A Fiber-Optic Thermometer
Based Upon
Temperature-Dependent Fluorescence Decay

1. Introduction

The temperature dependence of the fluorescence decay from an optically excited phosphor comprises an optical thermocouple that provides accurate and reliable measurements in environments where conventional temperature sensors are unreliable or inoperable. The phosphor can be incorporated onto an environmentally inert, non-conductive, non-metallic, miniature fiber-optic sensor, making it ideal for harsh operating conditions, in-vivo usage, or other applications where metal probes are useless.

This technique for measuring temperature is ideal for applications where high levels of electromagnetic interference (EMI) such as RF or microwave fields, or high voltages, are commonly encountered in such environments as electrical power generation, semiconductor fabrication, electronics testing, electrolytic processing, and RF or microwave heating and curing. Since the sensor itself is inert to chemical and biological agents, it is ideally suited to applications where a completely non-reactive sensor is required or where other types of sensors would malfunction or become damaged. Disposable sensors that fit in standard catheters, or sealed sensors, that can be catheterized and autoclaved may be utilized for medical applications. The sensors can also contain on-board calibration data, ensuring accurate temperature measurements.

Temperature calibrations are currently conducted according to the International Temperature Scale of 1990 (ITS-90) using thermodynamic transition points of melting, freezing, vapor pressure, and triple points of various pure materials. However, fluorescence decay from a phosphor may one day be used as a new standard of temperature. Researchers at Oak Ridge National Laboratory and University of Virginia have proposed to measure the laser-induced fluorescence lifetimes of rare-earth elements in single-crystal host materials relative to cycles of an atomic clock. This approach would yield a temperature scale tied directly to atomic constants.

2. Theory of Operation

Measurements are based upon the temperature-dependent fluorescence-decay process of a phosphor bonded to the end of an optical fiber, which constitutes the temperature sensor. Optical pulses from a low-power, broadband source propagate along the fiber to the phosphor material. The phosphor absorbs this optical energy at the excitation wavelength and spontaneously emits light at the fluorescence wavelength. A portion of the fluorescence emission is captured by the optical fiber and propagates back toward the source that is incorporated in the electronics package, where it is separated from the path of the excitation light and directed to an optical diode detector, as shown in Figure 1.

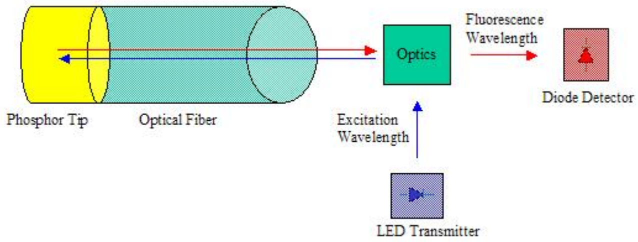

Figure 1. Excitation light pulses carried by an optical fiber are absorbed by a phosphor at the fiber tip. Fluorescence emission from the phosphor propagates back along the fiber toward the excitation source where it is separated and detected.

While the excitation pulse is present at the phosphor, the fluorescence signal slowly increases toward a maximum value. After the excitation pulse is switched off, the fluorescence signal then begins to decay exponentially. A higher temperature yields a shorter decay time. The repetition frequency of these optical pulses is limited by the excitation pulse width and the decay time for the fluorescence. Depending upon the temperature range, interrogation rates for the phosphor can be as high as several hundred hertz.

A portion of the fluorescence signal pulse that corresponds to an exponential decay occurring after the exciting optical pulse ends is detected, amplified, and then digitally sampled. All subsequent processing is performed in the digital domain. The goal of this process is to apply an algorithm to the data that yields a parameter associated with the shape of the decay curve. A calibration procedure is used to correlate the exponential decay parameter with the temperature.

Ideally, the calibration should be the same for all sensors. However, in practice there are slight variations in the calibration from one sensor to another sensor. In order to achieve greater accuracy, a calibration is usually performed separately for each sensor.

3. Hardware Features

The hardware used to implement a fiber-optic thermometer based upon fluorescence-decay technology involves a combination of optics and electronics. Actual temperature data is obtained optically, but the processing of that data is handled by electronics. A block diagram illustrating the system operation is presented in Figure 2.

