A FIBEROPTIC SENSOR FOR MICROWAVE FREQUENCY SUSCEPTIBILITY MEASUREMENTS

Often it is necessary to obtain sensitive measurements in an electrically hostile environment via a technique which will not alter or effect the environment in any way. An example is the measurement of high frequency electromagnetic susceptibility.

Kenneth A. Wickersheim, Earl M. Jensen, and Mei H. Sun, Luxtron Corporation, Mountain View, CA

INTRODUCTION

Electrical sensors, even if passive, have conducting metallic leads which can provide electrical leakage paths into the environment where the measurement is to be made. Also capacitive coupling between the sensing probe and the conductor may affect the measurement. In addition, electrical sensors may exhibit strong frequency dependence. Ferrite core current sensors, for example, do not work well in the GHz range because inductance limits high frequency response.

For these reasons, thermal techniques were adopted many years ago in weapons systems testing to measure currents induced by high frequency RF fields in the bridge wires of electroexplosive devices (EEDs).[1] The sensors developed for this application were custom fabricated, thin film thermocouples, which were positioned by trial and error close to, but not touching, the bridge wire of the EED to detect the resistive (I^2R) heating produced by the induced currents. Although these sensors are not particularly sensitive to direct heating by the RF fields, they do require electrical leads and can thus introduce uncertainty into the measurement through the possibility of perturbation of either the circuit under test or the local electromagnetic environment.

More recently, for real-time measurements, the electrical leads from such sensors external to the system under test have been replaced by fiberoptic data links.[2] However, this technique requires the addition of a fiberoptic transmitter within the system under test and thereby introduces the possibility of yet another source of measurement artifact. Apart from the electrical problems, the thin film thermocouples are difficult to fabricate and to install, particularly within the limited space available in most EEDs. Thus a simpler and more electrically passive sensor was needed.[2]

Also the purely electronic sections of weapons systems require a similar measurement technique.[3] As a result of these various needs, an all-optical temperature measurement system has been developed to replace the thin film thermocouples previously utilized.[4,5] Communication with each optical sensor is accomplished by a single optical fiber running from the sensor to the external instrumentation package. The sensor itself is remotely powered by light from the instrument so that no electrical power source or transmitter is required within the system under test.

This totally new technology may prove to be of value in a wide variety of EMC-related applications. In the following sections, the technology will be described; and the presently identifiable EMC applications will be discussed starting with the EED susceptibility measurements which led to its development.

ORDNANCE APPLICATIONS

For more than thirty years, the U.S. Navy has conducted safety testing of all naval ordnance exposed to shipboard electromagnetic environments. Such testing has been designated as HERO (Hazards of Electromagnetic Radiation to Ordnance) testing.[2] As shipboard radiation environments have become more hostile with time, the Navy's HERO concerns have increased. RF-sensitive EEDs continue to be used in most weapons systems. To ensure both the safety of the ship and the effective operation of the weapon in warfare, it is vital that the weapons be adequately insensitive to the RF fields to which they may be exposed.

Similarly, ordnance carried on an aircraft must be insensitive to the induction of currents in the firing circuits which may be produced by either the radiation environment or by electrical equipment onboard the aircraft. In order to be certain of this, electromagnetic compatibility (EMC) testing of weapons mounted on aircraft is also required.

Since the primary objective of the new fiberoptic sensor was to provide a replacement for the thin film thermocouples widely used in both HERO and EMC testing, that application is presently the most developed. The base technology utilized is called Fluoroptic[R] Thermometry and has been described in detail elsewhere.[6] In this technology, the sensor itself is formed from a fluorescent material (phosphor) located at the end of an optical fiber. All materials used in the sensor and probe are good electrical insulators and hence do not respond thermally to stray RF fields.

