

U.S. PRICE LIST & PROBE SELECTION GUIDE

OCTOBER 1, 1989

GENERAL PURPOSE FLUOROPTIC® THERMOMETERS

Model 755 – 4 Channels	\$14,000
Model 950 – 12 Channels	\$30,000

Both systems include DATASAVE, a built-in data collection system that can store up to 6000 readings for later retrieval. Systems also feature built-in calibration capability, adjustable temperature limits, RS-232C port, and one MSA-2 test probe.

Options

Model 755		
AOV	Analog Output (± 5 volts) (Factory installed only.)	\$1,500
GPIB	IEEE-488 Port (In addition to RS-232) (Factory installed only.)	\$1,000

Model 755HG

High Gain. Required when using some replaceable tip probes, transformer probe assemblies, and high vacuum feedthroughs. Recommended when using remote measurement and probe extensions. (Standard probes can be used with a high gain version if an extension is added for attenuation.) (Factory installation only, No MSA-2 test probe included) No charge when ordered with unit

Supply Items

Replacement Flash Lamps	
FL-750 for Model 750/755	\$250
FL-950 for Model 950	\$400
CC-755 Carrying Case	\$500
Service Manuals	
SM-750 for Model 750/755/950	\$150

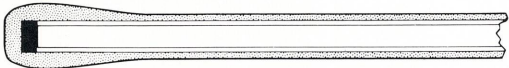
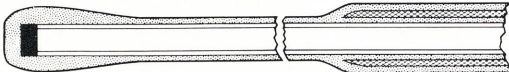
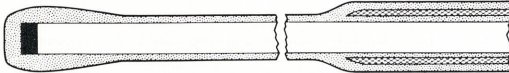
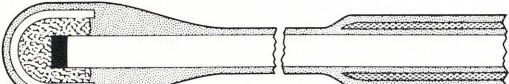
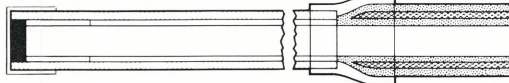
LUXTRON

Fluoroptic® Temperature Sensing

1060 Terra Bella Avenue, Mountain View, CA 94043 • Telephone (415) 962-8110 • Telex 705218 • Fax (415) 961-5978

FLUOROPTIC® TEMPERATURE PROBES

Immersion Type

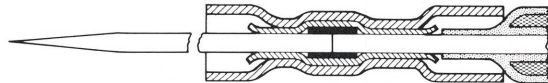
	Temp. Range (°C)	X = meters			
		2	4	6	10
MSA-X Standard Use PCS Fiber; Black PFA Teflon Jacket; Probe tip O.D. 1.0 mm max. 	0 to 200	\$420	\$480		
MIA-X Industrial Grade MSA with Kevlar cabling for extra strength, O.D. of cabled part 1.4 mm; Last 2.5 cm not cabled 	0 to 200	\$470	\$530	\$590	\$710
MIW-X Wide Range All-quartz fiber; PFA plus Kevlar cabling; Last 2.5 cm not cabled; Probe tip O.D. 1.0 mm max. 	-195 to +300	\$520	\$580	\$640	\$760
MIC-X Chemical/Oil Resistant Fiber and cabling like MIW; Sensor and oil-resistant sealant in glass capillary; Probe tip O.D. 1.2 mm 	-30 to +200	\$570	\$630	\$690	\$810
MIH-X High Temperature Range Fiber and cabling like MIW; Sensor at tip of 4" alumina ceramic tube. Probe tip O.D. 1.6 mm 	20 to 400 (450°C intermittent)	\$620	\$680	\$740	\$860
EA-X Cabled PCS extension		\$340	\$400	\$460	\$580
EC-10 Heavy duty extension, Kevlar cabled, O.D. 3.5 mm, length 10 meters					\$550
EC-30 Heavy duty extension, Kevlar cabled, O.D. 3.5 mm, length 30 meters					\$950
EC-50 Heavy duty extension, Kevlar cabled, O.D. 3.5 mm, length 50 meters					\$1,450
EC-75 Heavy duty extension, Kevlar cabled, O.D. 3.5 mm, length 75 meters					\$2,150

Replaceable Tip Models (Requires High Gain option on instruments)

