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Optical Thermocouples for Explosive Fireballs

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Abstract. We have developed optical thermocouples (OTCs) for use in explosive fireballs. The OTC consist of an optical fiber with a fluorescent phosphor coating. The phosphor, Dy-doped YAG, is a well-known two-color thermometry material, which is excited with a pulsed ultraviolet laser. As temperature increases, a higher excited energy level is populated and starts to emit fluorescence. Temperature can be determined by monitoring the intensity ratio of two fluorescence bands. We recently conducted our first field tests of these OTCs and report on their performance as well as further design improvements.

INTRODUCTION

Accurate gas-phase temperature sensing within explosive fireballs is a difficult task as gas temperatures undergo rapid changes and reach high peak temperatures [1]. Currently temperature measurements in explosions utilize traditional techniques – thermocouples (TCs) and pyrometry – but their accuracies are doubtful as survivable thermocouples have relatively slow rise times and pyrometers are limited to measuring the surface of a fireball due to the hot gases opacity [2, 3]. Given the limited usefulness of TCs and pyrometers in explosive fireballs much work has been done to develop new temperature sensing techniques that provide improved temporal response and survivability. Currently there are three main approaches to address this challenge (which are of interest to the Defense Threat Reduction Agency), including a technique involving temperature sensing based on water vapor absorption [4–8], a multi-TC approach, and optical thermocouples (OTCs) [9–11].

Temperature sensing using either water vapor absorption or multiple thermocouples have been under development for a number of years, and the OTC technique is currently the most recently developed approach for measuring gas-phase temperatures in explosive fireballs. This technique involves coating sapphire fiber probes with Dy-doped YAG (a well-known two-color thermometry phosphor), which are probed using a pulsed 355 nm Nd:YAG laser. The resulting photoluminescence (PL) is temperature dependent and can be used with an appropriate calibration curve to determine the temperature of the sapphire film. Due to the film being relatively thin ($< 10\,\mu$m), it is expected to have a fast rise time [10, 11].

Thus far the OTC technique has only been tested in controlled lab conditions using blow torches and CO_2 laser heating. In this study we report on the results of the OTC systems first series of field tests measuring temperatures in a test series consisting of three different explosive charges in a pseudo-closed chamber. We find that while the OTC equipment survives the explosions well and does provide some temperature data, there is a significant challenge with regards to background light from the explosive fireball which can cause the photodetectors to saturate. After discussing the OTC results from the test series we end with a discussion about vulnerabilities identified during testing and discuss ways of mitigating these challenges.

METHOD

Two-color thermometry of Dy:YAG is a well known temperature sensing technique [12–16] in which photoluminescence is used to probe the relative ratio between two closely spaced excited states ($^4F_{9/2}$ and $^4I_{15/2}$), whose relative

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populations are determined by the temperature and are related to the measured intensities as

$$\begin{aligned} \frac{I_2}{I_1} &\propto \frac{n_2}{n_1}, \\ &= \exp\left\{-\frac{\Delta E}{kT}\right\}, \end{aligned} \tag{1}$$

where ΔE is the energy spacing between the two excited states, T is the temperature, k is Boltzmann's constant, I_i are the measured PL intensities, and n_i are the populations with $i = 1$ being the ${}^4F_{9/2}$ state and $i = 2$ being the ${}^4I_{15/2}$ state. For the OTC probes we use use a thin layer ($< 5\ \mu$m) of Dy:YAG deposited on a sapphire fiber using pulsed laser deposition. The small thickness of the film is predicted to result in a fast time response in an explosion with a rise time on the order of several hundred μs [10, 11].

To measure the OTC probes' PL during field testing we built a portable fiber-based analysis system that couples laser light from a frequency tripled Nd:YAG excitation laser (Photonix industries DCH-355-5, 355 nm, < 7.1 W average power, 0–200 kHz repetition rate, 9-51 ns pulse width) into a long low-OH glass fiber that runs from the analysis system to the probe in the test structure. This excitation light excites PL from the Dy:YAG film, which gets coupled into the long glass fiber and is passed back to the analysis system which consists of a 400 nm long pass filter, a 50:50 beam splitter, two bandpass filters (10 nm bandwidth centered at 458 nm and 500 nm), and two Si PMTs (Thorlabs PMT1001). Note that we use an identical optical analysis system (without excitation light) as a reference measurement of background light in the chamber.

The bandpass filtered light from both the probe and reference fibers are converted into electrical signals using the PMTs, with the outputted voltages being measured by a DAQ at a 1 MHz rate. Once the electrical signals are measured they are first analyzed using a software-based boxcar averager, which removes a fast PL component arising due to fluorescence from the long glass fiber. This averaging results in a reduced data rate of 80 kHz. Once averaged, the resulting reference signals are subtracted from the probe signals to isolate the components due to probe PL. These isolated components are then used to compute the band integrated intensity ratios, from which we can determine the temperature using lab-based calibration. For field testing we place our OTC probe assembly in a multiroom test structure. The probe assembly is placed in the same room as the explosive charge, with the charge varying between test runs with three separate charges (A, B, and C) being used. Charges A and B are tested three times while charge C is only tested twice.

