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Phosphor Thermometry Of Gas Turbine Surfaces

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DISCLAIMER

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ABSTRACT

This paper describes a nondestructive method for thermometry applicable to ceramic surfaces and coatings. To date our primary application has been to turbine engine and air vehicle surfaces. This method makes use of thermally sensitive phosphors many of which, as it turns out, are also ceramics. These materials fluoresce when suitably illuminated by ultraviolet light. The fluorescence intensity and decay time are well-behaved functions of temperature and therefore serve as reliable indicators of the temperature of the substrate to which the fluorescing material is attached. It is a non-contact method in that the light delivery and collection optics can be remotely located. A range of phosphor materials have been tested and any temperature ranging from 8 to 1900 K can be measured by selection of the appropriate phosphor. Turbine blades, vanes, thermal barrier coatings, and panels are examples of surfaces which have been diagnosed to date in either engine or engine-simulation facilities. A variety of coating methods are used, including electron-beam deposition, radio-frequency sputtering, and curing with inorganic binders. This paper summarizes the results to date and status of this technology.

INTRODUCTION

The first application, to our knowledge, of phosphors to temperature measurement concerned aerodynamic surfaces (Urbach et al, 1949). However, the method for analyzing the data was cumbersome and laborious given the laboratory equipment available at the time. Nevertheless, since the 1960's, it has been in continuous use in aerodynamic heating wind tunnels at Arnold Engineering Development Center (Dixon and Czysz, 1966). Similar work is being conducted at NASA Langley by Buck (1988). Luxtron has marketed several phosphor thermometry devices since 1979 (Wickersheim and Alves, 1979) which are useful for a wide range of applications including medical and industrial environments (Wickersheim and Hyatt, 1990). Luxtron instruments make use of a phosphor, operable to 450 C, which is in contact with or proximal to an optical fiber. Since the early 1980's, our collaboration has generally addressed remote, high temperature (Noel et al, 1992), and high rotational speed surfaces (Allison et al, 1988) such as in turbine and combustion engine environments. Heat flux can be measured with a multilayer of phosphor also (Turley et al, 1989). The remote applications have involved distances ranging from a few centimeters to as much as 5 m between the phosphor-coated surface and collection optics.

Ceramic and ceramic-coated components will be of increasing importance in advanced engines which are under development. Ceramics allow engines to run at much higher temperatures than the superalloys in more conventional engines can survive. There are two options for non-contact high temperature measurements in ceramic-component environments, pyrometry and phosphor thermometry. Two difficulties are foreseen for pyrometry. First, pyrometry requires high emissivity. Ceramics are characterized by low emissivity. Further, emissivity is known to change with temperature and must therefore be characterized in detail for accurate measurement to be possible. Also, it appears that ceramics become translucent at high temperatures (Liebert, 1978). In such a case, blackbody radiation from the ceramic will originate from a distribution of points extending into the bulk of the material. Reflections provide a further source of optical noise. These factors complicate the optical design of the pyrometer. Phosphor thermometry, however, is just as applicable to these surfaces as to metallic engine component surfaces. Fluorescence measurements do not depend on emissivity. Furthermore, the phosphor is applied as a thin layer to the surface of interest and hence yields the substrate temperature. It is interesting to note that since many phosphors are also ceramics, it should be possible to incorporate the phosphor into many ceramic components without compromise of form or function.

DESCRIPTION OF THE METHOD

Any material which fluoresces can potentially be used to measure temperature since over some temperature range the fluorescence properties will change with temperature. Phosphor materials are designed to have high fluorescence efficiencies and are especially good for this however. The lighting, display, and solid-state laser industries have spent many years researching and developing these materials and consequently many durable and efficient phosphors have been developed. Also, they are fairly well understood. A phosphor is a solid to which an impurity, known as an activator, has been deliberately added. To produce the fluorescence, energy must be deposited in the phosphor by some means. For displays it is an electron beam which excites the activator. For medical fluoroscopy imaging, it will be an beam of X-rays. For thermometry applications, commonly a beam of ultraviolet or visible light is used. If the energy source is pulsed, then the fluorescence will persist for a characteristic period, falling off rapidly when the energy source is turned off. Often the time dependence follows a simple single-exponential dependence where I is the instantaneous intensity and I_o is the initial intensity:

$$I = I_o \exp(t/\tau)$$

The time, τ, for the fluorescence intensity to decay to 1/e of its initial value is known as the decay time or lifetime of the fluorescence. It is this property which exhibits the most striking change with temperature, as a rule. Figure 1 depicts the time dependence of a typical phosphor signal. The logarithm of the signal is shown in Figure 2. The decay time is the inverse of the slope of this waveform. The greater the slope, the shorter the decay time. The decay time may remain essentially constant over a particular temperature range, until, at a characteristic threshold temperature it will begin to rapidly decrease. A representative plot of lifetime versus temperature for several typical phosphors is shown in Figure 3. Such a plot for each phosphor is known as its calibration curve. It is seen in the figure that by selection of the appropriate phosphor, a wide range of temperatures may be determined. It should be noted that the calibration of any particular type of phosphor depends on dopant concentration, method of fabrication, particle size, etc.

Any system for thermographic phosphor thermometry will consist of the following basic components: a light source, an optical arrangement to deliver the excitation light and return the fluorescence, a detector which converts the fluorescence to its electrical analog, and a data acquisition and analysis system. Timing electronics are necessary if a laser must be synchronized with a rotating surface. Figure 4 shows a representative optical arrangement that is used (Tobin, 1990a). A high peak power laser is required for producing the brightest possible fluorescence, in this case it is a Nd:YAG laser operating at the third harmonic (355 nm). It is reflected by a dichroic mirror and focused into a large-core fused-silica fiber which exhibits a high optical damage threshold and efficiently conveys ultraviolet light. The probe consists of the fiber and a lens which focusses the light onto the surface and which collects the fluorescence thus generated. The return fluorescence, which is visible, is transmitted by the dichroic mirror and focused into a fiber connected to a photomultiplier detector. In other situations a lens system may replace the optical fibers if the distances are not too great and there is a clear line-of-sight.

BONDING CONSIDERATIONS

The method for attaching the phosphor to the surface of interest is very important. Much effort has been invested in developing and testing phosphor coating methods. This is one of the most important issues for turbine blade and vane applications since the combination of high temperature, vibration, and abrasion can remove a phosphor coating.

Especially when adhesion is critical, surface cleanliness and surface roughness are important concerns. In such cases, abrasive blast cleaning serves both purposes. A degree of roughness is required in order to provide a "microscopic tooth" to which the phosphor/binder may adhere. Blast cleaning should proceed only until the mirror-like surface sheen is lost. Damage to the substrate should be avoided. Ultrasonic cleaning may be used as well as conventional solvents (eg. acetone). Scrubbing with non-abrasive brushes to remove grit may be beneficial. Clean air blasting may remove loose grit. Lastly, the piece may be dried in an oven to minimize water absorption and other contaminations.

When phosphor thickness is not an issue, chemicals with adhesive properties can be mixed and applied to the surface. To our knowledge, epoxies may be used to about 350 C. Above this, a variety of binder materials, for instance, some based on silicates, silicones and silicates, water-mix refactories, can be used. Some up to 1200 C. The Sperex VHT-1 has become the all-purpose binder material in our lab. A cure cycle of one hour at 200, 400, and 600 C is recommended. In situations where this is not possible or practical, a room temperature cure may suffice if there is no exposure to solvents.

Electron-beam (E-beam) vapor deposition produces durable and thin coatings. The phosphor must be cold- or hot-pressed into a disk shape and mounted in the vacuum chamber. A typical system consists of a 24 inch vacuum chamber evacuated to $4*10^{-6}$ torr and beam set to 6 kV and about 40 to 50 mA. Deposition rates vary from about 0.2 to 2 μm/hour. Among the advantages are the great degree of film thickness control and the fact that there is no binder. The latter absorbs and scatters excitation light and decreases efficiency

RF sputtering functions similarly to E-beam deposition. For this, the target achieves the vapor phase by momentum exchange, a mechanical process. The results are very similar to those achieved with the E-beam technique.