ASC-X Probe Body (All-quartz fiber, PFA plus Kevlar cabling; mates with MIWR and MIHR tips.)	\$400	\$460	\$520	\$640
MIHR-TIPS (Package of 4 tips): Temperature range same as MIH probe. Replaceable tip approximately 2" long. Rigid 1" alumina ceramic tip. Probe tip O.D. 1.2 mm				
\$1200				
MIWR-TIPS (Package of 4 tips): Temperature range same as MIW probe. Replaceable tip approximately 18" long; O.D. 1.4 mm. Probe tip O.D. 1.0 mm				
\$800				

FLUOROPTIC® TEMPERATURE PROBES

Surface Measurement Type (High Gain option suggested.)

	Temp. Range (°C)	X = Meters		
		2	4	6
MEL-X Probe "10 Mil" surface temperature probe, 2" long, mated with a cabled PCS fiber. Includes: 2 MEL Tips Probe Body (does not accept MMT tips). 	-50 to +200 (250°C intermittent)	\$420	\$480	\$540
MMTKT-X Micro-tip Probe Kit "1 Mil" surface temperature probe, 5" long, mated with a cabled silica fiber. Includes: 3-Axis Micropositioner Non-conducting Probe Holder Probe Body 2 MMT (1 Mil) Probe Tips 	0 to 150 (200°C intermittent)	\$1900	\$1960	\$2020

MEL TIPS (Package of 8 tips)\$400

MMT TIPS (Package of 4 tips)\$1400

MIHR and MIWR tips are interchangeable and used with ACS probe bodies. MEL tips use the MEL body only. MMT tips use probe body furnished with MMTKT kit.

Remote Measurement (High Gain instruments suggested)

RPM Remote Phosphor Kit. Contains phosphor powder, three types of binders, a 2-meter open end PCS fiber and an instruction manual.....\$500

ASP-X All-quartz probes with polished open ends, in 2, 4, 6, and 10 meter lengths.Same prices as EA-X extensions

LAC Adjustable Lens Assembly with Connector. Used with an EA extension for making remote measurements at greater than 1/4" distance.\$135

Additional phosphor:

Half gram.....\$150

One gram\$300

Additional binder:

(Specify 150°, 250°, or 400°C binder)

One ml\$75

Accessories

VFT-10	Vacuum/Pressure Compression Gland Feedthrough. 5000 psi to 5×10^{-6} Torr. 0.762 mm opening for uncabled probe fiber.....	\$55
VFT-20	Same as VFT-10 except opening is 1.524 mm for cabled fiber.	\$55
HVFT	High Vacuum Feedthrough. Mounted on 2-3/4" Conflat® flange. 1×10^{-10} Torr. Requires EA extension and stainless steel connectors on probes (1, 2, & 4 meter lengths only) Requires High Gain option. Specify stainless steel connectors and add \$100 to probes when ordering	\$950
ACS/2	Surface Temperature Calibration System.	\$6500

Notes

1. 2 and 4 meter probes normally in stock. Allow 4 weeks for delivery of longer lengths.
2. Prices F.O.B. Mountain View, California and subject to change without notice.
3. 10% discount on probe orders of 5 or more of a single type.
4. Prices for high performance Model 850 and Medical Model 3000 thermometry systems are covered on separate price schedules, as are underoil probe assemblies for power transformer applications.
5. One year instrument warranty covers parts and labor. (Not applicable to probes and lamps.)

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BASIC TEMPERATURE MEASUREMENT CAPABILITIES OF THE MODEL 750

Introduction

The Model 750 affords a unique way to make temperature measurements and is frequently used in applications where more conventional instruments will not suffice. It is useful, however, to have a basis for comparison of performance with other types of temperature measurement systems. The first step is to define certain standard terms which can be applied to all temperature measurement systems. The next step is to characterize the capabilities of the Model 750, using these terms. The following section defines the key temperature-measurement terms as presently used by Luxtron:

