Advances in X-Ray Scintillator Technology

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Scintillator-based imagers

- One of the earliest techniques employed for imaging ionizing radiation
- Scintillator-based imagers remain one of the most flexible and successful techniques for x-ray imaging
  - Crystallography
  - SAXS/WAXS
  - Microtomography...
- However, conventional scintillators have significant limitations...
Limitations of conventional scintillators: point spread function

Point Spread Function (PSF) is limited by scattering in polycrystalline phosphor screen: typically > 100 ?m FWHM
Limitations of conventional scintillators: Light loss in demagnifying optics

- Conventional screens are Lambertian
- However, light emitted at *large angles* is lost in the optics
- Only *low angle* light is transmitted to CCD
Transmission efficiency scales as $1/m^2$.
Present day integrating detectors do not achieve optimal sensitivity

Gruner (1996) noted that for optimal dynamic range and near-quantum limited performance an integrating detector (CCD, a-Se, ...) should achieve a SNR of order 1.

Because of transmission losses and point spread, no present large area, integrating detectors satisfy this criterion...

<table>
<thead>
<tr>
<th></th>
<th>CCD (typical)</th>
<th>a-Se (typical)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Quantum gain</td>
<td>10 electrons</td>
<td>120 electrons</td>
</tr>
<tr>
<td>Noise</td>
<td>10 electrons</td>
<td>500 electrons</td>
</tr>
<tr>
<td>Integrated noise</td>
<td>40 electrons</td>
<td>500 electrons</td>
</tr>
<tr>
<td>True SNR</td>
<td>0.25</td>
<td>0.25</td>
</tr>
</tbody>
</table>
Design of high gain X-ray phosphors

Characteristics of efficient x-ray phosphors

- High x-ray absorption (large $x_{\text{ray}}$)
- Low cost per electron-hole pair (small $E_g$)
- Efficient electron-hole transport ($S > 1$)
- High luminescent efficiency ($QE > 1$)
- Low optical self absorption (small $\phi_h$)

\[ \text{x-ray absorbed by host atom; emits photoelectron} \]
\[ \text{energetic photoelectron} \]
\[ \text{luminescent center} \]
\[ \text{optical photons} \]
\[ \text{e-h pair production} \]
\[ \text{luminescent QE} \]
\[ \text{x-ray absorption} \]
\[ \text{e-h transport} \]
\[ \text{optical self absorption} \]
Development of high gain x-ray phosphors

- ZnSe:Cu,Ce has the highest known x-ray conversion efficiency
  - Three times higher than Gd$_2$O$_2$S:Tb
  - Status: commercially available
  - However, not suitable for MAD phasing because of Se edge
- ZnTe under development for macromolecular applications*
  - Collaboration with MBC, Georgia Tech, TTU.
  - Efficiency potentially comparable to ZnSe
  - No Se edge, suitable for MAD experiments

<table>
<thead>
<tr>
<th></th>
<th>$E_g$ (eV)</th>
<th>$E_{eh}$ (eV)</th>
<th>Gain (photons/x-ray)</th>
</tr>
</thead>
<tbody>
<tr>
<td>ZnTe</td>
<td>2.3</td>
<td>5.0</td>
<td>2,400</td>
</tr>
<tr>
<td>ZnSe</td>
<td>2.7</td>
<td>5.9</td>
<td>2,040</td>
</tr>
<tr>
<td>ZnS</td>
<td>3.8</td>
<td>11.0</td>
<td>1,040</td>
</tr>
<tr>
<td>CsI</td>
<td>6.4</td>
<td>16.0</td>
<td>755</td>
</tr>
<tr>
<td>Gd$_2$O$_2$S</td>
<td>4.4</td>
<td>17.2</td>
<td>700</td>
</tr>
<tr>
<td>CaWO$_4$</td>
<td>4.6</td>
<td>32.2</td>
<td>370</td>
</tr>
</tbody>
</table>
Design of high resolution scintillators: Thin film phosphors

- Very high spatial resolution possible using *thin film scintillators*
  - Thin (~15 µm) solid film deposited on glass substrate
  - No scattering, thus better PSF (e.g., Koch 2000)

- However, solid scintillating films are inefficient
  - Typically >90% of light is trapped in screen by total internal reflection
  - <10% of light is emitted

- *Thin film scintillators give high resolution but poor sensitivity*
Ideally, scintillator emission should be *forward peaked*

- Allows more efficient coupling to optics
- Prevents trapping by total internal reflection
- *How could such a screen be realized?*
Directional emission in a resonant cavity

- In a conventional scintillator, emission is spontaneous
  - Random, no preferred direction
- In a laser, emission occurs in a high-Q resonant cavity
  - Emission is stimulated: highly directional
  - Can this principle be applied to a scintillator?
Quantum Resonance Convertor (QRC)*

- Phosphor deposited between mirrors
- Mirror x-ray transparent
  - Low-Z dielectric stack
- Phosphor layer must be sufficiently thick so as to absorb incident x-rays
  - >12 μm for Gd$_2$O$_2$S, 8 keV
- Vacuum deposited on substrate
  - glass
  - fiber optic faceplate

*Patents pending
QRC vs laser

- QRC and laser have similar structures, however QRC is *not* a laser
  - There is no gain medium (i.e., no population inversion)
  - There is no amplification in a QRC, the same number of photons are emitted but the angular distribution of the emitted light is modified

\[ W_i \propto n \frac{2}{n} \left| \langle n | e^{-\frac{\hat{E}_T(R)}{\hbar}} | i \rangle \right|^2 d \theta \]

- In a conventional scintillator, emission probability is isotropic
- *In QRC, emission* is strongly peaked due to interference
  - Resonant modes (forward peaked) enhanced
  - Non-resonant modes (high angle) suppressed
Prototype QRC screens up to 220 mm diagonal have been produced to date.
QRCs exhibit strongly forward peaked emission

>3-5 times brighter than conventional screen demonstrated

*In theory, with improved cavity design gains >20 are possible*
QRC spatial resolution

- No scattering in screen allows high spatial resolution
- PSF < 20 microns: 5 times better than conventional phosphor screen

Pattern generated by 10 micron e-beam on QRC
Application of QRCs: Fiber optic coupled CCDs

- QRC screens will be back compatible with new and existing fiber optic cameras
  - Multilayer deposited on fiber optic faceplate
- Simple field upgrade
  - Improved sensitivity (est. >3X)
  - Improved point spread function (est. >4X)
Application of QRCs: Advanced lens-coupled cameras

- Forwarded-peaked emission from QRC couples more efficiently to lens optics as well.

- Lens-coupled QRC
  - large active area
  - very high sensitivity
  - high resolution
  - relatively low cost

- Especially suitable for high speed CCDs
  - Eg., Frelon camera…

[Image: 200 mm active area lens-coupled detector]
Conventional scintillator screens are not optimal
- Scattering degrades spatial resolution
- Lambertian emission couples inefficiently to demagnifying optics

Screens can be improved by
- Increasing the screen quantum efficiency: ZnSe, ZnTe
- Modifying the emission profile to be highly forward peaked: Quantum resonance scintillator

New scintillator technologies are compatible with both fiber optic and lens-coupled CCD camera designs
- Also TFT arrays or CMOS...