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Scanning translucent glass-ceramic x-ray storage phosphors

A. R. Lubinsky^{*,a}, J. A. Johnson^b, S. Schweizer^c, J. K. R. Weber^d, R. M. Nishikawa^e, P. Domenicali^f, and S. D. Fantone^f

^a Department of Radiology, SUNY, Stony Brook, NY 11794-8460

^b Department of Materials Science and Engineering, University of Tennessee Space Institute, 411 B. H. Goethert Parkway, Tullahoma, TN 37388

^c Fraunhofer Center for Silicon Photovoltaics, Walter-Hülse-Str. 1, 06120 Halle (Saale), Germany, and Centre for Innovation Competence SiLi-nano, Martin Luther University of Halle-Wittenberg, K.-Freiherr-von-Fritsch-Str. 3, 06120 Halle (Saale), Germany

^d Materials Development, Inc., 3090 Daniels Court, Arlington Heights, IL 60004-7708

^e Department of Radiology, University of Chicago, Chicago, IL 60637

^f Optikos Corporation, 107 Audubon Road, Wakefield, MA 01880

Abstract

A simple benchtop apparatus has been built, to measure the x-ray imaging properties of fluorozirconate-based glass-ceramic x-ray storage phosphor materials. The MTF degradation due to stimulating light spreading in the plate is lower in comparison to optically turbid screens resulting in higher image MTF. In addition, the degree of transparency, or the amount of light scattering at the wavelength of the stimulating (laser) light is adjustable by means of the glass preparation process. The amount of stimulating exposure required for plate readout is generally higher than in previous systems, but well within the range of commercially available laser systems, for practical readout times. The effects of flare or unwanted readout due to back-reflection from the imaging plate is also less than in previous systems.

A novel telecentric scanning system has been developed that is able to rapidly read out the latent image stored in the translucent imaging plates. This system features a reflective primary scan mirror to achieve telecentricity, optical correction for scan line bow, and the design should enable the construction of a relatively inexpensive scanner system for the translucent x-ray storage plates.

Keywords

Storage Phosphor; Computed Radiography; Readout; Telecentricity; Glass Ceramics

1. INTRODUCTION

Computed radiography (CR) is a means for producing digital radiographic images in which a photostimulable phosphor screen is used to store a latent image, which can later be read out in a scanner. Its cassette-based nature, portability, and wide dynamic range have led to wide usage in a number of clinical and other applications. The image quality of CR, as measured by the detective quantum efficiency (DQE), has however not kept up with flat panel digital radiography (DR) systems. These typically use a (prompt) scintillator or

*arl@mil.sunysb.edu; phone 1-631-444-7961; fax 1-631-444-9522.

photoconductor as the primary x-ray detector, and an integrated readout based on an active matrix TFT array. Thus it is of interest to investigate alternative approaches to CR, which can alleviate some of the past limitations.

2. BACKGROUND

The modulation transfer function (MTF) in conventional CR systems using a point scanning readout arises from the spatial spreading of the stimulating (laser) light in the phosphors, which are optically turbid (highly light scattering). It has long been realized that a photostimulable storage phosphor, which is transparent at the stimulating wavelength (λ_S) would be advantageous for improving MTF. DeBoer and Luckey¹ in the 1980's, for example, developed a system using optically isotropic storage phosphor grains in a binder whose refractive index was matched to that of the phosphor at λ_S . We will refer to systems such as this, which achieve relatively long optical scattering lengths compared to conventional turbid materials, as transparent or translucent storage phosphors (TSP).

A number of obstacles to the development of a practical TSP-based CR system have been identified previously: (i) The stimulating laser power requirement is expected to increase (although little actual data has previously been published). We show in this paper that this is not a fundamental limitation, with the present materials. (ii) Scattering of the stimulating light from scratches or defects in the imaging plate (IP) can be a problem. We also show in this paper that adjustment of the optical properties of the plate by thermal processing can alleviate this problem, with the present materials. (iii) In a point scan of a transparent imaging plate, the scanning light needs to be normally incident on the IP, in order to prevent non-normal internal reflections and to retain the advantage of high image MTF. We present here a design for a telecentric scanner for the TSP imaging plates.