RESULTS

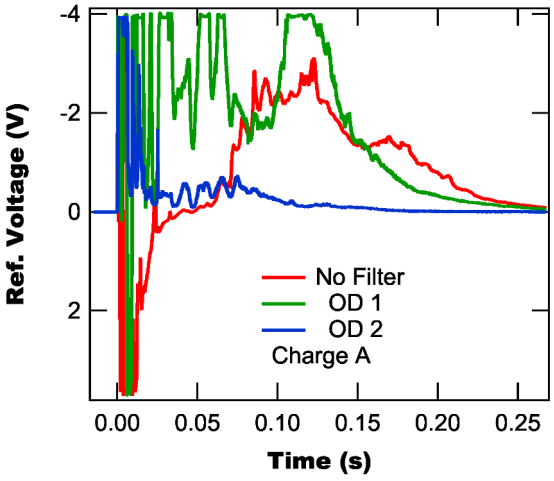
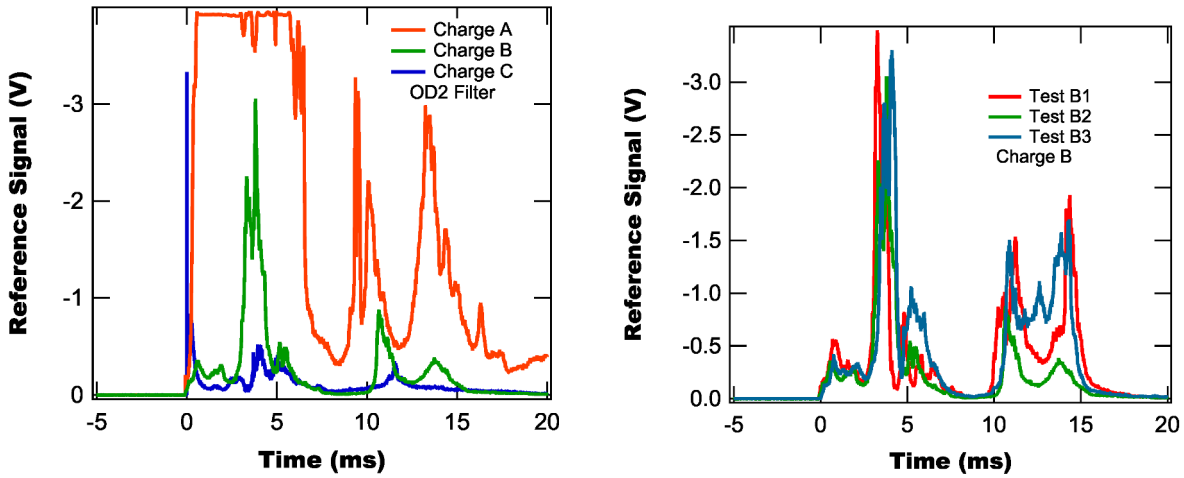


FIGURE 1. Light curves for charge A using different OD filters measured by the 500 nm bandpass reference channel.

We begin our discussion of explosive fireball testing by reporting on the general performance of the system. Namely, after performing 8 explosive tests we found that the probe mounts and coupling fibers were undamaged by the explosions. We also found that while the Dy:YAG films were undamaged by the explosion, they were coated in a layer of dust and dirt. These results are encouraging for the robustness of our technique when exposed to an explosion. While we changed the probes every shot (due to the dust and dirt on the probes), it is likely that a cleaning procedure could be developed to reuse the same probe for multiple shots. Additionally, we found that ground shocks from the explosions had negligible effects on the optical alignment of our analysis cart, which was placed outside (but near) the test structure.



(a) (b)

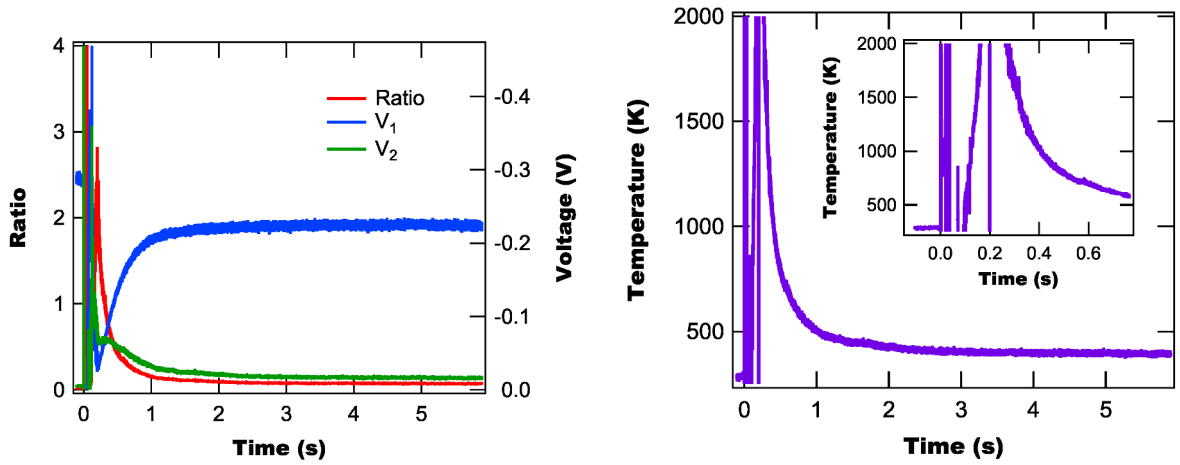
FIGURE 2. Comparison of light curves measured by the 500 nm bandpass reference channel (using an OD2 filter) for the different charges (a) and for three identical shots using charge B (b).

