a multi-scale detector, enabling non-destructive dynamic analysis of soft tissues [?]. Phase-sensitive imaging techniques (e.g., interferometry, analyzer-based, and grating-based methods) have been developed to extract phase information through algorithms and integrate 3D CT modalities, resolving complex sample structures [?]. Furthermore, multimodal approaches such as fluorescence/dynamic/diffraction CT have been implemented, with dynamic CT capturing real-time microscopic evolution in living insects [?].

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 integration 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 times 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-resolution and high-SNR imaging were achieved.

2. Imaging Principle

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

All studies were 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. 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 YAG scintillator is utilized for indirect X-ray imaging.

Under the estimation above, fluorescent patterns at different depths along the optical axis (z-direction) exhibit geometrically similar spatial distributions, and the finite thickness of the scintillator leads to multi-focal superposition (defocusing) and causes considerable X-ray scattering from the z-planes downstream. The imaging process is modeled through convolution operations where the PSF combines internal photon diffusion, optical system effects, and contributions from X-ray scattering. When the Field Coverage Angle for the X-ray source is much less than the Angular Acceptance of the downstream optical system, which is usually satisfied by a high NA system, the depth-dependent variation is minimal in the integral. In our system, the two angles are about 1.8° and 31°, respectively. 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 experimental PSF measurement. By analyzing the modulation transfer function (MTF) for 20 μm and 200 μm scintillators, we derived the relationship between them. Based on this analysis, we further define the deconvolution kernel for the 20-200 μm transition. Applying this kernel to 200 μm-thick YAG imaging restores high-frequency details while retaining high photon efficiency. As shown below, since defects in thin and thick YAG are uncorrelated, they can be suppressed via PSF truncation.

(2) 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× and 10×, with numerical apertures of 0.4 and 0.9, respectively. The camera pixel size is 6.5 m. 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 resolution 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× and 10× 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 m. 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 m-thick scintillator.

Simulations show that, with an MTF decrease to 30% as the criterion, the 5× lens can accommodate scintillator thicknesses ranging from 0 to 210 m without adjusting the back focal distance, while the 10× lens can only accommodate 45 to 55 m. With adjustable back focal distance, the range for the 5× lens extends to 0 to 300 m, and for the 10× lens, it extends to 0 to 100 m.

[Figure 1: see original paper] shows the optical layouts of two lenses and their corresponding MTF curves.

To further protect the CCD/CMOS 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, at the cost of a shorter depth of field (DOF).

[Figure 2: see original paper] shows MTF simulation results for lenses with defocus: (a) 5× lens with 5.5 µm defocus and (b) 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. ‘T’ and ‘S’ denote Tangential and Sagittal directions. The numerical values represent distances between test positions on the lens and the lens center.

As shown in Figure 2, for the 5× lens, at a spatial frequency of 384 lp/mm (corresponding to 2 imaging pixels, 2\$×\$1.3 m), the contrast drops to 0 when the defocus distance is \$$\pm 5.5\mu m(Figure2a),givingaDOFofabout11\mu m.Similarly,theDOFforthe10\times$\$ system is approximately 3.5 m (Figure 2b).

The thinnest scintillator foil currently obtained measures 20 m in thickness. This means that fluorescence images within the top 11 m depth exhibit actual resolution exceeding the camera’s pixel resolution (384 lp/mm, 2-pixel criterion), while in the deeper region they fall below this threshold. Nevertheless, images on the YAG foils with 20 m thickness were employed as standard images for the PSF-based recovery method. Cooperating with the high-NA lenses, a new recovery method was proposed in this paper, and overcame the DOF and scintillator thickness contradiction to achieve high resolution and high signal-to-noise ratio 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 X-ray scattering. Under the currently employed X-ray photon energy range and the depth of field (DOF) of the optical system, X-ray scattering is not the primary factor affecting resolution (discussed later).

3.1 Experiments

[Figure 3: see original paper] shows the schematic and photograph of the developed X-ray indirect imaging system. The experimental setup consists of an X-ray tube-based source, a scintillator conversion layer, and a high-NA visible-light microscope.

For high resolution, 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 m. 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. YAG:Ce^{3+} 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, 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 20 µm-thick YAG scintillator film has high resolution but weak signals, requiring longer exposure and imaging times. Accurate alignment of sample and background images is crucial to avoid information bias and ensure reliable analysis. As shown in Figure 4a [Figure 4: see original paper] and 4b, 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.

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 Figure 4c and 4d, 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, indicating 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 material properties or unavoidable factors in the fabrication process.

3.2 Data Analysis

As shown in Figure 5a [Figure 5: see original paper] and 5b, the PSF was yielded by deconvolving the resolution target image on 200 µm-thick YAG with that on 20 µm-thick YAG. The whole structure, a Gaussian-like peak and some adjacent structures, can be found in the central region (80% intensity). Therefore, the central region (60-pixel × 60-pixel) containing almost all these characteristics was selected.

As images on the two YAG scintillators are nearly autocorrelated, relevant signals lie in the PSF plane' s central area. Yet, defects on them differ, with sparse and irregular distributions, with most related signals in non-central areas. Thus, selecting the central region nearly eliminates defect effects. Also, processing and assembly can cause anisotropic peripheral spatial distribution of ultrathin scintillators' PSF. Considering inherent surface defects from mechanical processing during ultrathin scintillator fabrication, this method offers a viable strategy for high-quality imaging using ultrathin-scintillator-based imaging systems.

[Figure 5: see original paper] shows the convolution function: (a) the entire area, (b) the central area, (c1) the image obtained by deconvolving the resolution target image on 200 µm-thick YAG with the truncated PSF, and (c2) the original image on 20 µm-thick YAG.

Compared with the image in Figure 4c, the image deconvolved from the resolution target image on the 200-µm-thick YAG using the above-mentioned truncated PSF maintains high resolution. The details are clearer and sharper, edges are more distinct, and the overall image quality is significantly improved. Most defects that might have been present are almost gone. This shows that the truncated PSF method used in this work is effective at removing the influence of sparsely distributed defects while keeping image details intact.

Figure 6: 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. Figure 6(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. Figure 6(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 these defects don' t 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 the 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 background 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 (Figure 6c,d) clearly shows that deconvolution significantly boosts image high-frequency detail recovery. The 1D PSD (Figure 6d) indicates a significant SNR improvement in the mid-to-high-frequency range, 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-micron-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.

Therefore, 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-resolution” 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, making 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 depth [**?**], as control samples to further explore method performance in 10× magnification systems. This will help us better understand the potential and limitations of our approach in different experimental setups and imaging scenarios.

4. Discussion

(1) Effect of X-ray Scattering on Imaging

X-ray and electron scattering, along with the 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-ray 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, while Compton scattering has a considerable proportion. The X-ray source in the experiment has a spectrum containing 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 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.

(2) 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. Optical property variations between scintillators must be empirically measured and integrated into PSF calculations through conversion protocols. This approach will extend the method’ s applicability to diverse material systems.

5. Conclusion

We theoretically and experimentally proved that the image recovery method using a single PSF can be applied for high-resolution X-ray scintillation imaging systems with high-NA lenses. 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 an X-ray tube-based system. This study shows that our method does not require a perfect surface on ultra-thin scintillators 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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