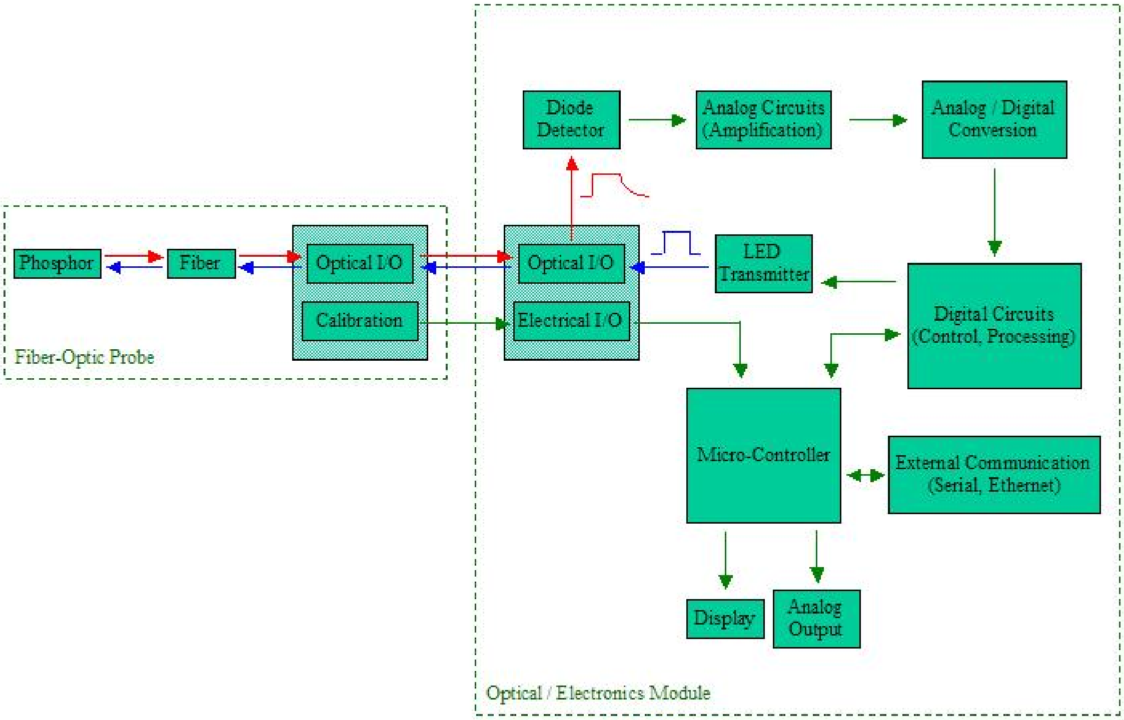

Figure 2. System block diagram for a fiber-optic thermometer based upon fluorescence decay technology.

An optical/electrical interface block in the electronics package typically contains a light-emitting diode (LED) for interrogating the phosphor at the excitation wavelength and a reverse-biased diode for detecting a return fluorescence optical pulse from the phosphor. The block also houses optics to couple light efficiently into the fiber from the LED and out of the fiber onto the active area of the detector. A special optical (Dichroic) beam-splitter is used to separate the excitation and fluorescence wavelengths.

A temperature sensor consists of an optical fiber with a phosphor on one end and a precision ferrule on the other end. The fiber diameters are generally on the order of 100 – 500 microns, with lengths that are typically up to a few meters. Since the temperature data is acquired at the phosphor, the length of the fiber, its diameter, or the environment surrounding it has no effect on the data. In theory, any combination of diameter and length may be used as long as sufficient signal strength is returned to the electronics to stay above the noise level. In some cases, the diameter of the fiber is limited by the application. An example would be a fiber sensor (or multiple sensors) required to fit within a catheter.