Finally, maintaining a high conversion gain (number of detected electrons per absorbed x-ray) is important in all detector systems, and particularly for CR, in order to achieve a high DQE. Including the uncorrelated noise term² in the frequency-dependent noise power spectrum (NPS) produced by a CR (or DR) detector, but excluding additive (electronic) noise, $DQE(f)$ has the form:

$$DQE(f) = \frac{A_Q}{\frac{1}{A_S L(f)} + \frac{1}{g \cdot MTF^2(f)}} \quad (1)$$

where A_Q is the x-ray quantum absorption efficiency, A_S is the Swank factor³, $L(f)$ is the Lubberts factor⁴, and g is the conversion gain. In DR systems, the gain is large and the second term in the denominator can be neglected (but the electronic noise cannot). In CR systems, the electronic noise can be ignored, but care must be taken in both the formulation of the phosphor material, and in the design of the optical collection and detection subsystem, to ensure that g is large enough, i.e. ~ 10 .⁵

3. METHODS

3.1 Translucent imaging plates

The methods of making the fluorozirconate glass ceramic plates used in the present work have been described previously.⁶ Briefly, the constituent chemicals are melted in a crucible, and poured into a mold. The samples are thermally processed in such a way as to produce BaX_2 crystallites within the glass matrix which show a pronounced photostimulable luminescence effect. The optical and luminescent properties of the sample show a strong dependence on annealing temperature and time, with lower temperatures producing smaller (~ 10 nm) hexagonal particles which show little PSL effect, and higher temperature

producing larger (~100 nm) orthorhombic particles with strong PSL activity. Increasing temperature and time produces larger particles with increased PSL and increased light scattering (turbidity). Even the most transparent samples show some scattering at λ_S however, since the average refractive indices are 1.74 and 1.52 for the BaCl_2 and the glass, respectively.⁷ Thus we refer to the present glass ceramic plates as 'translucent'. The light scattering is strongly wavelength dependent, via Raleigh scattering from the crystallites, with nearly an order of magnitude greater turbidity at the emitted light wavelength, than at λ_S .⁷ This effect is useful to increase conversion gain by decreasing trapping of the emitted light.

3.2 Benchtop scanner

A simple laser readout system for the glass-ceramic storage phosphor plates (benchtop scanner) has been constructed and tested. The main components include a 20 mW, 532 nm diode-pumped solid-state laser (Coherent 215M), x-y translation stages, stepping motors and controllers with 0.26 micron resolution and 4 inch travel (Newmark Systems NLS-4-50), detector module with integrated R6095 photomultiplier tube, HV power supply and preamplifier (Hamamatsu HC124-06), and data acquisition module (National Instruments NI6211). An internally reflective conical light collector with high efficiency (~75%) was designed and built. Four mm of (Schott BG3) blue glass and 2 mm of blue dichroic (Thorlabs FD1B) are used for filtration of the stimulating laser light at the detector. The scan control and data analysis software was written in MATLAB. A schematic drawing of the elements of the apparatus is shown in Figure 1.

4. RESULTS AND DISCUSSION

4.1 Stimulating exposure requirement

The stimulating exposure required to read out the glass-ceramic imaging plates was measured by illuminating a large (8 mm × 10 mm), stationary area of the plate with a uniform and constant intensity (532 nm) light source, and observing the decay of the photostimulated (filtered) signal. Normalized signal vs. time is shown in Figure 2 for three samples. The comparison is a commercial (Fuji ST-VI) screen. Sample 2 is a TSP plate with low light scattering and high transparency (TSP-LO), and sample 1 is a TSP plate which has been processed differently, by longer annealing time, resulting in higher light scattering (TSP-HI).

The decay curves (over times longer than shown in Figure 2) were approximately fitted with exponentials, to compare the required stimulating exposures. It was found that the exposure speeds of S1 and S2 were 21% and 9.3% of the comparison, respectively. The TSP-HI sample requires about five times the laser exposure of that required for the commercial turbid screen. Since commercial plate readers are known⁸ to require ~30 mW of laser power to scan plates at a reasonable throughput rate, it is seen that the laser power requirement for the translucent plates, although higher compared to conventional turbid screens, is easily within the reach of present-day laser systems.

4.2 Spatial resolution and MTF

The MTF's of the glass ceramic imaging plates were measured in the benchtop scanner; a representative example is shown in Figure 3. The plates were exposed behind a tungsten edge at high exposure, 40 kVp, and 147 cm source to plate distance. The edge spread function (ESF) (inset Figure 3) in the laser scan direction was measured by scanning with a 50 micron ($1/e^2$) beam width, sampled at 2.5 microns. The sample 3, shown in Figure 3, had optical properties similar to sample 1 (TSP-HI) shown in Figure 2. The sample was thinned mechanically to a thickness of 450 microns, and was placed on a black (absorbing) backing.

