Triboluminescence and its Application to Space-Based Damage Sensors

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ABSTRACT

The emission of light due to crystal fracture from triboluminescence is a phenomenon that has been known for centuries. Preliminary testing has been performed using ZnS:Mn in a specially constructed drop tower. For these tests a 0.13 kg spherical mass was dropped from various heights in air, and the emission intensity was measured. Through the use of specific fluor material, it is believed that sensors can be developed that will indicate the occurrence of an impact and its location. To apply triboluminescence as a damage sensor, it would need to be incorporated into some type of smart material or coating. This combination would need to have a phosphor suspended and evenly distributed in a resin that would then cover a grid of optical fiber. The optical fibers would be used to capture the emitted light and transmit it to a series of detectors. Through the careful monitoring of the detectors, the entire exterior of a spacecraft could be a passive sensor that can locate and determine the impact velocity or energy of a debris strike. Through the development process, other uses of the system will no doubt be generated.

BACKGROUND

Luminescence is the emission of cold light unrelated to the black-body radiation produced by heating an object to incandescence. It is produced as a result of an atom's first absorbing radiation energy at one wavelength, exciting electrons to a higher energy state. This is followed by a rapid emission of photons as the excited electrons begin their return to the ground state. Increasing the temperature of a substance generally reduces its fluorescence.

A distinction is usually made to denote the time delay between the completion of the excitation process and the start of photon emission for a luminescent material. When the emission of photons is due to a direct transition of less than 10 ms decay time, the luminescence is called fluorescence. It is the process where light emission is ruled by the lifetime of the emitting center. Materials that emit fluorescence are known as fluors and are used for applications where timing is important. Luminescence that persists for more than 100 ms after cessation of irradiation is called phosphorescence. In fact, phosphorescent materials can emit

luminescence many hours after cessation of excitation. In this event, atomic transitions through intermediate metastable states determine the exact duration of the phosphorescence. Materials that emit phosphorescence are known as phosphors and are used in powdered form for lamps, television screens, and related purposes. However, the light from phosphors in these applications exhibit decay times less than 10 ms.

TRIBOLUMINSECENCE

Triboluminescence (TL) is light produced while striking or rubbing two pieces of a material together. Sir Francis Bacon first studied it with sugar about 400 years ago and determined that it is basically light from friction, as the term comes from the Greek *tribein*, meaning "to rub," and the Latin prefix *lumin*, meaning "light". Up to the 20th century, research primarily produced lists of TL materials. A good history and review of research to 1977 is Walton [ref. 1]. Since then, much work has been done on characterization of materials, mechanisms, and possible applications. Of particular note is the work of Chandra and Zink [ref. 2] and Sweeting [ref. 3] on characterization and mechanisms; and of Sage, Bourhill, et al. [ref. 4] and Xu, Akiyama, et al. [ref. 5] on the use of TL as a stress and damage sensor.

When a TL material is fractured, electrons are torn away from their parent atoms. This results in a static discharge across the gap of the fracture. The light is emitted by several distinct, material-dependent mechanisms. The emission spectrum for sugar indicates that the light comes from the atmospheric nitrogen that fills the gap during fracture; the same source of light as lightning or touching a doorknob on a winter day. Spectra for other samples show emission from the material as well as the nitrogen lines, which suggest a secondary energy process. Still others show a spectrum characteristic of the material without the nitrogen lines. While the abrupt charge separation is the same in all cases, the mechanism(s) of emission depend on material.

EXPERIMENTAL APPROACH

The purpose of this preliminary research was to quantify the relationship between TL intensity and impact velocity for ZnS:Mn. This TL material was purchased commercially and was selected because it emits copious amounts of light when struck with a projectile. A typical emission spectrum for ZnS:Mn irradiated with a zenon lamp at a wavelength of 355 nm is shown in Figure 1. When excited, ZnS:Mn emits bright yellow luminescence with a broad emission peak centered at 585 nm and a full width at half maximum (FWHM) of about 125 nm. The spectrum shown in Figure 1 was collected using a Perkin Elmer LS 50B Luminescence Spectrometer.