The ferrule facilitates the optical alignment of the fiber-coupling end with the components in the optical/electrical block. It has a precisely controlled diameter that fits within a channel in the block to achieve the proper placement and orientation for optimized optical coupling. An outer housing containing the ferrule is often used to lock the ferrule into position. This outer housing can also contain an electronic memory chip that contains calibration information for the sensor. Another approach is to provide a separate part, or key, containing the calibration information for a sensor. This approach is less desirable since it inherently allows for the possibility of mismatches between calibration keys and sensors. Figure 3 illustrates the design of the connector end of a fiber-optic sensor for an Ipitek LT-X5 fiber-optic thermometer.

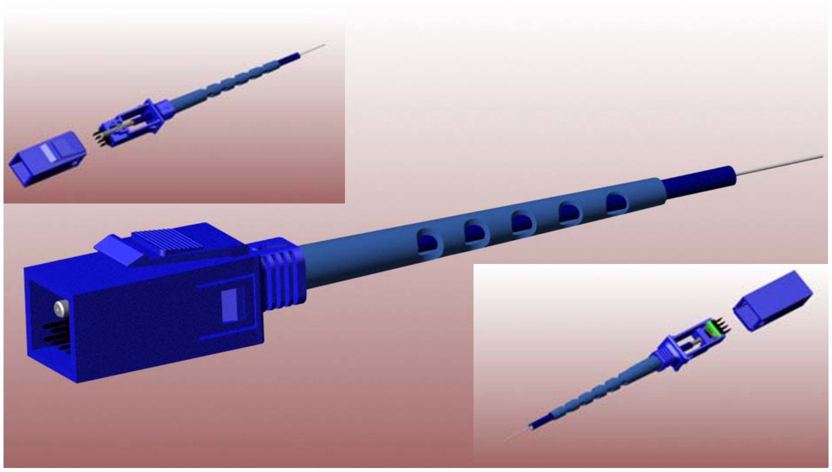

Figure 3. Connector housing for an Ipitek LT-X5 fiber-optic thermometer containing a precision ferrule for optical alignment and memory chip containing sensor-specific tailoring of calibration data.

A jacket material protects the fiber over most of it length, except near the tip. In most formats, an outer thin-walled tube covers the tip to seal and protect the phosphor. For medical applications the tip is made of material that meets biocompatibility requirements. The fiber itself may be made of plastic, glass, or other material depending upon the temperature range that is to be monitored. A suitable glass fiber, for example, could cover a range up to a few hundred degrees Celsius.

The detector converts the optical signal received from the phosphor (via the fiber) into a pulse of current that is subsequently converted into a voltage pulse by a high-gain trans-impedance amplifier. The signal level is increased further by additional amplification, mediated by an automatic gain-control loop.

After amplification, the analog signal is sampled with an analog-to-digital (A/D) converter. Additional digital circuitry and a micro-controller process the sampled data to extract the parameter that describes the exponential decay process in the phosphor. Calibration information provided by the calibration key of the sensor is used by the micro-controller to convert the parameter value to temperature data. Depending on the configuration of the equipment, temperature information can be conveyed over a variety of formats including serial, Ethernet, analog voltage level, or directly to a display.

Examples of hardware implementations are shown in Figures 4 and 5. Figure 4 is a photograph of an OEM version Ipitek LT-X5 measurement system featuring four-channels on one card, with a 3-meter fiber-optic temperature sensor connected to each channel. A modular version rack-mount is shown in the photograph in Figure 5. This rack mount accommodates up to seven four-channel modules, and utilizes Ethernet communication to software installed on a host computer. It is ideal for temperature mapping in medical or other applications where the temperature must be monitored within a given volume.

