Nanophotonic scintillators for improved X-ray imaging

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Since Röntgen discovered X-rays in 1895, X-ray imaging has undergone constant development, and today it finds applications in a wide array of established and emerging fields, including medical imaging, non-destructive testing, and security inspection. Many diagnostic and interventional clinical applications require a higher-energy beam to sufficiently penetrate patient anatomy. However, direct detectors, which directly convert X-ray interactions into a charge image by separating electron-hole pairs, are not suitable in these applications due to their low inherent X-ray stopping power[1].

Scintillation, the process of converting high-energy particles, such as X-rays, into visible and UV light, forms the foundation of indirect X-ray detectors, which are used in vital X-ray imaging and characterization technologies today. Given their extensive utility, there is a substantial interest in advancing scintillators to yield higher photon output and enhance both energy and spatial resolution. In general, an indirect X-ray detector-based imaging system consists of a scintillator, optics, and a sensor (CCD/CMOS).

In such a system, we can identify three fundamental phenomena that limit image quality: (I) Extraction loss and secondary quantum noise (SQN). Due to the high refractive index of most scintillators, a narrow escape cone results in significant total internal reflection, thereby reducing the number of photons that are detected. This low photon count forms an ”optical quantum sink,” a source of stochastic noise that lowers the signal-to-noise ratio (SNR). This reduction is especially pronounced at high spatial frequencies, where the signal transmitted by the modulated transfer function (MTF) is at its lowest. (II) Resolution loss due to depth-dependent spread (Lubberts effect): X-ray interactions distributed throughout the thickness generate optical photons that diffuse and spread laterally. Deeper events produce wider blur, so the resolution is a depth-weighted mixture of blurs. This mixture reduces MTF, especially at higher spatial frequencies (fine detail). (III) Gain variance (Swank factor, As): The number of optical photons detected per absorbed X-ray is stochastic. This variance has two components: intrinsic gain statistics and, in thick scintillators, a significant depth-dependent component arising from non-uniform light escape efficiency, g(z). This total variance, quantified by $A_S \in$(0,1] degrades the low-frequency SNR [1, 2].

Improving the scintillator's X-ray quantum efficiency would enhance detector efficiency and potentially reduce imaging dose for medical applications. This has been challenging due to the complexity in balancing trade-offs between the scintillator's X-ray absorption, spatial resolution, and noise characteristics. For example increasing scintillator thickness improves absorption (raising the low-frequency SNR), but it also worsens other metrics, such as the high-frequency MTF (resulting in a stronger Lubberts blur), the low-frequency Swank factor (leading to more g(z) variance), and the high-frequency "quantum sink" (where more optical scattering reduces the number of photons-per-event at the sensor). These negative effects can outweigh what can be achieved via improving X-ray absorption efficiency. Consequently, image details suffer first from the MTF drop (blur), and second from the dominance of the SQN "sink" (noise).

To address the challenges, past efforts have focused on searching for new materials with better emission properties, while present attempts revolve around refining the quality of existing materials, such as needle-shaped caesium iodide. A recent novel approach in scintillator research—referred to as “nanophotonic scintillators”—involves structuring scintillator materials at the scale of their emission wavelength to manipulate the emission properties, including light yield, directionality, detection efficiency, imaging performance, and timing. Such advancement opens new opportunities for more precise and efficient X-ray imaging technologies. A recent demonstration utilizing a nanophotonic platform, a 2D photonic crystal, shows that a sixfold enhancement in light yield (compared to unpatterned) can be achieved with a thickness of only 0.5 mm [3, 4]. This encouraging result indicates that the light yield can be substantially improved due to an increased number of photons reaching the detector. This enhancement in detected photons directly addresses the Secondary Quantum Noise (SQN) bottleneck by providing the high photon statistics needed to overcome the "quantum sink" at high spatial frequencies.

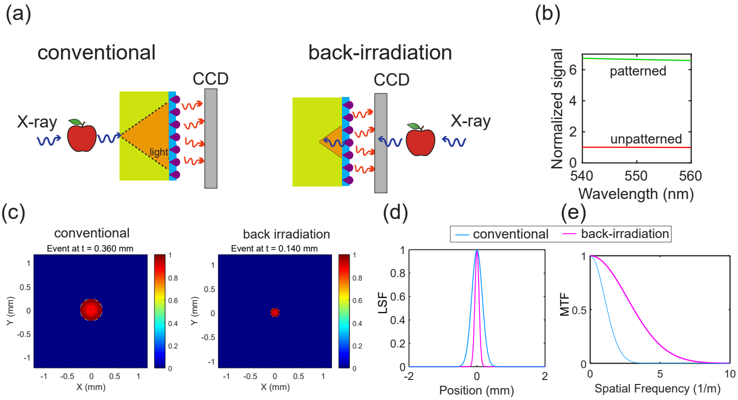

Figure 1: (a) Schematics of X-ray imaging configuration, conventional and back-irradiation, respectively. (b) Simulated intensity for unpatterned and patterned scintillators, indicating six-fold signal enhancement, taken from [3]. (c) The point spread function for conventional and back-irradiation configurations, respectively, also indicated X-ray interaction depth (effective thickness). (d) Line spread function and (e) the modulated transfer functions for both configurations.

In this work, we investigate the possibility of addressing the bulk-physics challenges (Lubberts and Swank) while keeping the already achieved six-fold emission enhancement due to the nanophotonic scintillator to improve SQN. To do so, we depart from the conventional front-irradiation configuration (where scintillation light is detected opposite the X-ray entrance surface) and instead employ a back-irradiation (BI) configuration (see Fig. 1a). In BI configuration, X-rays pass first through the imaging sensor (CCD/CMOS) and excite the scintillator from the back side (patterned surface). This geometry leverages the Lambert–Beer law, allowing X-rays to produce optical photons closer to the exit surface of the scintillator on average [5]. This has a dual function: it mitigates the Lubberts effect by preferentially weighting the highest-resolution MTF(z,f) kernels (those nearest the sensor), and it improves both the Swank factor and the mean signal by weighting the highest-gain, lowest-variance g(z) kernels (also nearest the sensor). We demonstrate that the new strategy optimizes the spatial resolution, while the 6-fold emission gain of the nanophotonic structures rescues this optimized signal from the high-frequency quantum sink (SQN).

The emission enhancement, as reported in previous work [3, 4], is shown in Fig. 1b, and the resolution comparison between conventional and back-irradiated nanophotonic scintillators is presented in Fig. 1(c-e). Events occurring far from the exit surface will, on average, yield less light and have greater spatial blur than those occurring near the exit surface (see Fig. 1c). We propagate a point source from the depth of interaction through the scintillator to the front surface and combine it with the transfer function of the nanophotonic surface, subsequently projecting it through collimation optics to find the final image quantification parameters. In the same configuration, switching from front to back-irradiation narrowed the PSF from 0.36 µm FWHM to 0.16 µm (Fig. 1d) and increased MTF at 1.5 lp/mm from 0.5 to 0.9 (Fig. 1e), with MTF50 shifting from 1.5 to 4 lp/mm (about 2.2-fold spatial resolution improvement). These changes are consistent with a coupled model: BI simultaneously mitigates depth-of-interaction gain variance and blur by optimizing bulk physics, while 6x emission gain due to nanophotonics provides the high photon flux to overcome the secondary quantum noise sink at high frequencies.

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