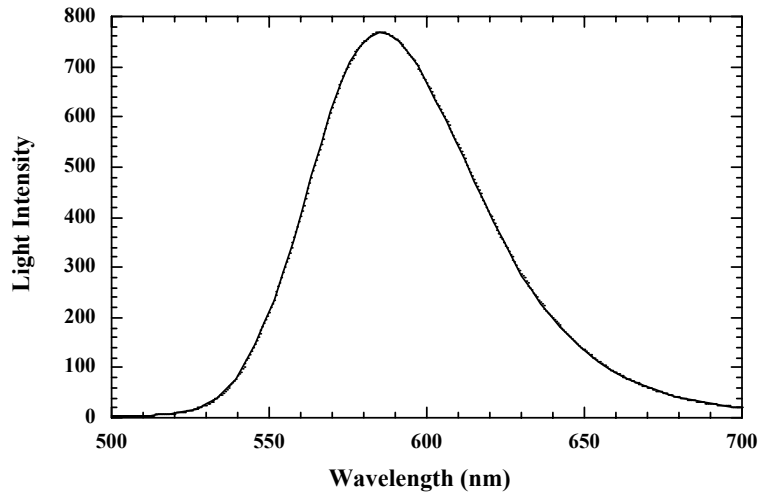

Figure 1. Sample ZnS:Mn emission spectrum excited with a UV laser.

The authors constructed a specially designed drop tower for less than $20.00 that is shown in Figure 2. It was constructed from 0.75 inch (19 mm) medium density fiberboard, 0.25 inch (6 mm) plexiglas plate, and a common 1.25 inch (32 mm) piece of PVC pipe. The pipe has holes drilled in measured increments. These holes are used to place a pin that holds a 1.25 inch (32 mm) diameter steel ball (0.13 kg) bearing, and serves as the release mechanism.

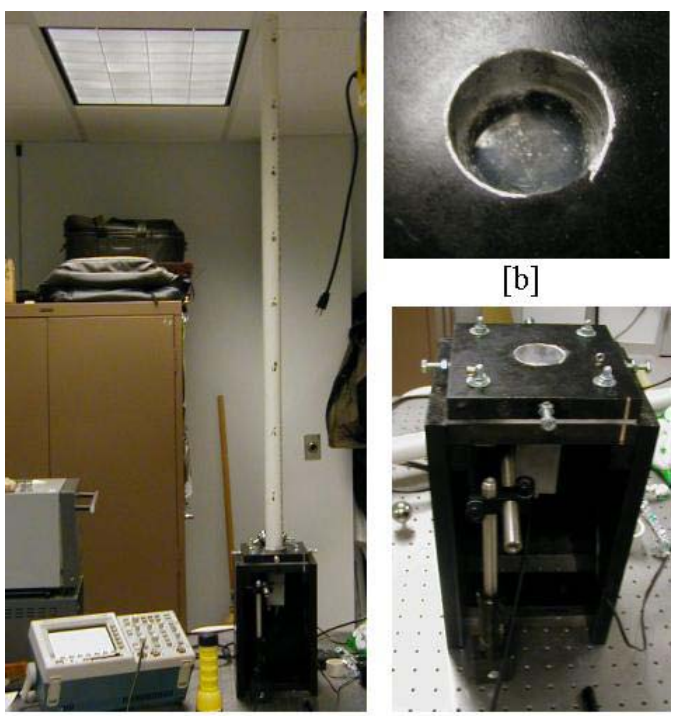

Figure 2. Drop tower experimental arrangement: [a] Drop tower with oscilloscope, [b] sample tray formed by tube support and plexiglas bottom, and [c] drop tower base showing the mounting of the photomultiplier tube (PMT).

The sample powder is placed on the plexiglas plate as shown in Figure 1b. The material is arranged so that it is aligned about the center of the tube. After several drop tests, the plexiglas begins to pit from the impact of the drop mass. These pits are used to align the sample so that the majority of the material is in the impact zone.

The ZnS:Mn powder can be widely displaced by the impact. After each test, the drop tube is removed, the drop mass is cleaned, and the powder redistributed near the center of the target area. This redistribution is accomplished by placing a small piece of PVC in the tower base and arranging the powder into an even layer. After each test, a small amount of the powder is removed when the ball bearing is cleaned. This change in sample mass does not appear to affect the intensity or repeatability of the measurements.