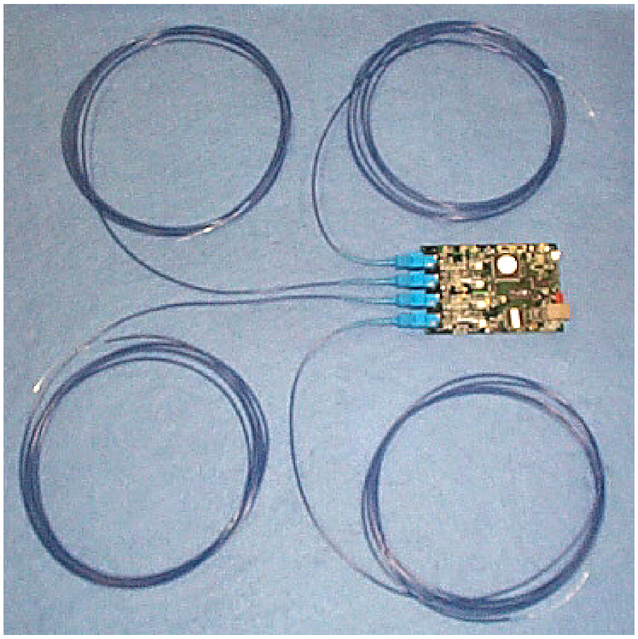

Figure 4. A four-channel OEM Ipitek LT-X5 temperature measurement system is shown with four 3-meter long fiber-optic sensors.

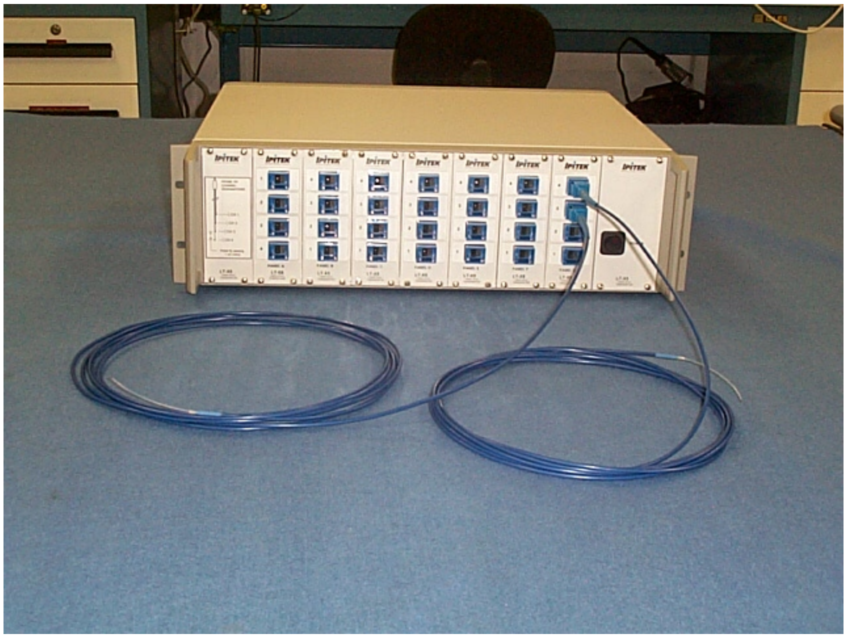

Figure 5. Rack-mount modular version of an Ipitek LT-X5 temperature measurement system. This configuration can monitor up to 28 independent channels. In the photograph, standard fiber-optic sensors are shown connected to two channels on one of the seven modules.

4. Operational Features

Assuring accuracy of the temperature measurements and validity of processed data are important requirements for a temperature sensor, especially in medical applications. The Ipitek LT-X5 sensors address the accuracy requirement by individually calibrating and verifying the calibration of each fiber-optic sensor. The calibration information is in the form of a look-up table that relates the fluorescence decay parameter for the phosphor to the temperature of the phosphor. Ideally, this table should be the same for all sensors, however there are some small differences from one sensor to another sensor. Therefore, the calibration of a sensor is actually a sensor-specific refinement or tailoring of a standard calibration look-up table. As discussed previously, this information is stored on a memory chip (calibration key) that is located in the connector housing for the sensor. The calibration key also contains other information about the sensor, including serial number, fabrication date, latest calibration date, and possibly user-specific information. At power-up, or when a new sensor is connected to a temperature module, the calibration information is read by the micro-controller. Temperature data is marked invalid until the calibration information is successfully processed. Similarly, if a sensor is unplugged or damaged, the temperature data is also marked invalid. A broken sensor, or loss of signal, is distinguished from an unplugged one by the presence, or absence, of a calibration key. The loss of signal that occurs in either case is observed in comparing the digital samples to pre-set threshold values.

