

Scintillating Quantum Dots for Imaging X-rays (SQDIX) for Aircraft Inspection

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Abstract. Scintillation is the process currently employed by conventional X-ray detectors to create X-ray images. Scintillating quantum dots (StQDs) or nano-crystals are novel, nanometer-scale materials that upon excitation by X-rays, re-emit the absorbed energy as visible light. StQDs theoretically have higher output efficiency than conventional scintillating materials and are more environmentally friendly. This paper will present the characterization of several critical elements in the use of StQDs that have been performed along a path to the use of this technology in wide spread X-ray imaging. Initial work on the scintillating quantum dots for imaging X-rays (SQDIX) system has shown great promise to create state-of-the-art sensors using StQDs as a sensor material. In addition, this work also demonstrates a high degree of promise using StQDs in microstructured fiber optics. Using the microstructured fiber as a light guide could greatly increase the capture efficiency of a StQDs based imaging sensor.

INTRODUCTION

Scintillating quantum dots (StQDs) are nanometer-sized materials that are able to absorb X-ray radiation and to emit visible photons that are of a specific wavelength. In contrast with StQDs, traditional single-crystal scintillators are bulky in size and difficult to produce. The quantum dots in this work act as scintillators or radio-luminescent phosphors. Scintillators are generally comprised of two types, organic and inorganic. The quantum dots used in this work are an inorganic scintillator, due to their material composition of ZnS(MgS). Also, these StQDs are cadmium-free, which is an advantage that makes them environmentally friendly in comparison with conventional scintillator materials. Using StQDs and solution-processing techniques has the potential create large, or very small highly sensitive X-ray imaging systems.

One concept for such use of StQDs as part of an X-ray imaging system has been developed by the authors and is called the scintillating quantum dots for imaging X-rays (SQDIX) system. This work has an initial focus on aircraft inspection.

The SQDIX system has the unique advantage of having instantly variable focus and resolution. By comparison, traditional X-ray imaging requires a physical configuration change to achieve a similar effect. Development of the SQDIX system will also theoretically enable high-speed X-ray imaging due to the StQDs fast return to nominal state. Using a high-speed SQDIX system enables characterization of micro cracking in composites or X-ray inspection of in-service turbine engines, thereby improving aircraft safety and sustainability.

Furthermore, an extension of the SQDIX concept through the use of StQD-based microstructured fiber optics has a number of application in structural health monitoring and X-ray detection. The use of microstructured optical fibers enables super resolution x-ray imaging with pixel sizes 1/100th of the current state of the art, current start of the art pixel resolution for flat panel detectors is currently 100 μm .

THEORY

The scintillating quantum dots used in this study are comprised of zinc sulfide nanocrystals doped with magnesium sulfide, ZnS(MgS) [1]. The process of scintillation is one of luminescence whereby light of a characteristic spectrum is emitted following the absorption of radiation. The emitted radiation is usually less energetic than that absorbed (i.e., lower wavelength). In rare cases, some quantum dots can upconvert [2] energies but generally at very low conversion efficiencies. ZnS(MgS) quantum dots can interact with photons from a band of energy that extends from the ultraviolet (UV) up to energies reasonable for X-ray inspection. Depending on the X-ray's photon energy, X-ray photons can interact with the StQDs through absorption, pair-production, or Compton scattering, and a cascade of lower energy photons are emitted as visible light at a peak wavelength of 580 nm. In order to avoid self-absorption, the gap between the emission and absorption peaks must be separated. As seen in Figure 1, the gap for ZnS(MgS) peak re-emission at 580nm under UV excitation.

Using solution-processing techniques to create scintillating detector plates that have quantum dots dispersed throughout the matrix material can result in imaging plates usable for X-ray imaging. Because StQDs emit in the visible spectra, spectrum standard imaging cameras and optics can be used to collect the re-emitted photons to create X-ray images. The use of solution processing techniques allows for large-scale production of SQDIX based detectors. Further development of these production techniques will improve detector production and quality on various substrates. Fabrication of robust X-ray detection systems based on StQDs and nanocomposites for imaging is possible using solution processing techniques. Using these solution-based techniques will greatly enhance the production quality while reducing production costs. Typical X-ray detecting flat panel detector are on the order of \$150,000, whereas a StQDs based panel made via solution processing would be significantly less.