The sensor is stimulated to fluoresce by a short pulse of blue light from a flash lamp which is transmitted down the fiber from the instrument. The resulting red fluorescence from the sensor is transmitted by the same fiber back to the instrument where it is detected. The fluorescent decay time is determined by measuring the rate of decrease of the fluorescent afterglow once the exciting flash has terminated. The decay time is an intrinsic property of the sensor material. Its behavior versus temperature provides the calibration table from which sensor tempratures can be determined. This calibration is stored in the form of a digital look-up table within the instrument.

To fulfill the HERO-test needs, a program was launched[7] in which the following specific requirements were to be met:

- Measurements were to be made on actual bridge wires in the specific EEDs normally used in the particular weapon system under test. In short, the bridge wire

Figure 1. Photomicrograph of Miniminally-sized (Fast Response) Phosphor Sensor on 0.001-Inch Bridge Wire of Mark 1 EED. Tip of Tapered Fiber Which Illuminates the Sensor with Blue Light and Collects the Red Fluorescence Is Shown Above the Wire.

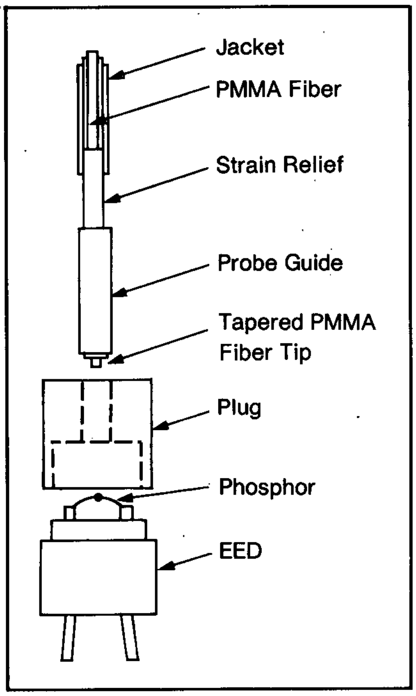

Figure 2. Cross Sectional View of Instrumented Mark 1 EED, Optical Fiber Assembly and Plastic Alignment Fixture. The Tapered Fiber is Used to Simplify Optical Coupling with the Small Sensor.

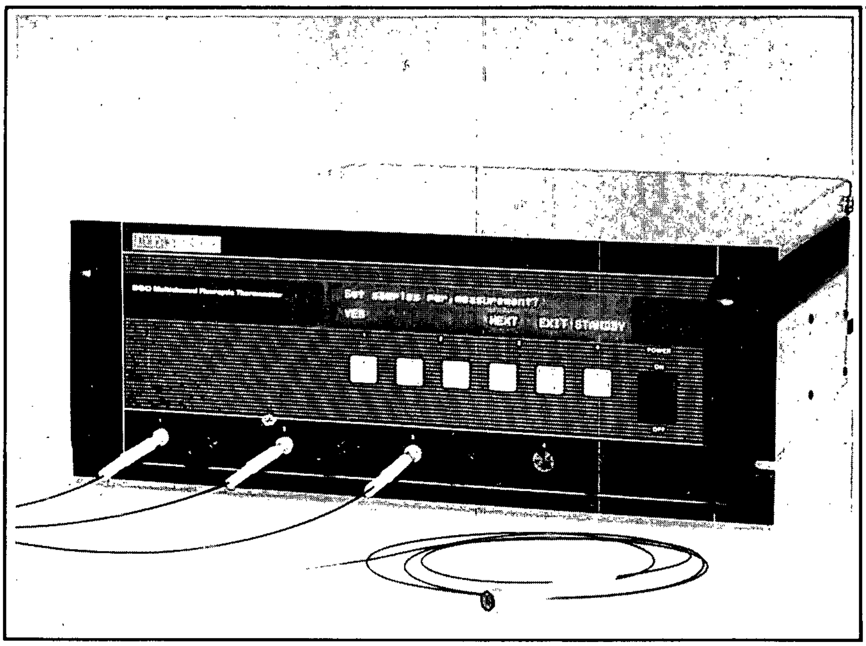

Figure 3. Fluoroptic Thermometer Developed for Use with EED Sensors.

could not be replaced by other sensitivity-enhancing or simulating structures. Rather, the temperature rises of the unaltered bridge wires within the weapon being illuminated by RF radiation had to be sensed directly. These requirements placed severe constraints on possible configurations for the sensor.