Regardless of the method used for preparing and bonding the phosphor to the surface of interest, there are significant increases in efficiency to be obtained by post-annealing. After such post-processing, efficiencies ranging from 30 to 60% of the pure phosphor powder can be achieved.

FIELD TEST APPLICATIONS

Our collaboration has tended to address situations involving developmental test installations. The program began when there was a need for measuring the surface temperature of a high speed gas centrifuge (Cates et al, 1984). The temperatures were ambient. A significant technical hurdle related to the fact that the fluorescing surface moves into and out of the field of view of the collection optics during the measurement. This was solved by first noting for the particular phosphor used (La_2O_2S:Eu) that there was an emission line whose lifetime did not change in the range of interest. A comparison was made of a stationary and the moving signal of this temperature-independent fluorescence line. The ratio of these two signals yields the motion factor. It was used to succcessfully normalize the temperature-dependent signal. The next step was to test the approach in a combustion environment. This was first done at a high-altitude simulation wind-tunnel at Arnold Engineering Development Center. There, exhaust from the aft end of a PW F100 engine impinged on a variable-area extractor (VAE). Measurements were made of the surface, even when an afterburner flame intervened between the surface and detection optics. The water-cooled VAE was still at a fairly low temperature, about 150 C (Allison et al, 1987). This was the beginning of a program still in progress for developing the methodology for turbine engine diagnostics.

In preparation for subsequent engine experiements, test were performed at a burner-rig installation. This is a device for exposing turbine blades to an engine simulating environment. Several blades are attached on a carousel and rotated (at fairly low speeds) in a jet fuel flame. Phosphor thermometry tests by Tobin et al (1990b) in such an installation demonstrated the technique to 1100 C. In concert with this, a spin-pit test was conducted which simulated the higher rotational speeds and intermediate temperatures (but without a flame) encountered in turbine engines.

The in-situ engine experiments have involved a PW2037 engine at Pratt & Whitney (PW) in Hartford, CT. (Tobin et al, 1990a); an ATEGG (Advanced Turbine-Developmental Military Engine) engine at PW of West Palm Beach, FL. (Noel et al, 1992); an experimental turbine engine at Virginia Tech (Tobin et al, 1990b), and a JTDE (prototype Joint Technology Developmental Engine) engine also at PW West Palm Beach (Noel et al, 1994). From these, collectively, it has been shown that phosphor materials based on yttrium oxide, yttrium vanadate and yttrium aluminum garnet (YAG) can survive for several weeks even in the first stage of a turbine where the blades are adjacent to the burner. Signals were obtained and measurements were made to in excess of 1000 C. The optical probe design has evolved to a two-fiber configuration with internal optics designed with coatings to minimize 1) stray reflections, 2) laser-induced damage to the input fiber, and 3) blackbody background light.

THERMAL BARRIER COATING

A phosphor has been incorporated into two tests involving thermal barrier coatings (Domingo, 1991.) The heat-transfer effectiveness of such coatings are of importance to diesel engine and diesel-fueled low-heat-rejection engines. A thin (20 to 25 micron) phosphor layer was applied to a plasma-sprayed, partially stabilized, zirconia coating on a cast-iron test disk. A luminous flame from an n-butane/air burner heated the specimen. Several phosphor materials were tested and all worked effectively in their operating range. A small nitrogen laser illuminated the sample through the flame and a simple lens imaged the fluorescence onto a monochromator which selected the emission line to be measured. Whereas thermocouples provided reliable measurement on the opposite side of the disk, it is clear that their high thermal conductivity, size and shape render them suspect for the flame side of the specimen. Clearly, pyrometry is not effective, either, for the flame-immersed side of the sample. Phosphor materials are particularly appropriate for heat-transfer measurements of this type.