To monitor TL intensity, a photomultiplier tube (PMT) was placed approximately 0.75 inches (19 mm) under the plexiglas plate as shown in Figure 1c. In order to reduce stray light, a 589 nm filter is positioned in front of the PMT. Recall from Figure 1 that the maximum emission from ZnS:Mn occurs at a maximum of 585 nm. A Tektronix TDS 3052 oscilloscope captures the luminescence data in single sequence mode. The room light was turned off to further reduce background light. The PMT gain was adjusted using a screw potentiometer until it was about half its maximum range. This was required because the emission was too bright for the PMT when it was set to maximum gain. With the gain reduced, the PMT response is linear.

RESULTS

An example triboluminesent response from the ZnS:Mn powder is shown in Figure 3 for a drop height of 39 inches (1 m). For this research, the drop height is initiated at the maximum setting and incrementally decreased. These tests were performed without replacing the powder lost during the cleaning process. This would tend to indicate that the total mass loss per shot of the ZnS:Mn was small and did not affect the luminescent intensity. Figure 4 plots the variation in light emission characterized by the output potential from the PMT (volts) versus the drop velocity (m/s). The impact velocity is defined using Newton's equations for a free falling object [ref. 6]. These equations assume that air resistance is negligible and the ball does not make contact with the sides of the drop tube. The approximate measurement uncertainty is about ± 5%, as noted by the error bars shown in Figure 4.

The intensity of the triboluminesent response appears to be a function of impact velocity with two regions of interest as shown in Figure 4. The first region is in the threshold velocity range below 2 m/s. The production of TL light appears to have a threshold of approximately 0.5 m/s. Above the threshold, the projectile has sufficient velocity (or energy) to break ZnS:Mn crystals and to produce TL light. The TL luminescence increases rapidly until about 2 m/s. The second region begins at 2 m/s and appears to be more like a saturation state, where the slope is shallow which indicates less sensitivity to impact velocity. Understanding these relationships will be very beneficial towards the design of smart materials to detect damage caused by impact of foreign objects. Once an impact is detected, the severity can be determined without the need

for immediate inspection. This impact data could also be saved in a database and used to determine a maintenance and inspection procedures. In the course of testing, it was found that the reduction in TL material encountered in testing does not affect the repeatability of the measurements. This is important since once deployed, it would be difficult to replace depleted phosphor in the smart material.

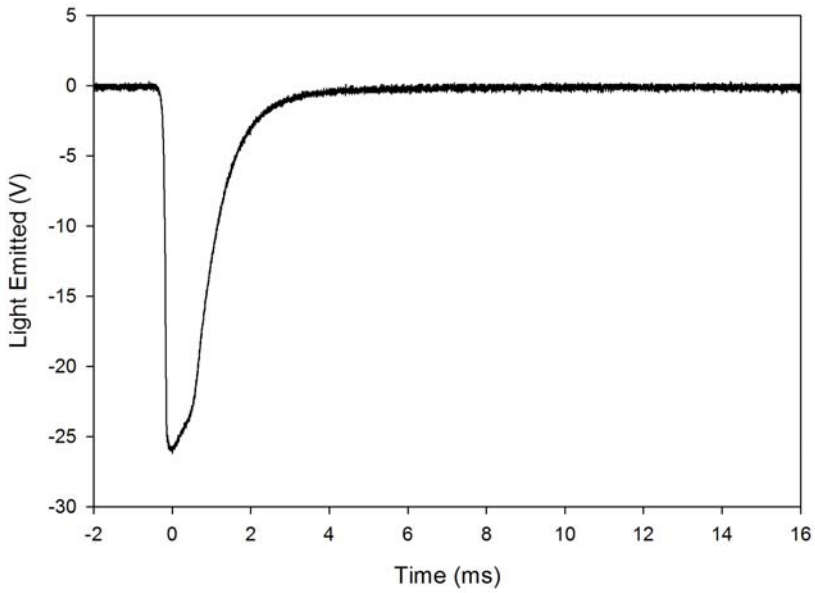

Figure 3. Example PMT potential response for ZnS:Mn. Notice that the luminescence decay appears to follow standard exponential decay.