- Sensitivity had to be adequate to allow reproducible measurement of induced current down to 30 dB below the Maximum No-Fire Current (MNFC) rating of the EED being tested. The resistances and hence MNFCs of EEDs vary considerably from one type to another. For example, this standard of sensitivity requires the measurement of an induced current of 6 mA in the one ohm bridge wire of the fairly common Mark 1 type EED, which has an MNFC of 200 mA.

- Speed of response had to be sufficient to allow the measurement of transients which might be produced by the arcing of nearby electrical equipment or by pulsed RF or microwave power sources. Typically EEDs are tested in an inert configuration, i.e., without the presence of the explosive mix around the bridge wire. The Mark 1 type bridge wire has a thermal response time of 10 to 20 milliseconds. Ideally the technique developed would not increase the thermal response time of the bridge wire significantly in relation to these expected values. This goal dictated that the sensor itself be quite small so as to minimize its own thermal mass and that the optical fiber used in detecting the signal from the sensor not contact the bridge wire. Finally, the data rate of the measurement system needed to be reasonably fast.

- From a practical standpoint, it was desirable that both sensor fabrication and sensor installation be kept simple. The resulting technique also needed to allow the use of extension cables ranging from approximately 10 meters to perhaps as much as 70 meters in length as required by the test facility geometry. Lastly, the ΔT calibration (and hence the ΔI calibration) needed to be quite stable over long time periods and insensitive to changes in ambient temperature.

To meet these requirements, a technique was developed for coating a very small amount of the phosphor sensor material directly onto the bridge wire in the form of a 0.001 to 0.005 inch dot (see Figure 1). A tapered, light-concentrating fiber was then fixed in a position close to the sensor, but not touching it, so as to illuminate the sensor with the excit-

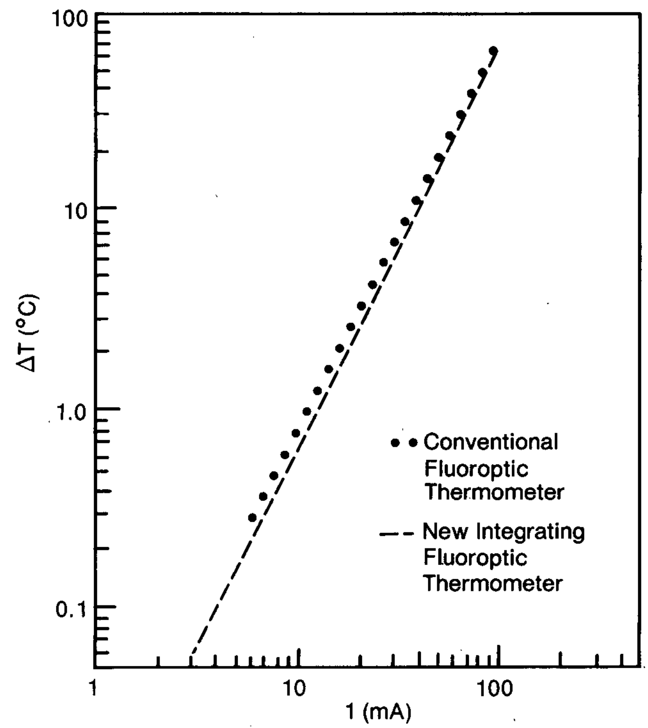

Figure 4. Data Taken on the Same Instrumentated Mark 1 EED with a Conventional Fluoroptic Thermometer and a Newer High Sensitivity Fluoroptic Thermometer. More Recent Improvements Have Pushed Sensivity Down to Nearly 1 mA.