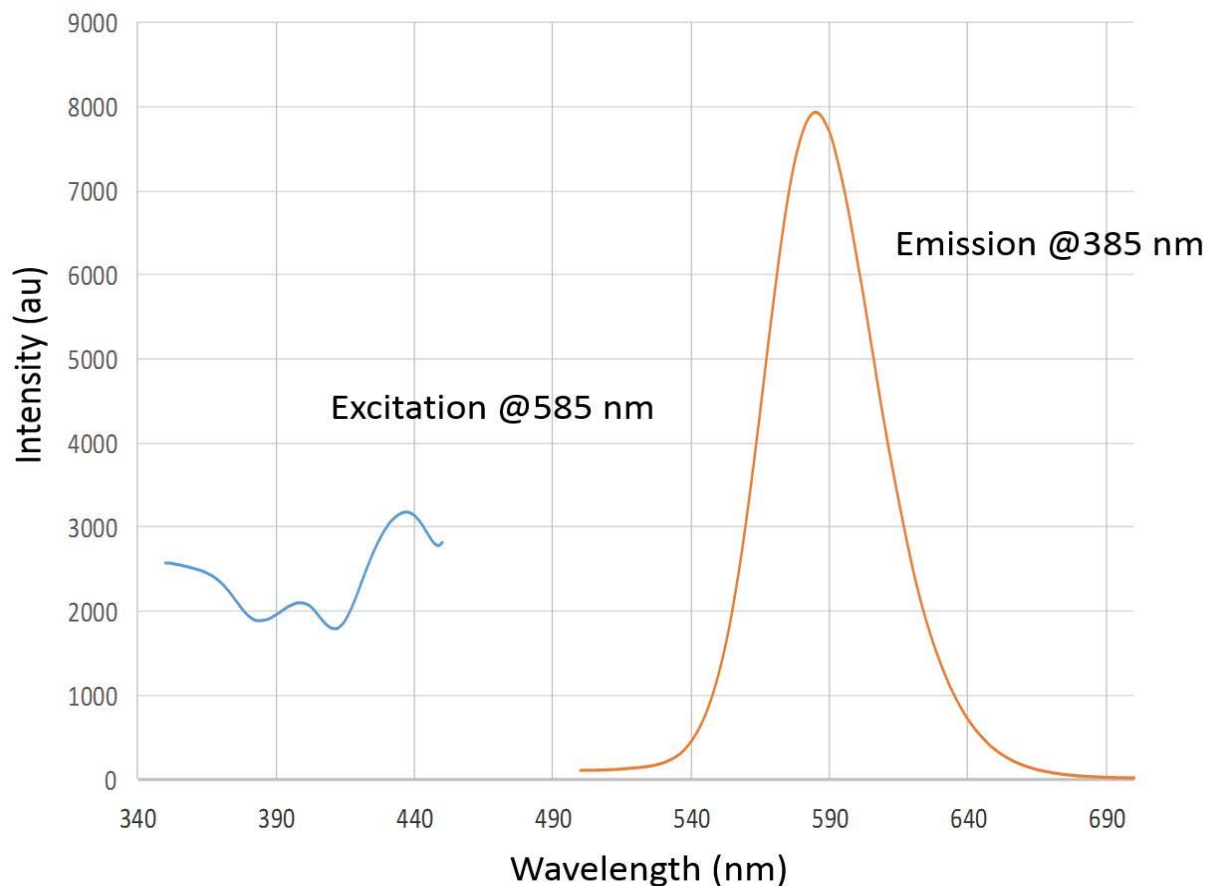


FIGURE 1. Excitation-emission spectra of ZnS(MgS) quantum dots in toluene from spectrophotometry. The peak emission is between 580-610 nm.

RESULTS AND DISCUSSION

This study centered on experimental characterization and optimization of StQDs for X-ray imaging. Several concentrations of StQDs were tested up to 50% by weight concentration in 10% increments in toluene. Concentrations below 30% weight did not yield sufficient output for testing. Concentrations above 50% weight cause the nanoparticles to crystallize out of solution. Configurations included but were not limited to: StQDs in solution, in polymer matrix material, StQDs placed in a plastic cast, and StQDs placed in microstructured fibers. In this case, the microstructured fiber used in this study contains a collection of parallel hollow tubes within the fiber.