Having provided an overview of general OTC equipment observations from the testing, we next consider the background light curves from the three shots using charge A with three different levels of neutral density filters (no filter, OD 1, and OD 2). Figure 1 shows the voltage traces measured for the 500 nm bandpass filtered reference channel at three different ND levels. From Figure 1 we find that for both no filter and an OD of 1, the PMTs saturate and result in voltage artifacts (i.e. the voltage changes sign). Note that the OD2 filter trace also saturates, but doesn't display the voltage artifacts.

After observing the strong background signal for charge A, we switched to using an OD2 filter for subsequent shots using charges B and C. Figure 2a compares the background voltage traces for all three charges using an OD2 filter. From Figure 2a we find that all three traces display a jump in signal within 500 μs of detonation. This rise in signal is consistent with modeling predictions of when the charge casing breaks and the fireball begins expanding. Thus this first bright peak is most likely due to light from the fireball as it begins expanding. About 3 ms after detonation we see another peak in the light curve which fits with the predicted timing of the arrival of the fireball at the OTC sensor. This peak can be attributed to thermal emission from the fireball as well as thermal emission from the probe tip as it heats up. For all three charges there are subsequent spikes due to the evolution of the fireball with time [1].

While Figure 2a compared the light curves from the three different charges, it is also useful to consider how reproducible the light curves are for repeated shots with the same charge. Therefore we plot the reference light curves for three shots using charge B in Figure 2b. From Figure 2b we find that the three light curves are similar, with the timing of peaks being very consistent between shots. However, we find that there are variations, especially when looking at the signal at 10 ms $< t <$ 15 ms.These variations are to be expected as an explosion is a very chaotic event.

Thus far we have considered how the background light signal changes with differing OD filters, charges, and repetitions. While this information is helpful in better understanding the dynamics occurring in the signal measured by the PMTs, it is not the primary goal of the OTC system, which is instead to measure temperature. To determine the



(a) (b)

FIGURE 3. Integrated voltages and their ratio as a function of time for charge A (a) and the corresponding temperature calculated from the voltage ratio (b).

temperature we compute the gate-averaged and background-subtracted band voltages and the resulting ratio between the two voltages, both of which are shown in Figure 3a for the charge A shot using an OD1 filter. With the ratio determined we then calculate the temperature measured by the OTCs using Equation (1) and in lab-calibration data. Figure 3b shows the calculated temperature for the charge A/OD1 shot.

From Figure 3 we find that the PMT voltages are difficult to interpret within the first 100 ms due to the PMTs saturating, which results in a messy signal. However, after this initial spike we find that the signals decrease such that we can correctly compute an intensity ratio. This intensity ratio is found to increase with time, spiking near 200 ms, which is followed by a bi-exponential decay. The fast decay component has a time constant of $\approx$ 500 ms, while the long term decay is on the order of 10s of seconds. These ratio results correspond to a temperature curve consisting of an initial spike in temperature to over 2000 K, followed by a brief period of cooling before there is another high temperature spike, with the two spikes being separated by $\approx$ 150 ms. During the final cooling the temperature cools to around 450 K within the first second after the explosion, but remains near 450 K for a significant amount of time, which we attribute to the pseudo-closed chamber design.

CONCLUSIONS

In the above sections we provided a brief overview of our OTC system and the performance results of its first field test series. While we were able to obtain some temperature data for the test series, we found that background light from the explosion is a significant challenge for the OTC approach, with background light causing saturation of the PMTs and complicating the analysis of the PMT signals. To address these challenges we have determined five improvements for future tests, including: (1) Utilize a physical shield to block direct light from the explosive case, (2) Paint probe mount black (to eliminate reflected light from the mount), (3) Position probe in a location that will minimize direct light from the explosive case, (4) Increase the pump power to improve the signal-to-background ratio, and (5) Utilize a lock-in amplifier to remove background. Improvements 1-3 are relatively simple physical changes designed to minimize the observed background, while # 4 is designed to improve the measured signal, and # 5 is designed to remove the background light without relying on a reference probe.

At the same time as these improvements are being implemented we are also planning on performing several secondary equipment improvements, including: changing to a UPS designed specifically for working with generators, improving ruggedization of the optics cart, and implementing a more reliable networking solution. These improvements promise to improve the reliability and portability of our system.

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