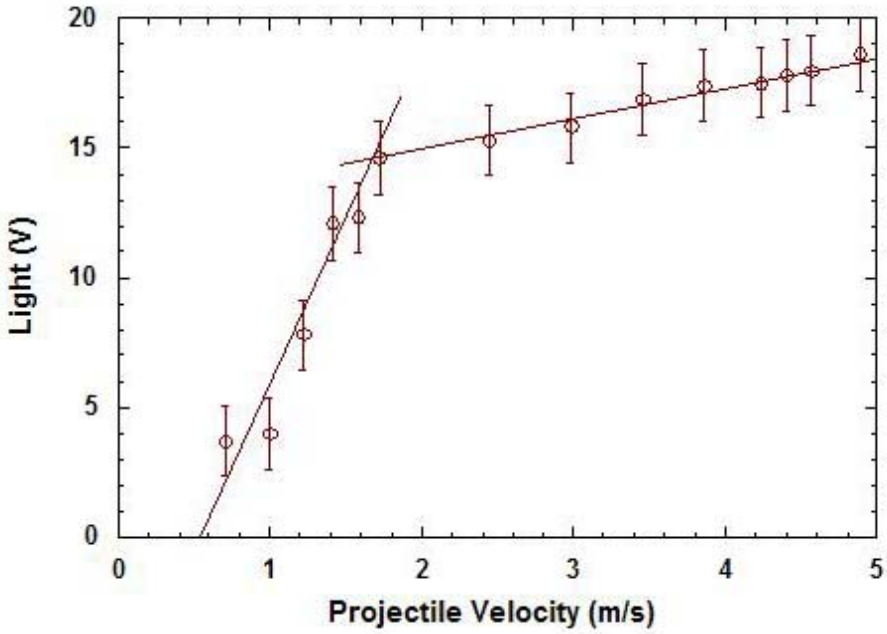

Figure 4. Plot of the PMT potential as a function of impact velocity for ZnS:Mn powder.

APPLICATIONS

The obvious application of the TL data is to design a smart material or structure. This structure would be capable of determining if a particle had hit a surface, and record the relative intensity of the impact. These records could then be used in maintenance and inspection scheduling. This system can also be used for a distributed temperature measurement. For this, a thermographic phosphor would be used [ref 7]. The application could take a variety of forms, including the following key components: 1) an optical fiber grid such as the one shown in Figure 5, 2) a triboluminesent doped opaque resin material, and 3) a sensitive light detector.

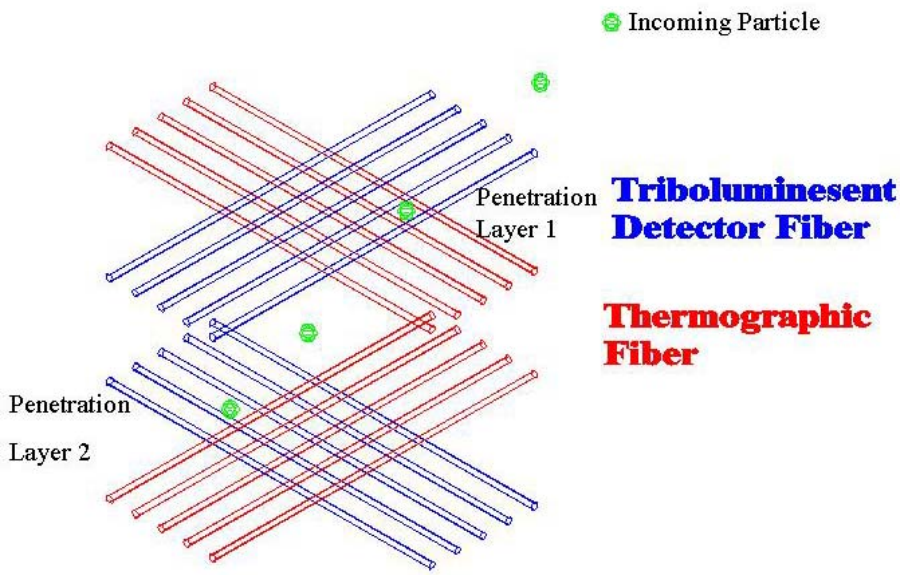

Figure 5. Conceptual smart material optical fiber grid arrangement.