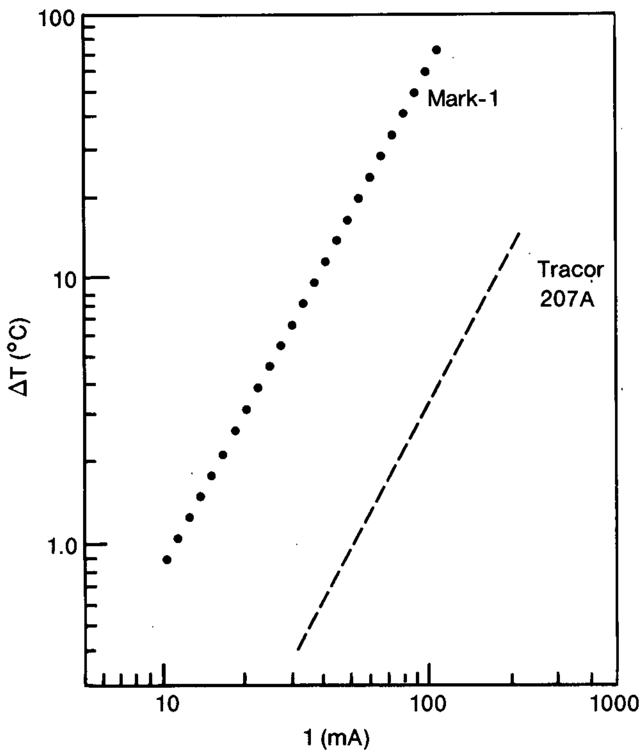

Figure 5. Plot of Resistive Heating Versus Current for Two Different Types of EED: the Mark 1 Has an MNFC of 200 mA Whereas the Tracor 207A Has a MNFC of One Amp.

ing blue light and to collect the resultant red fluorescence from the sensor for return to the intrument.[5] Special fixtures and techniques for aligning the fiber tip with the sensor were developed. To increase the sensitivity of the instrument, a self-normalizing signal integration technique[6] was developed, thereby improving the sensitivity of measurement of the decay time relative to standard fluoroptic thermometry systems. The maximum flash rate was also increased from 10 per second to 30 per second. Finally, the optical throughput of all portions of the system was increased to the maximum degree possible so as to ensure adequate optical signal levels even with long cables and with the very small, remotely-viewed sensors.

A cross-sectional view of the configuration of the EED sensor for a Mark 1 EED and its alignment fixture is shown in Figure 2. Figure 3 shows the newly-developed, high performance thermometer designed specifically to be used with the EED sensor and its associated extension cables. Figure 4 shows the results obtained for a Mark 1 EED. Figure 4 also indicates the sensitivity achievable, both with the new integrating fluoroptic thermometer and with the more conventional fluoroptic thermometer. Recent results indicate that currents down to nearly one mA (or about one microwatt of power) can be detected and measured. Figure 5 compares the results for two different types of EEDs having different bridge wire resistances and MNFCs. Figure 6 shows the response of an EED sensor of the type shown in Figure 1 to a step function change in current. While most of the measurements shown were made using injected dc currents, it has been demonstrated independently at the Sandia National Laboratories[3] that dc and RF results agree up to 10 GHz, at least to within the errors to be expected of typical RF susceptibility measurements.