The measured edge spread function (ESF) was fitted with the sum of two erf functions with differing widths, the line spread function (LSF) was calculated by differentiation and is also shown as an inset in Figure 3. The MTF was obtained from the fast Fourier transform of the LSF. It is noted that the LSF of the translucent sample shows a bimodal character, with a narrow peak due to the scanning beam width, and a broader part due to light scattering. This behavior for glass ceramics has been noted in previous simulations and experiments by Winch and Edgar.⁹ The resultant MTF for the TSP IP is much higher than a commercial turbid CR screen, with significant modulation at or beyond 10 lp/mm. The highly transparent sample (TSP-LO) has even higher MTF at high frequencies, but as noted above its stimulating exposure requirement is also higher. (It should be noted that for imaging, an 8-pole Butterworth filter is used in the scan direction, and optical blurring is used in the cross scan direction, to eliminate or reduce aliasing.)

4.3 Sensitivity to defects and flare

It was found experimentally in imaging tests that the more highly scattering translucent samples like TSP-HI (Figure 2) were much less sensitive to laser scattering from scratches and defects, compared to lower scattering samples like TSPLO. This illustrates that the plate processing conditions may be used to produce plates that are more useful for specific imaging applications. The translucent glass ceramic samples also have the property that more of the incident stimulating light is transmitted to the back (absorbing) surface, than in a conventional turbid screen. This reduces the problem of 'flare', or re-stimulation by reflected light in CR systems.

4.4 Telecentric scanner design

The performance of CR systems depends on both the imaging plate properties, and on the design of the readout scanner. To work advantageously with the glass ceramic translucent plates, we desire a scanner which can realize the potential for high image MTF, maximize conversion gain, minimize artifacts and noise, and perform the readout in a reasonably short time. In addition it is desirable to have the scanner be relatively inexpensive. The imaging plate format size is 24 cm $\times$ 30 cm. Analysis showed that an optical design based on a rotating galvanometer mirror and a reflecting primary mirror was workable in terms of scanning spot size and shape uniformity and telecentricity. A schematic optical layout is shown in Figure 4.

The expanded and ellipticized beam from the laser (not shown), after reflection from two turning mirrors (not shown) passes through a pre-scan objective lens, before reflection from the scanning mirror and a first folding mirror, the primary mirror, and a second folding mirror. Initially, the primary mirror was chosen to be a paraboloid, but it was recognized that this could be replaced by a section of a spherical mirror, to a sufficiently accurate approximation. This is quite advantageous because the spherical mirror can be fabricated at a smaller F/number, yielding a smaller focal length, less folding, and a smaller scanner. It is also less expensive. The mirror to be used has a focal length of 985 mm. The overall size of the optical scanner in the present design is about 45 cm (W) $\times$ 45 cm (H) $\times$ 89 cm (L). In addition to the use of the spherical mirror, a small amount of tilt is introduced between the axis of the incident laser beam and the plane normal to the scanner axis of rotation to correct for transverse scan error (scan line bow). The prescan objective lens corrects for field curvature, and minimizes spot shape variation with scan angle. A calculation of transverse and linear scan errors is shown in Figure 5, and it is seen that the design is extremely well corrected.

Finally, a CAD rendering of the optical scanning system is shown in Figure 6. The laser (Coherent 315M-150) and associated optics, galvanometer scanner (Cambridge Model

6650A), and linear stage (Nelson Air RAB6-M-350) are illustrated. The collection optics, photomultipliers, and signal and control electronics are not shown.

4. CONCLUSION

The imaging properties of translucent glass ceramic x-ray storage plates have been studied. The properties depend on the method of preparation of the plates, and can be adjusted for particular applications. Spatial resolution and flare performance is very good, and stimulating exposure requirements are in a practical range. A novel telecentric scanning system has been developed that is able to rapidly read out the latent image stored in the translucent imaging plates, and the design will enable the construction of a relatively inexpensive scanner system for the plates.

Fluorozirconate glass ceramics show promise as x-ray image storage plates. With continued work to develop workable imaging systems and optimize system conversion gain, these could become very useful in computed radiography applications.

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Figure 1.
Schematic of simple benchtop scanner for testing glass ceramic plates.

Figure 2. Stimulated (normalized) signal vs. exposure time for two translucent storage plates (samples 1 and 2), and one comparison turbid screen.

Figure 3. Edge spread function (upper inset), line spread function (lower inset), and MTF for a translucent imaging plate sample.

Figure 4. Isometric view of optical layout with rays traced for five scan positions.

Figure 5.
Calculated transverse and linear scan errors.

Figure 6.
CAD rendering of optical scanning system for translucent imaging plates.