A microstructured optical fiber is a fiber optic that has a pattern of small-bore channels within the fiber. A typical microstructured optical fiber in cross-section can be seen on the left in Figure 2. The quantum dots in the microstructured optical fiber configuration were prepared by placing quantum dots in the fiber [2]. Quantum dots suspended in a toluene solution were drawn into the channels via capillary action. A side view of a StQD impregnated

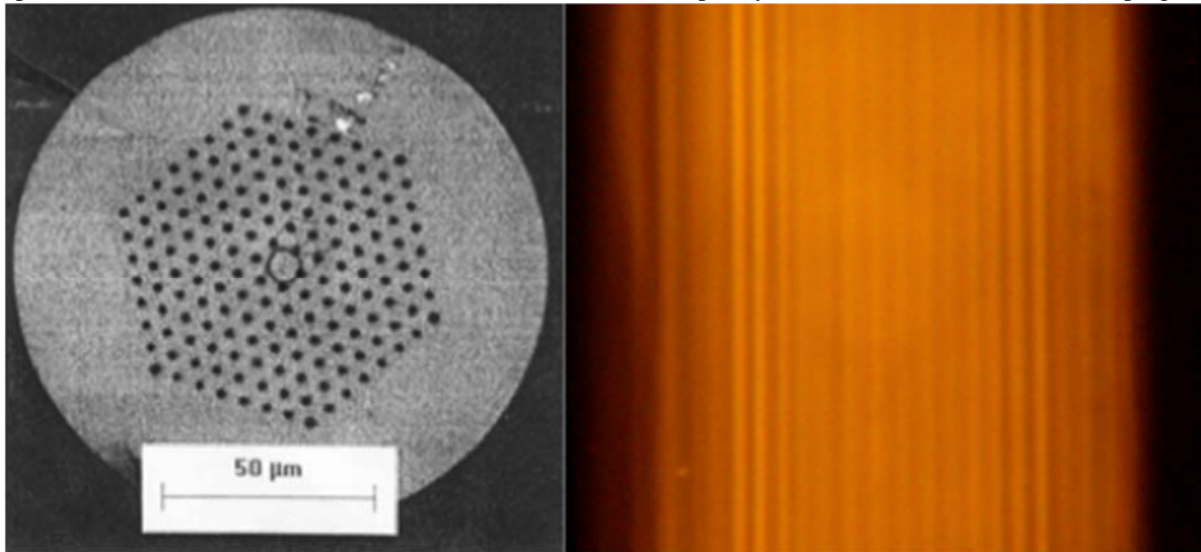


FIGURE 2. Scintillating quantum dots in microstructured fiber under UV excitation.

fiber can be seen in Figure 2 under UV excitation. The results of scintillating quantum dots in a microstructured fiber are shown in both cross-section (left in Figure 2 when illuminated with visible light image) and on the right (along axis) when illuminated with the StQDs under UV excitation.

Two forms of solution-processing based detector plates were successfully attempted during this study. Both detector plates are shown in Figure 3. Using a UV-cured polymer, the 50% by weight concentration of StQDs were placed in the polymer matrix, mixed in, and finally UV cured. Due to the high concentration of StQDs, aggregates of nanocrystals formed in the polymer during the curing process giving the sample a cloudy appearance, as shown in the left image of Figure 3. The second plate was created using a polymer form and letting the toluene in the StQD liquid suspension evaporate under vacuum. Using this method, a large but fragile polycrystal of StQDs was created in the form. This large StQD crystal fractured in the form after fabrication as shown in the right image of Figure 3, but areas of the crystal were still uniform enough to produce usable X-ray images.