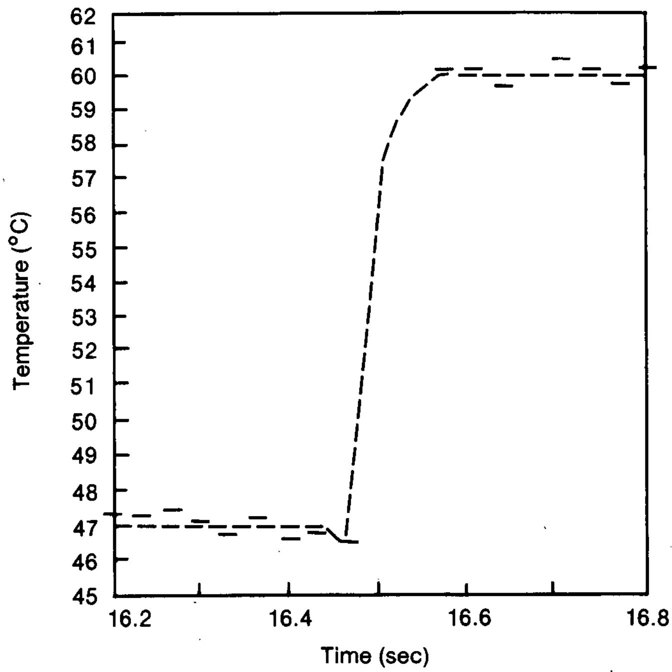

Figure 6. Response Time Data Taken with a Minimally-Sized Mark 1 Sensor Similar to That Shown in Figure 1. This Shows the Temperature Change Corresponding to a Step Function Increase in Current Through the Bridge Wire. The Time Interval Between Each Measurement Is 33 ms.

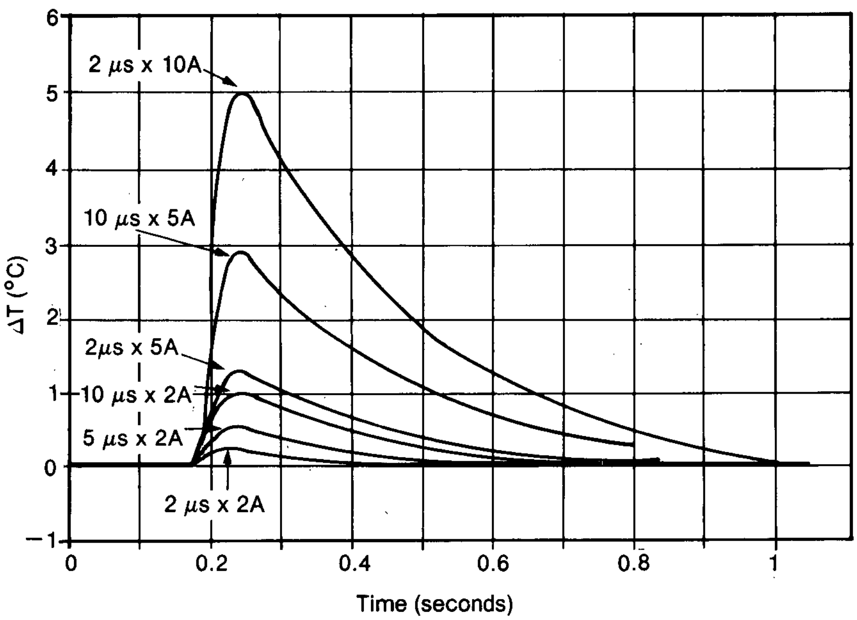

Figure 7. Typical Thermal Response Curves Obtained by Repeated Sampling Using Time-Corrected Data for Very Short Current Pulses Injected into the Bridge Wire of an Instrumented 1.6 Ohm Microfuse. In this Case the Sensor Was Made Substantially Larger than the One Shown in Figure 1 in Order to Be Able to Stretch Out the Thermal Effect in Time.

APPLICATIONS TO ELECTRONIC CIRCUITS AND CABLES

As noted earlier, there is also a need for detecting induced currents in the electronic subsystems of weapons. For example, such currents