Terminology

- 1) **Resolution** — The smallest unit that can be displayed or read out from the system.
- 2) **Precision** — The reproducibility of a measurement as determined by the noise fluctuations observed in the output data.
- 3) **Accuracy** — How close the reading is to the *true* value. (A reading can be precise but inaccurate.)
- 4) **Calibration** - Means by which the accuracy of the system can be improved. This involves a correction based on a comparison with a standard temperature reference.
- 5) **Sensitivity** — The smallest change in temperature that can be detected. The ultimate sensitivity limit is set by the noise-equivalent-temperature difference (NETD) of the system. However, in practice the observable sensitivity limit may be set by the resolution or precision of the system.
- 6) **Stability** — Short-term stability is synonymous with precision. Long-term stability is determined by system drift.
- 7) **Range** — The temperature region over which meaningful measurements can be made. The limits may be set either by the sensor itself or by the materials used in the probe adjacent to the sensor.

Application of Terms to the Model 750

- 1) **Resolution** — The Model 750 can display or read out via its data ports a temperature whose smallest unit is 0.1° . Hence, the Model 750 has tenth degree (C or F) resolution.
- 2) **Precision** — If the Fluoroptic™ sensor is in a highly stable thermal environment, and if 20 to 30 individual measurements are made before an average value is computed and a reading is displayed, the typical RMS precision of the Model 750 reading, using standard length probes, is observed to be approximately $\pm 0.1^{\circ}$ C. However, if individual (single-flash) measurements are displayed without averaging, the scatter from reading to reading is more typically $\pm 0.5^{\circ}$ C. Thus, precision can be increased by integration but with a decrease in output speed. Stated precision is $\pm 1/\sqrt{n}^{\circ}$ C where n is the number of samples averaged. Precision will vary somewhat with the temperature being measured, since both the rate of change of decay time with temperature and the fluorescent signal level from the sensor vary with temperature. The stated precision is deliberately conservative to encompass temperature range and probe length variations, as well as other possible sources of signal loss.
- 3) **Accuracy** — Because the Model 750 determines temperature by measuring a single intrinsic property (the fluorescent decay time) of the phosphor sensor, its accuracy is only a function of the signal level available (versus noise), the timing accuracy of the system, and any conformity (compositional) variations from batch to batch of the sensing material. Allowing for such variations, the typical accuracy of a measurement made *without* calibration using a standard length probe is $\leq \pm 2^{\circ}$. If higher accuracy is needed, it will be necessary to calibrate the system. By calibration against a standard reference bath whose temperature is known to $\pm 0.1^{\circ}$ C, system accuracy can be improved typically to $\leq \pm 0.2^{\circ}$ C at the calibration temperature and to $\pm 0.5^{\circ}$ C or better over a range 50° C on either side of the calibration temperature.

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- 4) **Calibration** — Calibration can be accomplished by first informing the Model 750 of the true temperature of a stable reference into which the sensor has been placed and then instructing the instrument to apply the observed difference between the known and measured temperature to future readings. Note that each probe must be calibrated. The calibration needs to be repeated if a probe is disconnected and reconnected since the system may have readjusted its Automatic Gain Control (AGC) setting in the interim.
- 5) **Sensitivity** — The true limit of sensitivity with long integration, set by the noise-equivalent temperature difference of the instrument, is about 0.05°C under ideal conditions. However, because of the resolution of the Model 750, it is not possible to detect a change smaller than 0.1°C when using the Celsius scale. Switching to the Fahrenheit scale may allow an improvement in the observed sensitivity since 0.1°F is approximately equal to 0.05°C .
- 6) **Stability** — As noted previously, *short-term stability* can be related to the noise fluctuations observed in the normal course of readings and is thus equivalent to precision. *Long-term stability* is related to system drift, and reflects gradual changes in signal levels or electrical component values such as might be produced by ambient temperature changes or by component aging. Long-term drift, though not specified, is typically of the order of $\pm 0.1^{\circ}\text{C}$ over one hour and not greater than 0.5°C over many days or weeks (assuming the ambient temperature of the instrument does not vary by more than $\pm 10^{\circ}\text{C}$).
- 7) **Range** — Measurements can, in principle, be made from -200°C to $+450^{\circ}\text{C}$ with the standard sensor material. However, the rate of change of τ , the fluorescent decay time, with temperature is substantially reduced below about -180°C . The Model 750 presently operates only down to -99.9°C because of data display limitations. The upper limit is set by the very rapid rate of decline of τ to less than 1 ms above 400°C coupled with a rapid decrease of fluorescent intensity in the same range. Different probe types may operate over only a portion of the sensor range because of limitations of materials used in the fibers or probe tips. For example, to work at the high temperature end of the range, special materials are required to support the sensor at a distance from the optical fiber, since the fibers contain organic buffers and plastic jacketing materials which cannot tolerate temperatures above 300°C .