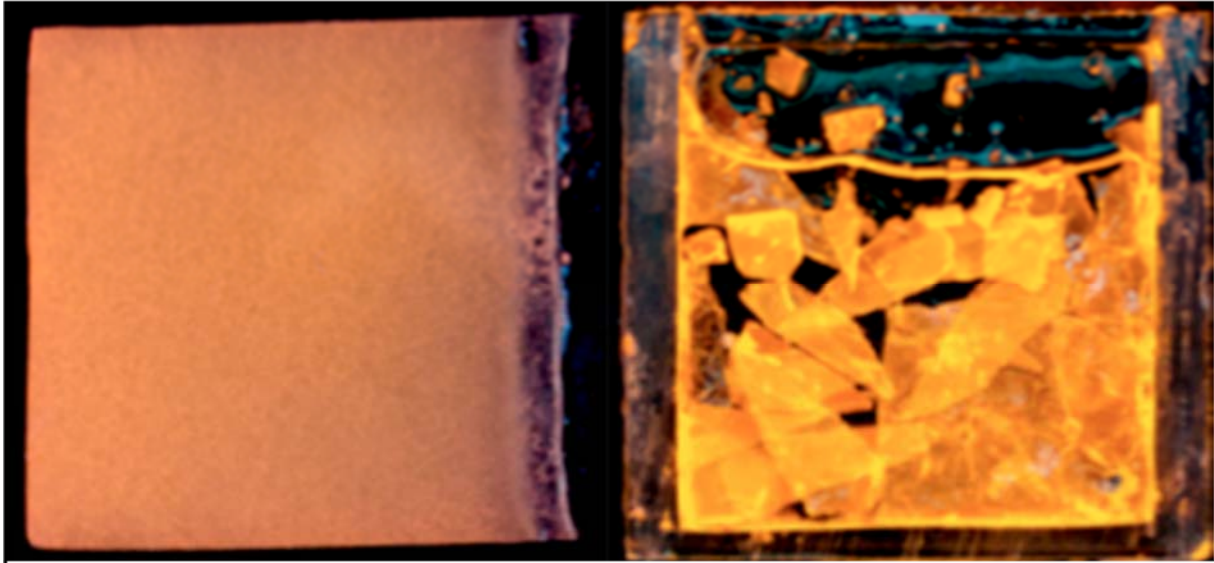


FIGURE 3. StQD solution –processing based polymer detector plates under UV excitation.

Both of these samples responded well under X-ray excitation and were able to produce viable X-ray images with good dynamic range and resolution. These samples were then tested under laboratory conditions at X-ray energies ranging from 30 KeV up to 150KeV in 30keV increments to obtain the dynamic range. This represents a good standard range for general X-ray inspection. Normalized output vs. X-ray excitation voltage results are shown in Figure 4. Both manufactured samples produced approximately linear output relative to the input energy of the X-ray excitation. During our testing the polymeric sample was fit using a least squares linear fit with an $R^2 = 0.9375$, and the cast crystal least squares linear fit $R^2 = 0.9967$.

A standard visible light camera with applicable optics were used to take images of both plates with and without the presence of a lead target arrow in the radiation field between the source and imaging plates. The image without the target arrow was used as the reference background image for subtracting plate nonuniformities. The results of these difference X-ray images are shown in Figure 5. All forms of the StQDs generated a linear energy response and good spatial resolution. An almost linear energy resolution and high sensitivity confirm that StQDs are ideal materials for use in X-ray detection.

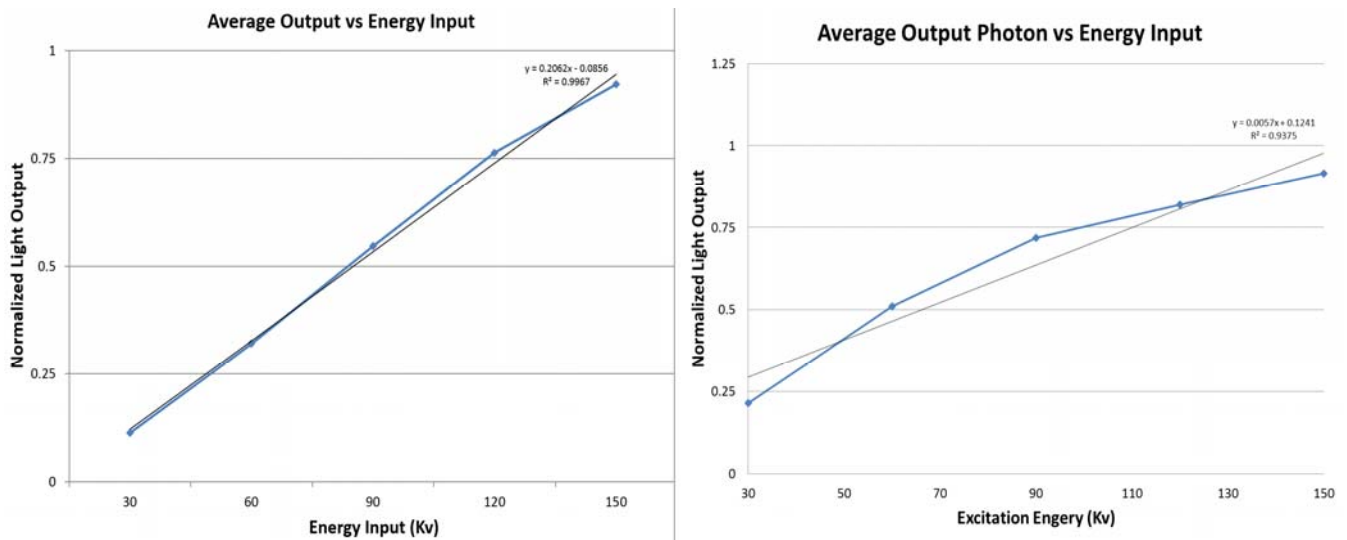


FIGURE 4. Solution Based Polymer Normalized Photon Output vs. X-ray excitation energy input (left), Cast Crystal Normalized Photon Output vs. X-ray excitation energy input (right)