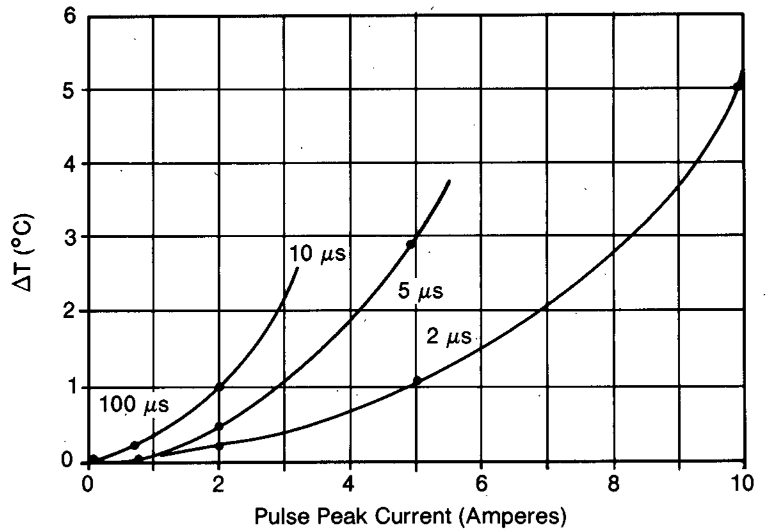

Figure 8. Curves Showing the Quadratic Dependence of ΔT on Current for Different Lengths of Square Wave DC Current Pulses Injected into the Instrumented Microfuse Bridge Wire.

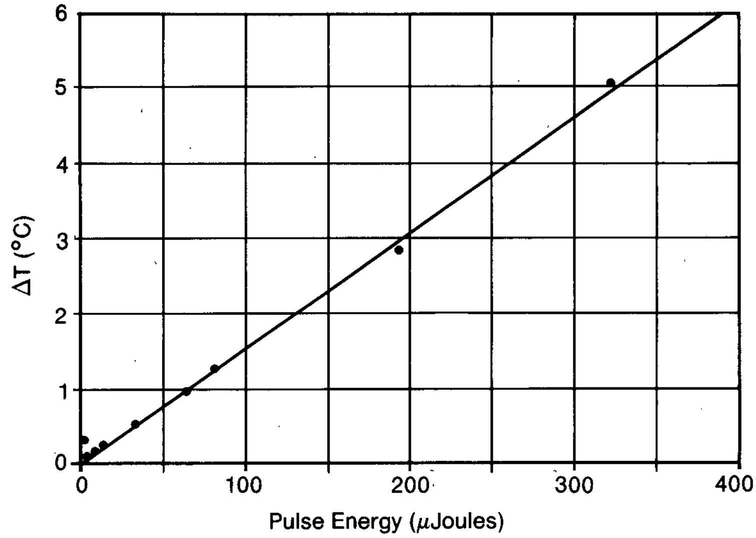

Figure 9. Plot Showing the Dependence of ΔT on Total Pulse Energy for All of the Pulses Shown in Figure 8. From This It can be Seen That the Data are Quite Linear Down to About Two MicroJoules.

could alter the functioning of a guidance system and thereby affect the performance of the weapon. Currents adequate to upset a sensitive electronics system are typically smaller than those needed to cause accidental detonation of an EED; hence even higher sensitivities may be required for such measurements. To achieve these measurements with the fiberoptic technique, it is necessary to insert an impedance-matched resistive sensor into the circuit of interest before testing.

Several prototype sensors have been constructed for this purpose, and their performance has been evaluated under RF test conditions.[3] While more work remains to be done to perfect the implantable sensor design, the cw measurement results obtained using the experimental sensors with impedance-matching are in fact quite encouraging.

In this application, sensor geometry is less constrained than with the EED testing application. As a result, the thermal, electrical and optical properties of the sensor are more readily optimized to achieve the desired sensitivity. At the present time, it seems most likely that the final sensor design for this application will utilize a thin film of luminescent material coated onto a small, thin film resistor, with the sensor then coupled to the instrument by non-contacting optical fibers similar to those used in the bridge wire sensor. Sensitivity can be maximized by tailoring the area of the resistor, and its resistance, while keeping its total thermal mass and its thermal contact with the environment to the minimum level possible. The resistive sensor would be formed as part of a transmission type strip line structure fitted with appropriate connectors and impedance-matched to the circuit of interest.

