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TITLE SENSING APPLICATIONS OF RARE-EARTH DOPED LUMINESCENT MATERIALS

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Sensing Applications of Rare-Earth Doped Luminescent Materials

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Abstract

We are developing sensing techniques using phosphors and luminescing crystals. While their use in temperature sensing is becoming well known, there exists the potential to exploit them for other diagnostics. Examples are stress/strain, heat flux, skin friction, pressure, laser-beam profiling, aerodynamic flow, and radiation. We describe our recent results in these areas.

Introduction

Phosphors, such as rare-earth-doped oxides and oxysulfides, are noted for exhibiting sharp fluorescence and fluorescence decay rates with striking temperature-dependence. We use these materials for various temperature sensing applications. This collaboration has presented papers on the topic at the last five ICALEO conferences, including the previous paper in this session.¹⁻⁵ In the present work we describe our efforts to extend the use of these phosphors or their crystalline forms to measure the following parameters: stress/strain, heat flux, pressure, laser-beam profiling, aerodynamic flow, and radiation. These quantities are of importance to a variety of industrial and aeronautical processes. The sensing schemes have the same advantages as described previously for temperature sensors. They provide for noncontact measurement of moving surfaces, work in hostile environments, and can be used with fiber optics.

Stress/Strain

Better ways to measure stress/strain in high temperature and rotating environments are needed. Potential applications are to be found in the turbine industry, for instance, where rotor blades, vanes and other parts are critical components. For a

related technology involving the U. S. Gas Centrifuge Enrichment program, we developed a technique for measuring in-plane deformations of rotating components.⁶ It makes use of an Archimedean spiral pattern applied to the surface. While the pattern rotates, an optical emitter/detector pair located at a given radius measures change in reflectivity. The light/dark duty cycle correlates with dimension changes which in turn relate to strain. An important variation of this method is to use a phosphor as the pattern material. The reason is that luminescence from the phosphors will be visible at high temperatures even in the presence of significant black body radiation and emission from combustion gases, a situation which would render image contrasts of simple paints or surface shadings to be undetectable. The patterns we are using and/or considering are the Archimedean spiral, linear/rectangular/curvilinear patterns, and random artificial speckle patterns. An example of the linear pattern applied to a turbine blade is shown in Figure 1.

Figure 1. Turbine Test Blade.

An ultraviolet light source such as a nitrogen laser (337 nm) induces fluorescence from the phosphor. This fluorescence is narrow band and is distinguished from the background by an interference filter. There are two basic methods to measure change in the applied pattern. The first uses optical fibers. One fiber conveys the laser light to the sample and a separate fiber (or fiber bundle) receives the light. Figure 2 shows our first feasibility demonstration set up. A fiber illuminates the edge of one of the stripes. As the blade is stressed, the line

edge will move so that more (or less) fluorescence will be collected by the receiver fiber. Thus far, it appears that we have demonstrated a resolution of less than 100 microstrain.

Figure 2. Stress/strain Experimental Set-up.

The second method for observing the phosphor pattern involves an imaging system. It includes a color camera, a telescopic microscope, and the blade of figure 1 mounted on a micrometer-adjustable table. A Helium Cadmium laser illuminates the phosphor. The telescopic microscope can magnify the 1/16 in. wide phosphor stripe to where it fills half of a monitor screen. Using this set-up in conjunction with an image processing system, we have measured the equivalent of 20 microstrain.

Heat Transfer

The feasibility of using thermographic phosphor technology for optical, surface-heat-flux gauge measurements has been demonstrated.⁷ It is an extension of temperature measurement techniques we have been developing. The approach consists of measuring the temperature at two different depths of a film or tape applied to a surface of interest. A prototype gauge was constructed by depositing the phosphors $\text{La}_2\text{O}_2\text{S:Eu}$ and $\text{Cd}_2\text{O}_2\text{S:Tb}$ on the two faces of a polymethyl pentene insulator. The top layer of phosphor and the insulator are sufficiently transparent to allow the lower layer to be excited. The two phosphors thus fluoresce simultaneously at different wavelengths. Therefore, simultaneous observations of temperature are possible. A heat flux of 40 kW/m^2 was measured. This was a steady-state heat flux at a single point on a stationary surface. However,

the gauge is designed to measure transient heat flow as well. The technique is conceptually expandable to two-dimensional measurements. The camera mentioned previously and an image processing system will soon be used in a study of this.

Skin Friction

Skin friction or fluid-induced shear stress is an aerodynamic property that is often important when there is relative motion of a body in a fluid. The method of skin friction determination we are investigating is based on the use of heat transfer measurements. The approach is an extension of a method due to H. Ludwig.⁸ Ludwig's gauge, shown in figure 3, consisted of an electrically-heated metal strip in the surface to be measured in conjunction with a thermocouple surface temperature monitor. The temperature rise relative to the fluid temperature associated with a known quantity of heat deposited in the surface by the metal strip is related to the shear stress.

Figure 3. Ludwig's Sensor.

Our embodiment is depicted in figure 4. It shows a CW laser beam impinging on the surface as a heat source as an alternative to Ludwig's heater. The associated surface temperature is determined by the thermographic phosphor technique rather than by a thermocouple. By combining laser heating with laser thermography using a thin layer of temperature-sensitive phosphor applied directly on the surface, we have the capability of non-intrusive, remote measurement of shear with the additional advantage of rapid scanning. As an added benefit, the technique will yield transient or steady state measurements of heat

transfer as well as wall shear. It may thus be used as a means for detecting transition to turbulence in the boundary layer.