Fiberoptic Thermometry and its Applications

Kenneth A. Wickersheim and Mei H. Sun

This paper reviews briefly the reasons for interest in fiberoptic thermometry and the various types of fiberoptic temperature sensors which have been developed to the point of commercialization. It then focuses on a particular technology in which the rate of decay of fluorescence from a phosphor sensor is utilized to determine temperature. This technology provides essentially calibration-free operation and easy interchangeability of a wide variety of applications-specific probe types. After describing the available systems, the paper addressed briefly a number of key applications including usage in high voltage transformers, industrial microwave heating applications, electromagnetically-induced hyperthermia, electronics fabrication and testing and magnetic resonance.

Key words: Fiberoptic thermometry, temperature sensors, phosphor, fluorescence decay, applications.

Like the laser, it has taken many years since initial invention for optical fibers to find their primary roles in everyday life. As with the laser, a driving force during this protracted period of development has been the wide bandwidth capability of coherent light when used as a carrier for voice and data communications. Optical losses in fibers have been reduced steadily by increased purity of starting materials and by the development of improved fiber drawing technology. As a result, fiberoptic cables are now increasingly replacing electrical cables in high capacity communications transmission lines.

Again, like lasers, optical fibers have a variety of attractive features other than their data

transmission capacity. They are made from insulating materials and can thus be used for safe, noise-free applications in electromagnetically hostile environments. They are very small and yet efficient in carrying optical signals over long, tortuous paths. And, they are typically made of materials capable of withstanding both electrically and chemically adverse environments. These attributes suggest a variety of scientific, medical, and industrial measurement and control applications. The key to implementing these applications is the development of appropriate optical sensing technologies.

Fiberoptic Temperature Measurement Systems

Overview. Fiberoptic thermometry is of special value for use in electrically-hostile environments, such as in high dc electric or magnetic fields, or in strong rf or microwave fields. In such environments, the electrically-conducting leads of thermocouples, thermistors, or RTD's could cause serious problems. First, they would perturb the environment electromagnetically — causing a high voltage shorting path, perturbing magnetic field homogeneity, or reflecting incident microwaves. Second, in high frequency alternating fields, they would pick up noise and be heated by induced eddy currents. The thermal conductivity of the electrical leads can also lead to perturbation of the temperature being measured. The electrically non-conducting nature of the optical fibers is also important in safety applications, such as when making measurements in an explosive environment or internal to a critical-care patient. The optical nature of the technology is significant because it allows the sensor to be separated physically from the rest of the system. This increases sensor design versatility and allows remote measurements.

While there are also infrared radiometric systems which utilize optical fibers, this paper will concern itself with externally powered sensing systems which utilize either a change in the optical properties of the fiber with temperature or the change with temperature of the optical properties of a sensor coupled to the optical fiber. Typical fiberoptic sensors operate in the visible or near-visible spectral range and are useful primarily for measurements in the low to moderate temperature range.

ABOUT THE AUTHORS

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Fiberoptic thermometry

The most sensitive systems use the fiber itself as the sensor. To fabricate a temperature measurement device, the fiber is configured in such a way as to be stressed by the temperature change being measured. For example, the fiber may be coated with a material whose thermal expansion coefficient is different from that of the fiber. When heated, the fiber is stressed by this coating and the optical path length within the fiber is altered slightly. This change can be detected interferometrically by sensing the difference in phase between light emerging from the sensing fiber and that from a second unstressed reference fiber. Workers at the U.S. Naval Research Laboratory, who have done a great deal of development of fiberoptic interferometry systems for sensing of a wide variety of parameters, report extremely high sensitivities for temperature sensors of this type [1].