In order to compensate for variations in signal level from one sensor to another (due mainly to optical coupling tolerances) or temperature-related variations in fluorescence intensity for a given sensor, an automatic gain control system is employed. A digital sample of the signal taken near the beginning of the fluorescence decay is used by the micro-controller to determine the gain setting for a voltage amplifier in the analog section of the electronics module. The gain is then set via a digital potentiometer.

Digital samples are also taken along the decay waveform and used to perform integrations in three distinct, but contiguous, regions. Each region represents a different time slice along the fluorescence decay. The results of these integrations are then combined mathematically in a manner that provides optimum discrimination against low-frequency noise with periods on the order of the overall decay time. The result is a solution generally related to the “shape” of the decay curve. Subsequent application of the look-up calibration table, with interpolation where necessary, is used to extract the temperature data. Fluorescence decay parameter values are first checked to make sure that they are within the range of calibration in order for the data to be considered valid.

5. Performance Characteristics

The performance of an instrument or technique for measuring temperature can be characterized in terms of accuracy, precision, response time to changes in temperature, and range of temperature measurement. The accuracy, or deviation of temperature readings from the true temperature, is obtained by comparing the instrument under test with a temperature standard that has been calibrated against standards maintained by the National Institute of Standards and Technology (NIST). This type of measurement requires a stable temperature environment and is usually conducted in a stirred oil bath. A typical comparison between a 500-micron diameter Ipitek LT-X5 fiber-optic sensor and a NIST-traceable temperature standard (Azonix A1011) is shown in Figure 6. Such fluorescence decay temperature systems are presently capable of achieving accuracies below ± 0.1C, which is consistent with the data plotted in the figure.

Precision, or how close measurements at different temperature can be to each other and still be resolved, may be determined using the instrument under test and a stable temperature bath. A temperature standard is used to monitor the stability in temperature for the bath but is not used for comparison with the data. This type of testing indicates that the precision for the LT-X5 systems can be as low as ± 0.02C.

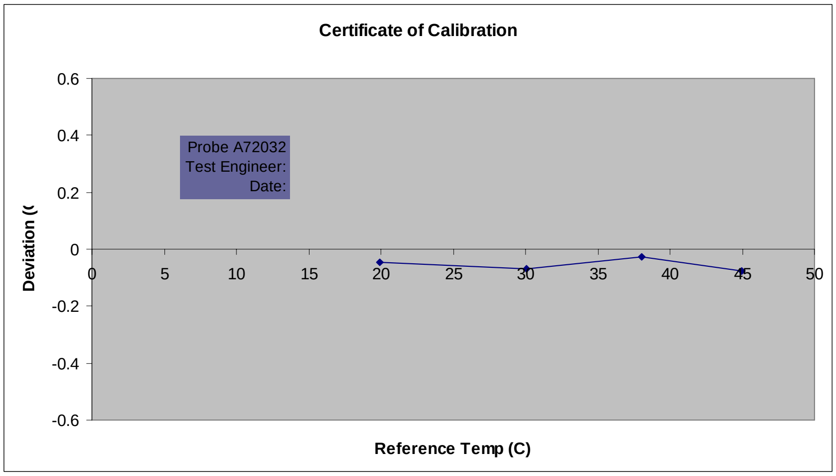

Figure 6. Data shows the deviation of the temperature readings from an Ipitek LT-X5 temperature sensor with respect to a NIST-traceable Azonix A1011 temperature standard. Both sensors were immersed in a stirred oil bath for this test.

Response time to temperature changes is a more difficult parameter to characterize. The overall response time is determined by both the sensor response time and the signal processing time, which could include signal averaging. Ideally, the overall response time is dominated by the sensor response. This situation is typically achieved in practice.

The sensor response depends on the thermal mass and heat capacity of the material in the sensor tip, and the thermal conductivity of any other protective material surrounding it. What the tip is actually sensing is the temperature of the phosphor, and the response time is basically how long it takes to bring the temperature of the phosphor into thermal equilibrium with its surroundings. This process involves transferring energy from between the environment and the phosphor, and therefore the type of environment also affects the response time. For example, the transfer of heat energy will be faster when the environment consists of human skin in contact with the sensor tip, compared to having the sensor surrounded by calm air.