The concept shown in Figure 5 shows two sets of optical grids a set distance apart. This design allows for the measurement of the penetration depth of a particle strike. However, it also allows for the possibility of a measurement of the heat flux from the structure since there are temperature sensing layers spaced a known distance apart and with a known material between it. While both of these possible applications are interesting, they also add to the weight and cost of the system, and a single layer placed close to the surface would still allow for the distributed temperature sensor and damage monitoring system.

Fiber optic grid systems such as described here have been used by researchers from Oak Ridge National Laboratory (ORNL) in research aimed at monitoring the health of pressurized tanks [ref. 8]. Figure 6 shows one such tank where a combination of embedded fiber optics and an optical time domain reflectometer (OTDR) were used to monitor the outer shell of a composite compressed natural gas (CNG) tank. Other testing was performed on a panel of similar composite material with embedded optical fiber and fiber optic strain sensors. These

embedded sensors were used to measure the effect of bending stresses on the composite. The panel was then tested for impact loading and it was found that damage from these impacts could be determined by changes in the response from the OTDR after the impact testing had been completed.

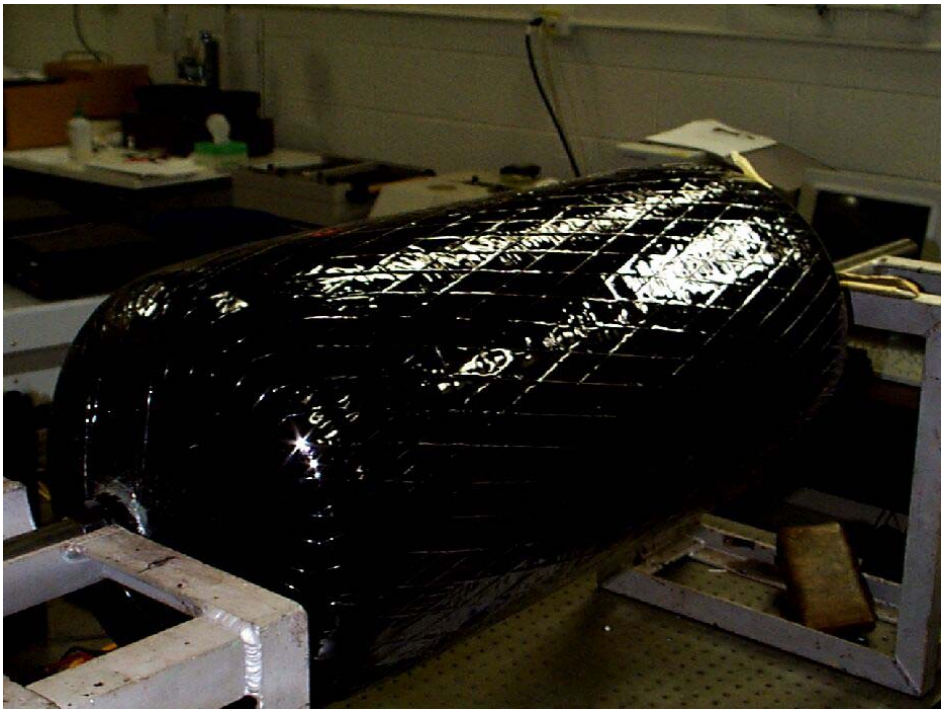

Figure 6. Picture of a fiber optic grid system used for smart tank applications at ORNL.

CONCLUSIONS

The preliminary research shown here demonstrates the ability to systematically reproduce triboluminesent response in a simple drop tower apparatus. Results showed that drop velocities greater than 0.5 m/s produced measurable TL light from ZnS:Mn. The loss of small amounts of powder after each drop trial did not appear to affect the results. This fact leads to the conclusion that the light produced was from interaction of the mass and a small number of luminescence centers in the powder. These results become very important in the development of a smart material damage sensor. Since the intensity of the response can be related to the impact velocity or energy, a sensor can be developed that not only detects an impact but also determines the severity of the strike. This information could be saved and used as part of a maintenance and inspection schedule. The other important fact obtained is that the phosphor can withstand multiple strikes and still produce repeatable data. This is very important since once deployed as part of the smart structure it we would be difficult to replace the expended phosphor. While many questions remain to be answered the basic premise of a triboluminesent based smart material damage sensor can be established.

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