However, on the assumption that commercial sensors must be small, simple to make and standardize and relatively low in cost, the bulk of the development work on fiberoptic temperature measurement instrumentation has been focused on various types of non-interferometric sensors formed using optical materials attached to the end of the optical fiber.

Any material whose optical properties change with temperature can, in principle, form the basis for an optical temperature sensor. Possible parameters which might change with temperature include: absorption or transmission, reflection, index of refraction, rotation of the plane of polarization, and fluorescence or phosphorescence. Temperature sensing devices using all of these parameters have been fabricated and some have been developed to the point of commercialization.

It is convenient to divide such fiberoptic sensors into two categories: (1) those in which the sensor material modulates the intensity of light transmitted through or reflected from the sensor in relation to sensor temperature; and (2) those in which the incident light generates luminescent radiation of a different wavelength, the changes in luminescent characteristics being interpretable in terms of temperature.

Reflective or Transmissive Sensors. Among the sensors of the reflective type are those in which the sensor material is a liquid crystal film. Such sensors were among the first fiberoptic temperature sensors to be developed. Rozzell *et al.* [2] developed such a sensor for use in medical and biomedical applications. More recently, Windhorn and Cain [3] have developed a more elaborate sensor in which the plane of polarization is rotated by a sensor formed from a mixture of liquid crystals. The limitations of liquid crystals lie in their narrow range of operation

and their inherent chemical instability. The latter problem leads to both calibration instabilities and unacceptable hysteresis and has prevented such systems from becoming commercially successful.

Three technologies involving transmission changes of a solid with temperature have been developed to the point of commercialization. The first involves a sensor constructed from a semiconductor material (gallium arsenide) whose band edge shifts with temperature. This device, first described in a Russian patent [4], was independently developed by Christensen [5] for use in conjunction with medical hyperthermia. The sensor is constructed as a small prism which requires at least two fibers for transmission of light from a gallium arsenide light emitting diode (LED) through the sensor and back to a detector. As the gallium arsenide band edge shifts with temperature, the absorption of the LED emission varies. The signal change can be calibrated in terms of temperature. This system has been licensed to Clini-Therm, a manufacturer of hyperthermia therapy equipment.

The second technology involves the change in transmission of a ruby glass filter with temperature. This technique was developed by Saaske [6] under a contract from the Electric Power Research Institute for purposes of monitoring the temperatures of windings in high voltage power transformers. Since that time, Saaske has formed his own company, Technology Dynamics, Inc., and has introduced a commercial fiberoptic sensing system designed to measure a variety of parameters including temperature.

The third system of the transmissive type was developed by Cetas [7]. It utilizes as the sensor a small crystal whose birefringence changes strongly with temperature. If light incident on the crystal is polarized, this polarization is altered on transmission through the sensor. If the emergent light is then passed through an analyzing polarizer, the alteration of polarization is detected as an intensity change which can be correlated with crystal temperature. This device has been licensed to Cheung Laboratories, another manufacturer of hyperthermia therapy equipment.

Luminescent Sensors. Sensors formed from luminescent materials have a variety of inherent advantages relative to the reflection/transmission types of sensors mentioned above. The advantages are as follows:

1. If one wishes to minimize errors produced by intensity changes arising from fiber bending, source fluctuations, or changes in optical coupling or transmission with time, either the measurement of an intensity-independent parameter or the use of some self-referencing technique is

required. Such techniques are relatively easy to accomplish with luminescent materials but are much more difficult with the reflection/transmission systems described above.

2. For a sensing technology to be practical in a commercial sense, the sensor should be easily manufactured at moderate cost and yet should have highly reproducible characteristics. The transmission devices are typically difficult to manufacture reproducibly as precision optical components because of their very small size. The sensors are typically not identical and therefore require individual multipoint calibration. The luminescent sensors, since they do not require transmission *through* a precision fabricated component, are very simple and inexpensive to fabricate and exhibit easily standardized characteristics.
3. In some instances, for example in microelectronics applications and in medical hyperthermia, it is desirable to minimize probe size. Being able to use a single fiber for both incoming and outgoing radiation can therefore be an advantage. This is easy to do with the luminescent sensor, since the exciting radiation is at a different wavelength than the luminescence, but is again more difficult with the reflection/transmission types of sensors.
4. Sensor design versatility is important since the solution to each specific application need frequently requires a unique sensor configuration. The luminescent approach offers this versatility. Because most luminescent sensing materials can be obtained as powders or liquids, they can be mixed in an appropriate vehicle or binder and formed into any sensor configuration of interest.