If the temperature of the environment surrounding a sensor were to change “instantly,” the temperature measurement system may begin to respond very quickly. However, it will approach the new temperature asymptotically. Therefore, response time would have to be characterized in terms of the reading being within some range or percentage of the new temperature value. An example of this response characteristic is found in the “finger-test” data plotted in the graph of Figure 7. The family of curves was obtained by repeatedly grasping the tip of a fiber-optic temperature sensor with one’s fingers, waiting for the data to reach a steady-state value, and then releasing the tip into the ambient air. When grasped with one’s fingers the temperature of the sensor tip begins to increase, resulting in a decrease in the parameter value for the fluorescence decay process. This response occurs relatively quickly for the sensor used in this example, with the data starting to change very quickly and reaching 90% of the full excursion on the order of a second in most cases, depending on the contact between the fingers and the tip of the sensor.

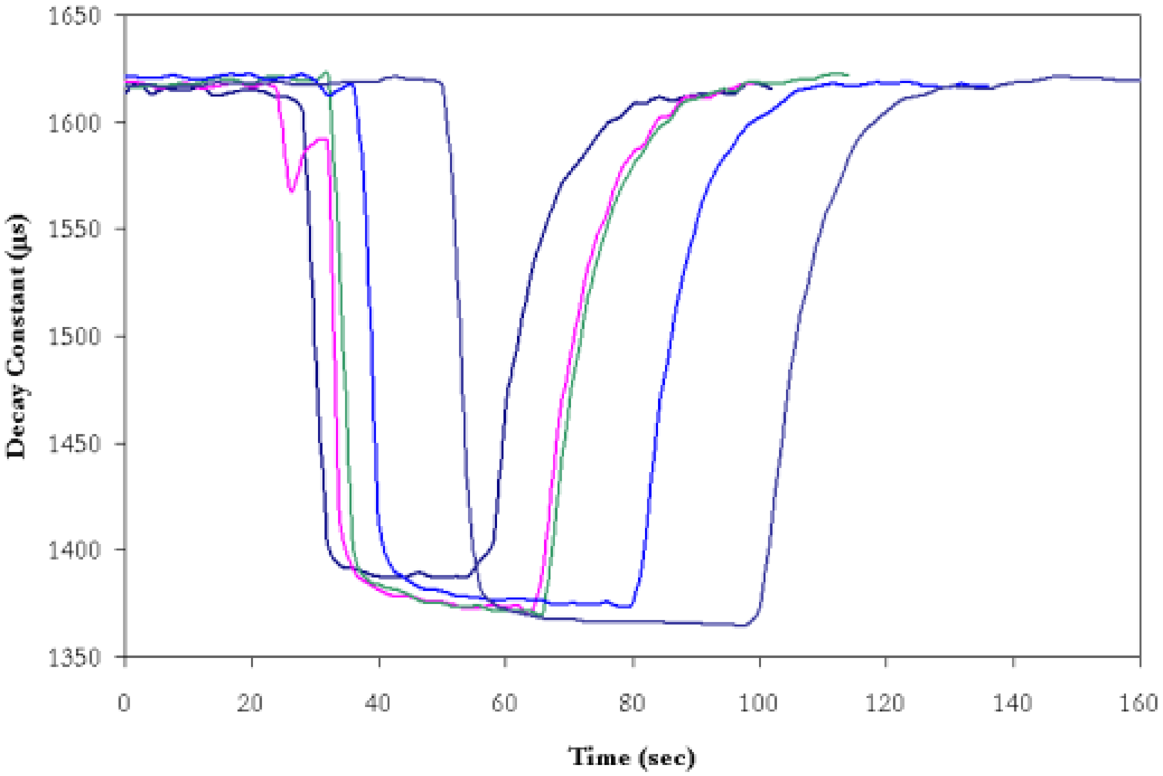

Figure 7. A family of curves showing the change in the decay parameter value (temperature) for a fiber-optic sensor tip repeatedly grasped with one’s fingers and then released into the ambient air.