SENSITIVITY ENHANCEMENT TECHNIQUES

In addition to optimizing the thermal qualities of sensor design, there are a number of other ways in which sensitivity can be enhanced. First, if measurements are to be made in a cw environment, signal integration techniques can be used to enhance sensitivity. With the fiberoptic sensor, for example, ΔTs of 0.02°C can be measured using a 30 sample (one second) integration time while measurements down to 0.005°C can be made with a 10 second integration. This capability depends of course, on ambient temperature changes which do not exceed the induced current effects being measured. Second, if the inducing fields are modulated on and off slowly, correlation techniques can be utilized to improve data reduction. Refinements to this approach include eliminating the rising and falling portions of the resistor heating and cooling curves and thus using only the equilibrium portions of those curves. Finally, to handle the problem of ambient temperature changes, a differential technique can be employed. In the case of the slow cw modulation method mentioned above, a new base line can be taken each time the inducing power is turned off. Thus, base line changes can be applied as a correction to yield more accurate current-related ΔTs.

However, when signal modulation is not practical, a second temperature sensor can be located near the induced current sensor to track the ambient temperature changes and thereby allow only the induced current-related ΔT values to be determined. It should be noted that ambient temperatures can vary signficantly when working in the 0.01°C sensitivity range.

PULSE MEASUREMENTS

Ordinarily it would seem unlikely that a relatively slow thermal technique such as the one being described, would be useful in the measurement of the effects of very short RF or microwave pulses. It is possible, however, to take advantage of the thermal inertia of the sensor to allow measurements of the thermal effects produced by fast electrical pulses. In Figure 7 the thermal response of an EED-type sensor with a rather thick, and hence slow, phosphor coating is shown. Short dc current pulses of various durations and peak values were injected into the bridge wire circuit. The resultant thermal curve shapes were produced by repeated random sampling and integration. It can be seen that pulses as short as two microseconds, if they have sufficient power, produce easily detected thermal effects having a duration of as much as a second. It is found that the resultant ΔT readings (either using the peak signal or the area under the curve), follow the same I^2R behavior (Figure 8) as is true with cw measurements. Further a sensitivity limit similar to that obtained in cw measurements is achievable. (Figure 9).

Since this technique detects only the total energy deposited in the bridge wire, it is not possible to tell the difference between a longer but lower-power pulse and a shorter pulse with a higher peak value. It is clear, however, that the sensor can be used as a calorimeter for detecting the energy deposited by short microwave pulses and that enough data points can be obtained even from electrical pulses of microsecond duration to allow good curve fitting. It should be noted that single flash data will be substantially noisier than the curves shown in Figure 9, which were obtained from repeated pulses using extensive signal averaging.

OTHER AREAS OF FUTURE DEVELOPMENT: FIELD SENSING

In addition to the sensor projects mentioned above, there is also work underway to explore the potential of similar devices for free field measurements. Workers at the National Institute of Science and Technology (NIST) in Boulder have, for example, been exploring the possibilities of using this approach to construct broadband E-field sensors for use at frequencies of up to 120 GHz.[8] At such frequencies, a conventional dipole antenna would be difficult if not impossible to fabricate.

Work is also going on to develop small E field and H field probes for use at lower microwave frequencies (i.e., 915 and 2450 GHz) to measure local power distributions within microwave ovens and in microwave chambers used for industrial processing.[9] For lower-power EMC-type field sensing applications, the primary issue is likely to be one of sensitivity. For this reason, luminescent materials with higher luminescent efficiencies and higher thermal sensitivities are also under investigation.

SUMMARY

This modified fiberoptic sensor technology provides a new method for sensing small, high-frequency currents in a resistive conductor. With the combination of improved instrumentation and improved sensor design, the system is able to measure microwave frequency induced currents in a 1-ohm bridge wire to nearly 1 mA. Since all the materials in the sensor and probe are non-conducting, this technique is ideal for measurement of high-frequency RF-induced currents. Ease of sensor fabrication and alignment also compare favorably with thin-film thermocouples. While the technology was developed principally for ordnance susceptibilty measurements in which the standard phosphor sensor material is applied directly to the bridge wire of an EED, other types of sensors and sensing materials are now being explored with the expectation that the technology will become more broadly applicable to high frequency EMC measurements. ■

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