Figure 4. Phosphor-based shear stress sensor.

Our analytical investigations show that the method is applicable for shear stress for the case of interest to us, supersonic flows of moderate Reynolds's numbers.

Pressure

The fluorescence intensity and duration of $\text{La}_2\text{O}_2\text{S:Eu}$ and similar phosphors is dependent on pressure.^{9,10} Line shifts can also be produced by high temperature but the effect is small. The emission spectrum, shown in figure 5, of this material consists of four series of lines. Each series exhibits a unique characteristic response to temperature and pressure. The emission intensity and decay constant is essentially independent of temperature until a threshold temperature is reached. At that point, intensity and decay times decrease with increasing temperature. The threshold temperature for each series is different. An increase in pressure has a similar effect on the emission that cooling the phosphor would have. From measurements made by Webster⁹ and by Seals¹⁰ et. al., it is observed that pressures of 5 to 10 kbar are necessary to observe a noticeable effect. With appropriate design, mechanical amplification of pressure by a factor of ten and more is possible. Figure 6 is a schematic of a sensor design we have used for demonstrating that sufficient fluorescence intensity is available. The fiber core diameter was 600 μm . Alternatively a single fiber has been used as well. The fluorescence generated is conveyed to suitable

optics and detectors in order to ratio the two chosen colors.

Figure 5. Fluorescence Spectrum.

Figure 6. Phosphor-based Pressure Sensor.

It may be useful to note that simultaneous temperature and pressure measurements may be possible with proper test design. Line shifts versus pressure have not been measured for this

material. Judging from the weak line shift versus temperature however, the effect is not expected to be great. A line shift method has the benefit of being essentially instantaneous.

Laser-Beam Profiling

A knowledge of laser beam profile is necessary in many applications, particularly in laser processing. To monitor and control the beam shape requires a means to observe it. This is particularly difficult with invisible lasers, ie. in the ultraviolet and infrared. Whereas phosphors have been used to some extent over the years in locating laser beams, they are increasingly being used in more quantitative beam measurements. In this area, Omar¹¹ et. al. have described their experiments with glass fluorescing materials to convert ultraviolet light from a KrF laser to visible luminescence. This luminescence is recorded with a standard video camera. In this manner, they obtained single-shot laser-beam profiles.

There are at least two ways to view infrared light with these types of materials. There are phosphors which emit visible light when excited by infrared radiation from sources such as a Nd:Yag laser. Imaging screens and even polymer cubes with phosphor uniformly suspended in them are available commercially. These are typically electron trapping materials which must first be excited by visible light. Visible fluorescence results from liberation of the electrons by infrared laser light. These materials work best in the near-infrared.

The other approach is to use the heat generated by an infrared beam. McInnes and Wilson¹² have demonstrated the approach. They used a mylar film as the laser-heated target and a thermal imaging camera. A natural extension is to use thermally sensitive phosphors for applications where conversion to visible light is necessary. For instance, this would allow an image to be conveyed via a fiber bundle. The phosphor must first be stimulated by visible or ultraviolet light. The heat produced by the infrared source usually quenches the fluorescence. This is the basis of a commercial spectrometer. On the other hand, we have observed an interesting effect with certain phosphors whereby it is possible to increase emission by means of laser-generated heat. We have shown in previous work that the associated ultraviolet absorption of these materials shifts to the red with increase in temperature. As seen in Figure 7, this shift is approximately 5 nm per 100°C for $Y_2O_3:Eu$ for example.¹³ By properly choosing the ultraviolet excitation wavelength, the laser-generated heat can shift the absorption band into resonance with excitation light, thus increasing the phosphor emission. We have observed this effect, for instance, with $Y_2O_3:Eu$, $La_2O_2S:Eu$, $YVO_4:Dy$, and $Mg_4(F)GeO_6:Mn$, among others. It should work with any phosphors with absorption-width features that are temperature dependent. We have used a nonimaging detector thus far. With a camera, two-dimensional data can be obtained.

Figure 7. Temperature-dependent Excitation spectrum.

Aerodynamic Flow Measurements

Sweet and White¹⁴ demonstrated in 1970 that a hydrogen diffusion flame could induce rare-earth oxides doped with terbium and europium to luminesce. They had coated a substrate with phosphor and immersed it into the flame. This in itself suggests the use of seeding phosphor particles in aerodynamic flows for time-of-flight velocity measurements as well as temperature. Goss¹⁵ et. al. have performed the only work along this line to our knowledge. They initially investigated luminophors as a means of measuring surface temperatures in solid-fuel propellants. In subsequent work they seeded a flame with particles of Dysprosium doped Yttrium Aluminum Garnet. They observed fluorescence signal in the environment and thus demonstrated the feasibility of the approach. They plan further work.

Radiation

Many of these materials were originally designed for cathode ray, X-ray and Gamma ray applications. We have done some preliminary investigations into another area of radiation detection, that of high energy particle beams. Two phosphors, La₂O₂S:Eu and Y₂O₃:Eu, were subjected to 30 ps bursts of a 100 MeV electron beam. As expected, essentially the same spectra were observed as with lower energy excitation. In addition, some transients of nanosecond or faster duration were seen the origin of which has not been clearly identified. Nonetheless, the

materials are quite hardy and point to possible uses in this area.

Conclusion

It is clear that there are a large number of potential sensing uses for luminescent materials. As the cost of excitation sources, detectors and analysis systems decrease, applications in science and industry will increase.

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