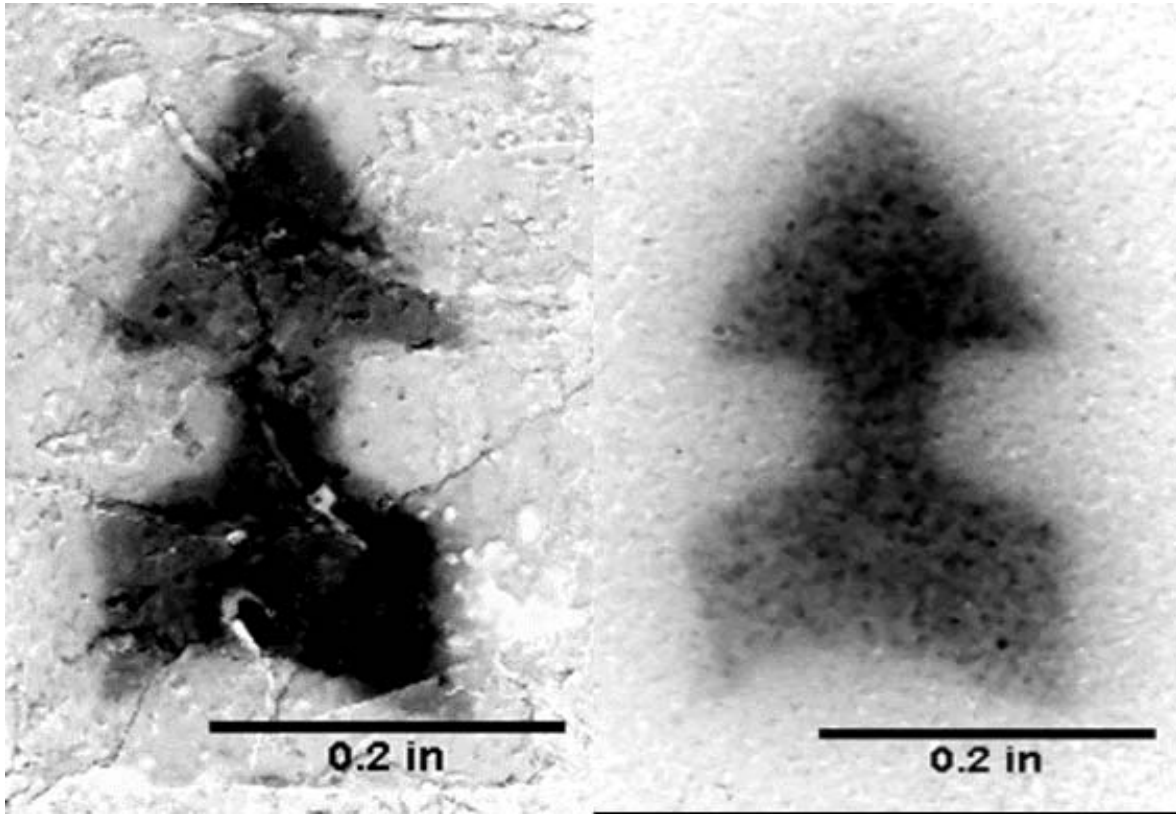


FIGURE 5. Differenced image of Polymerized Quantum Dot Imaging Pate (left) polymerized quantum dot imaging plate and difference image of StQD crystal (right) under 70 keV-kV X-ray excitation.

CONCLUSIONS

The SQDIX system is a technology that may impact a number of fields. The SQDIX system is based upon the use of nanometer-sized scintillating quantum dots (StQDs), which are able to absorb X-ray radiation and emit visible photons that are at a specific wavelength. In contrast with StQDs, traditional single-crystal scintillators are bulky in size and difficult to produce. The StQDs investigated in this work also are cadmium-free, which makes them more environmentally friendly in comparison with some conventional scintillator materials.

Based on the current concept described herein, solution-processing techniques can be employed to create very large or very small highly sensitive X-ray imaging systems. The use of these solution-oriented processing techniques could lead to inexpensive high volume X-ray detector production. The use of sensitive StQDs X-ray imaging plates coupled with the potential cost reduction of using solution-processing techniques could make X-ray imaging possible where it was cost prohibitive.

Within NASA, creation of the SQDIX system will improve our ability to perform X-ray imaging of spacecraft parts for safety, quality and mission assurance. Resolution and sensitivity improvements to perform inspection using 3D X-ray tomography addresses the Aviation Safety challenge in the 2010 National Aeronautics R&D Plan to monitor and assess aircraft safety. Current and future aircraft rely more heavily on composite materials, and will benefit from improved X-ray inspection techniques to enhance overall aircraft safety [4].

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