ASEA, a Swedish company, has introduced a fiberoptic temperature-sensing technology in which a luminescent semi-conductor material [8] is located at the tip of an optical fiber. The sensor is a small crystalline sandwich of gallium arsenide between gallium aluminum arsenide layers. The sensor is caused to luminesce in the vicinity of its band edge by incident radiation from a gallium arsenide LED. Presuming the sensor is at a temperature above that of the LED, the photoluminescence occurs at a longer wavelength than the exciting radiation. As the temperature of the sensor is raised, the emission band shifts to longer wavelengths. If the luminescence is viewed through two filters with adjacent pass bands and the intensity in each pass band is measured, an intensity ratio can be constructed which can then be correlated with temperature.

While the temperature range of this device (0° to 250°C) is somewhat limited, the ASEA system does have one excellent feature, namely, the ability to

use as the exciting light source an infrared LED. Such a source is small, efficient, and long-lived. Furthermore, the wavelengths of interest are all in the very near infrared, an especially good region for transmission by quartz fibers.

Omron, in Japan, has developed a luminescent sensor made from a crystal of yttrium fluoride doped with erbium and ytterbium which is also excited by an infrared LED but which utilizes a two-photon excitation process [9]. Though the excitation is presumably relatively inefficient, forcing the use of a moderately large crystal volume, it is sufficient to allow reasonable sensitivity over the range from -30° to $+200^{\circ}\text{C}$. The system utilizes a string of exciting pulses with the integrated intensities of the afterglow being measured after the exciting pulses have ceased. The integrated afterglow intensity is greater the lower the temperature.

Kolodner [10, 11, 12, 13] of Bell Telephone Laboratories has also used luminescent films of a europium chelate to make sensitive remote thermal measurements on operating integrated circuits. These materials are excited efficiently in the ultraviolet even when deposited as very thin films. Because the change in luminescence with temperature is quite large, good sensitivity is achieved with high spatial resolution. On the other hand, this technology is not easily adapted to general purpose sensing because the sensing materials are not stable.

Luxtron's original technology utilized europium-activated lanthanum or gadolinium oxysulfide as the phosphor sensor [14]. The fluorescence from these rare-earth phosphors consists of sharp lines originating from different excited states of the trivalent europium ion. Since the relative populations of these excited states are strong functions of temperature, the relative intensities of the emission lines are also. By isolating and measuring the intensities of two lines originating on different excited states, one can construct an intensity ratio which can be correlated with temperature. This ratio does not depend on the intensity of the exciting radiation or the transmission of the fiber. This technology was reduced to practice in the form of an instrument capable of operating over a range of from -100 to 290°C with a precision of $\pm 0.1^{\circ}\text{C}$. Although a substantial number of systems of this type were built, it was felt that the technique had limitations in terms of performance and cost. As a result, a second technology based on the measurement of fluorescent decay times was developed [15, 16, 17].

The Decay Time Technology. In this technology, a material exhibiting a long exponentially decaying fluorescence is utilized as the sensor. An efficient