A further development of use to thermal barrier and heat transfer applications is a heat flux gauge which consists of a sandwich of two phosphor separated by a thin plastic layer (Turley et al, 1989). Heat flux is proportional to insulator thickness and thermal conductivity as well as the difference in temperature determined by the two phosphors.

CONCLUSION

For high-temperature applications and in engine environments with high thermal radiation backgrounds, phosphor thermometry is particularly well suited. Its major advantages are in being unaffected by emissivity and being relatively immune to blackbody emission and electromagnetic backgrounds. The technique is fundamentally an absolute measurement of temperature and can be extended over essentially the entire range of the solid state of many materials. Because many phosphors are refractory materials, their surface application to thermal barrier coatings is particularly attractive, both from considerations of durability and aerodynamics. Developments continue which are leading toward practical use of high-temperature heat flux gauges and thin-film crystalline layers. As gas turbines are improved in efficiency and performance for future demands, the accurate non-interfering monitoring of critical temperatures will be a fundamental necessity, moving phosphor thermography into an increasingly more important role.

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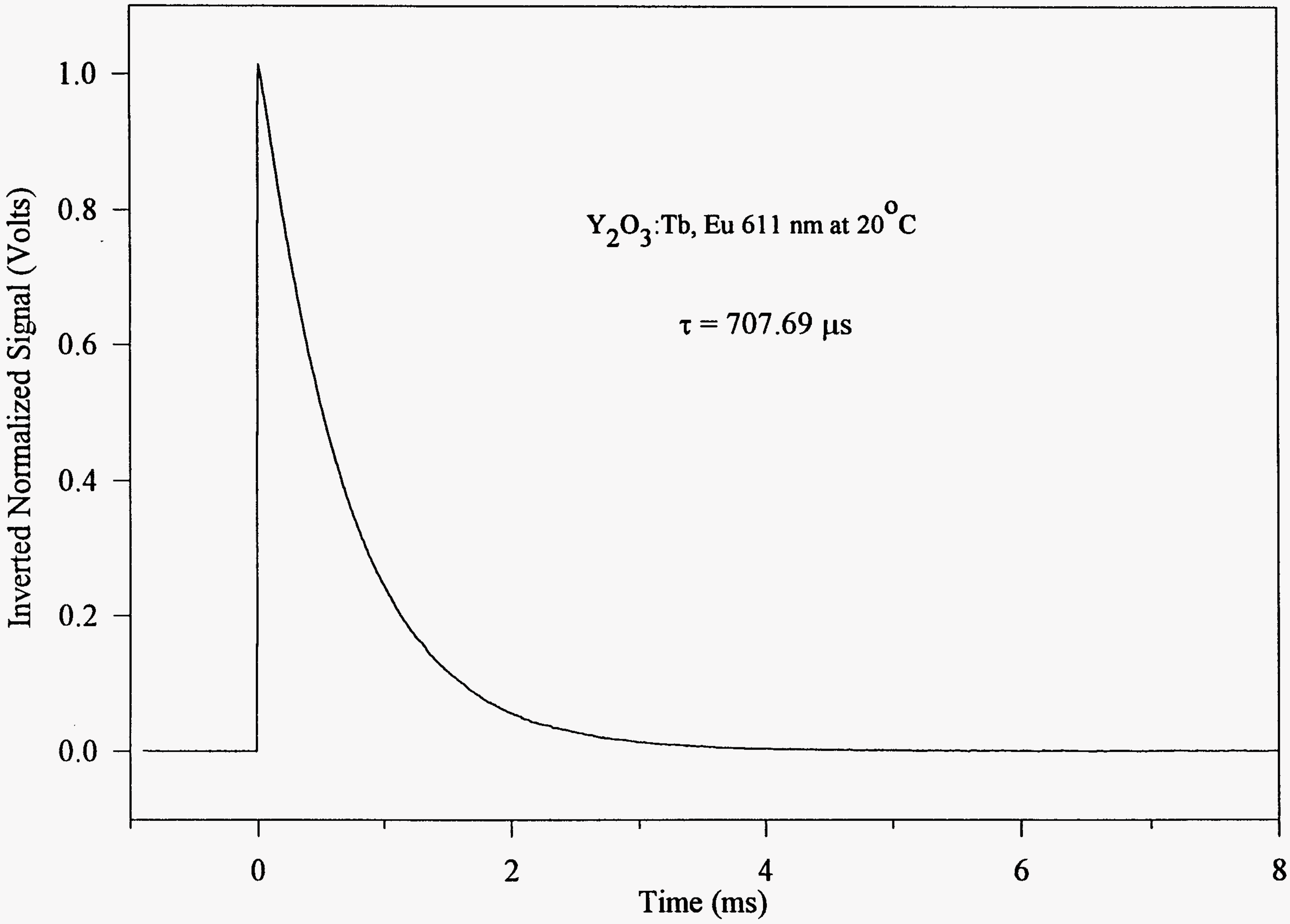

Figure 1. Time Dependence of Phosphor Emission.

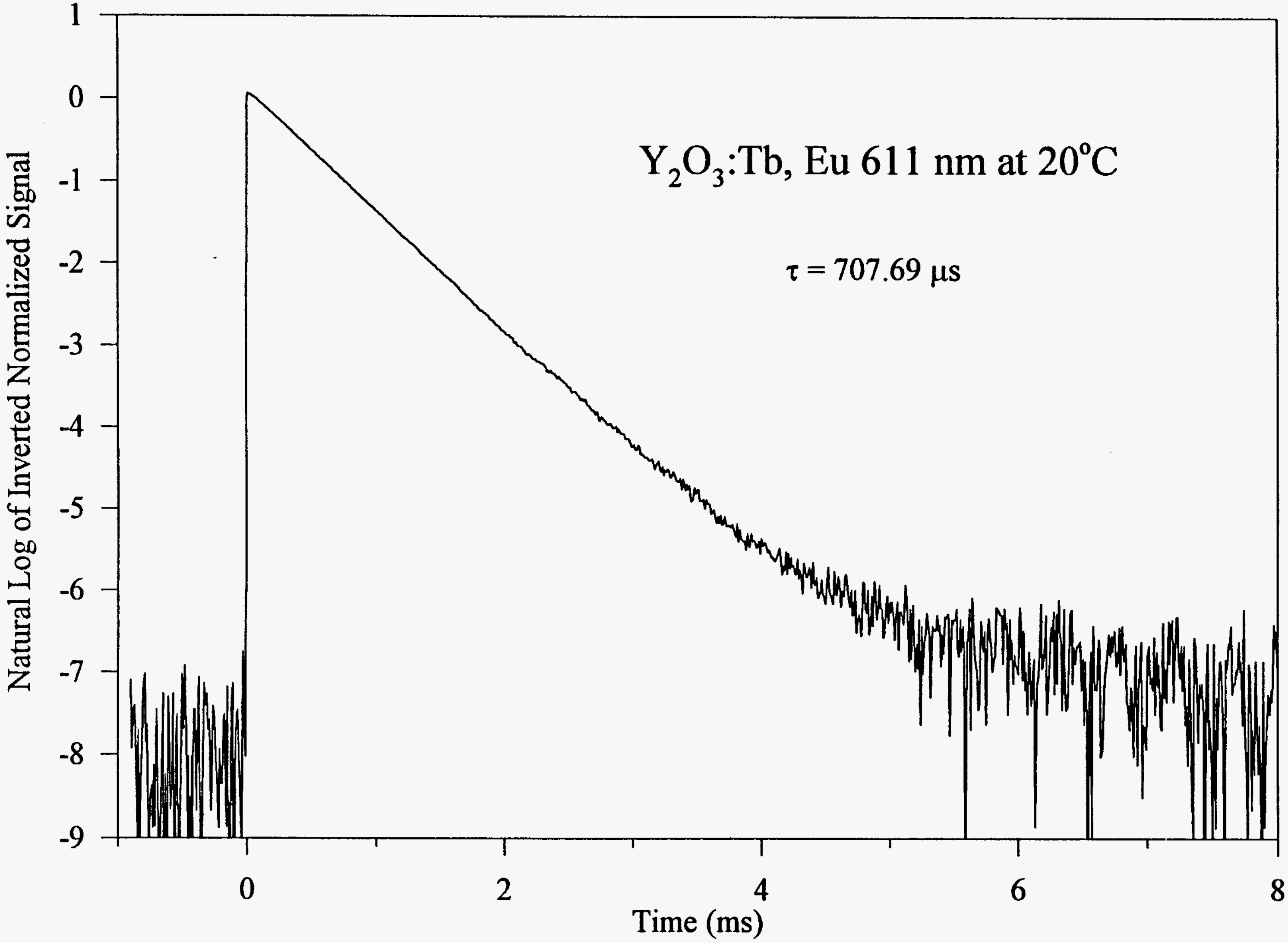

Figure 2. Logarithm of Emission Time Dependence.

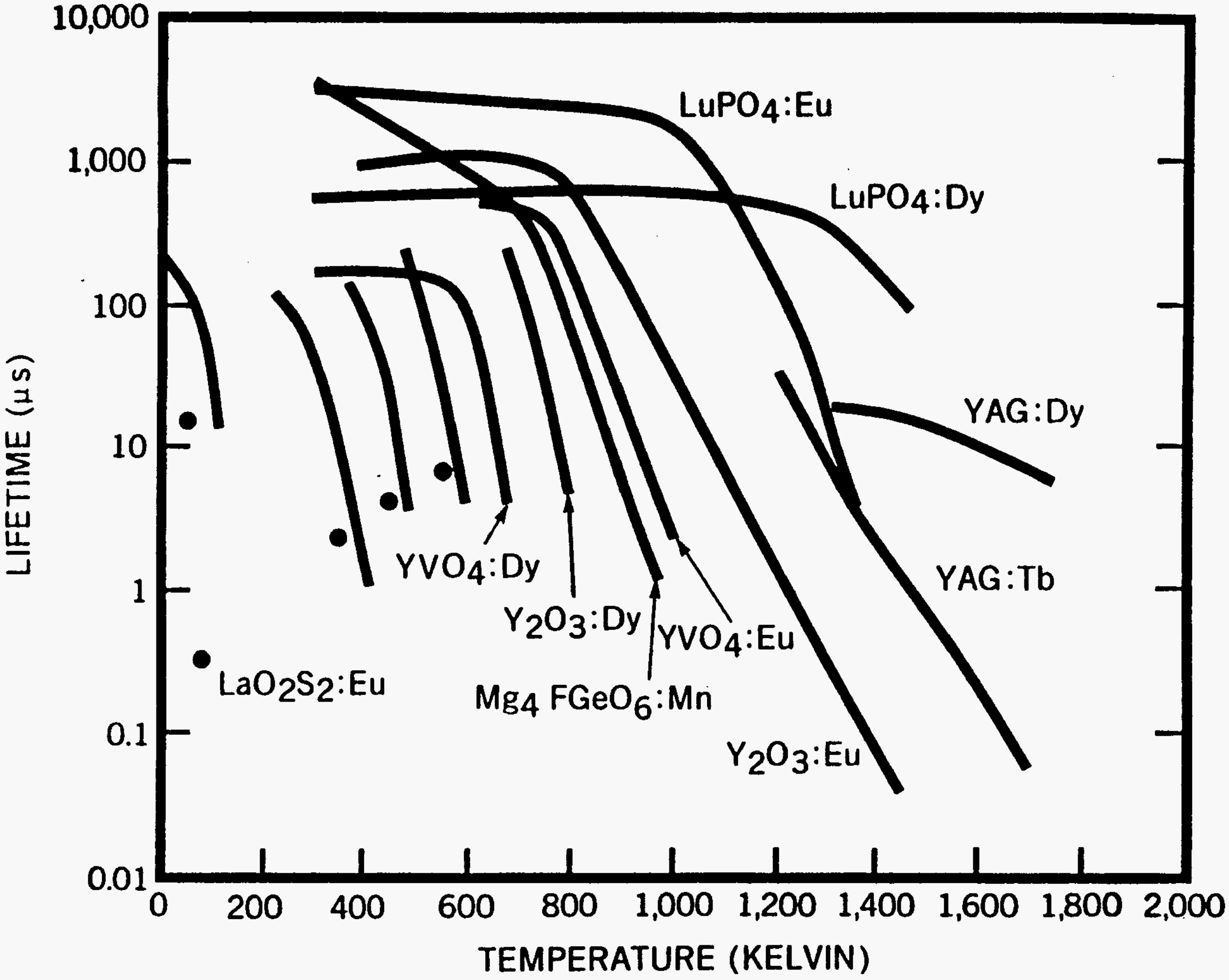

Figure 3. Representative Decay Time vs Temperature for different Phosphors.

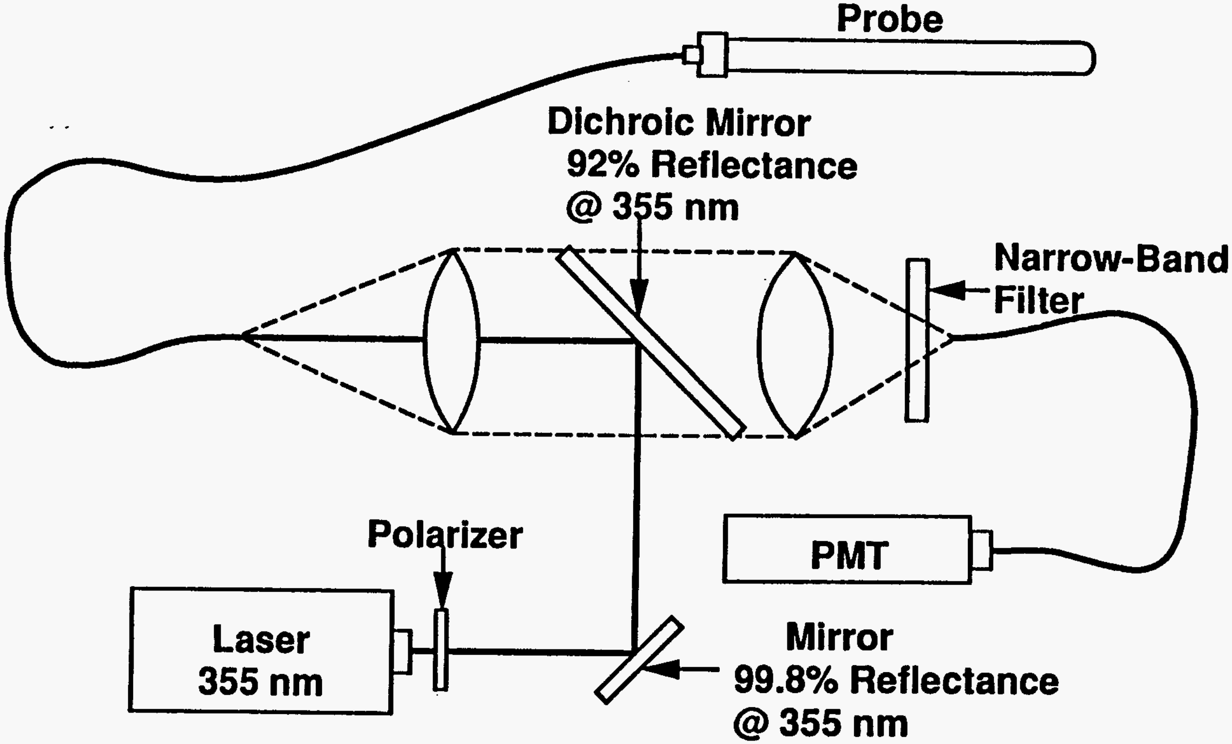

Figure 4. Optical Set-Up.

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