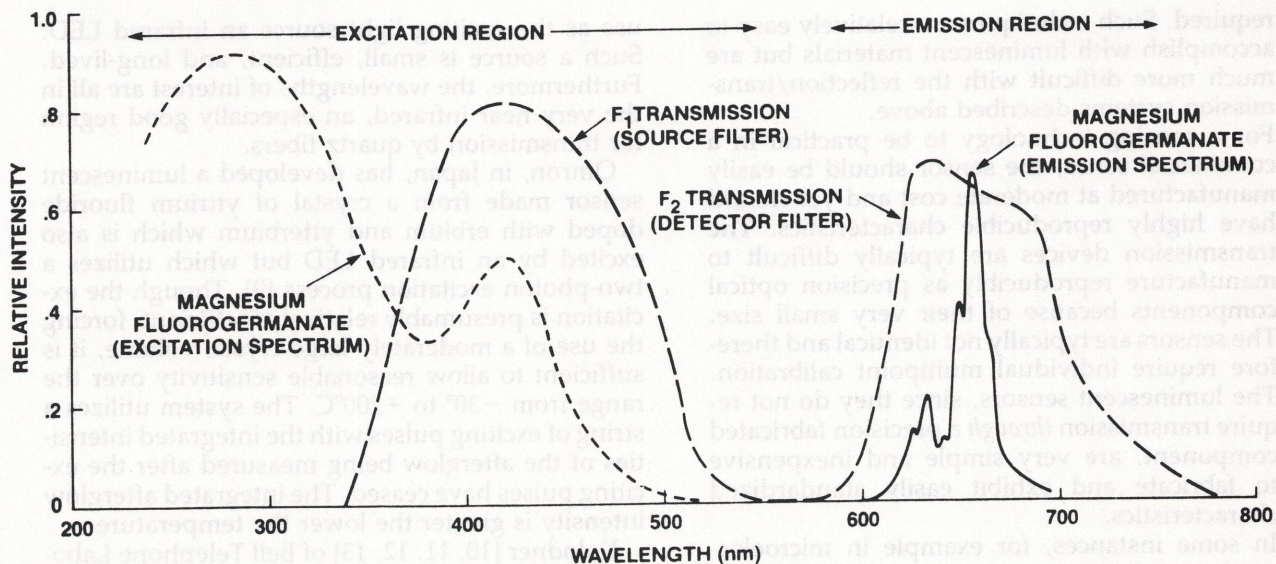


Figure 1. Excitation and emission spectra of the manganese-activated magnesium fluorogermanate sensor. Also shown are the transmission spectra of the two filters used to isolate the exciting and fluorescent radiation at the source and detector.

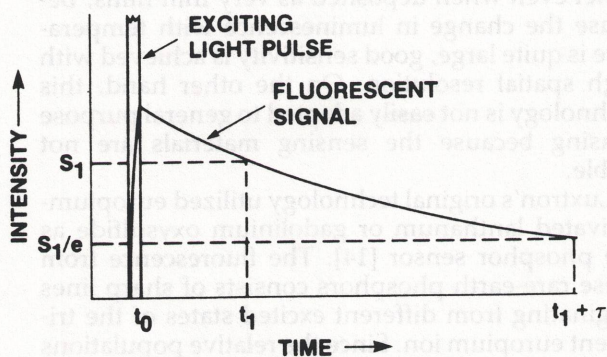


Figure 2. Method for measuring the fluorescent decay time of the phosphor sensor. The time between the initial measurement of the signal level, S_1 , and the cross-over of the decaying signal with $S_{1/e}$ is the decay time.

phosphor, magnesium fluorogermanate activated with tetravalent manganese, was selected as the sensor material. This red emitting phosphor can be excited by short wavelength visible as well as ultraviolet radiation — Figure 1. The sensor material is able to withstand high temperatures, is relatively insoluble chemically, and is quite benign from a biological standpoint. Since the temperature of the phosphor can be determined from the measurement of a single intrinsic parameter (its decay time), the system is to a first approximation calibration-free. With this decay-time system, virtually any probe configuration can be used interchangeably since measurement of the phosphor

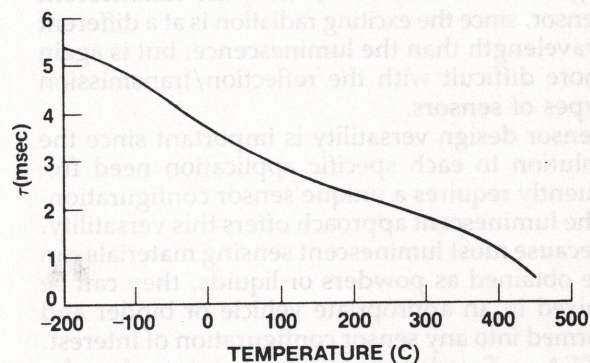


Figure 3. Plot of decay time versus temperature for the magnesium fluorogermanate phosphor sensor. This is the basic calibration curve for the system.

decay time does not depend on exact signal level or on optical configuration. In order to handle differences in signal level with sensor type or probe length, the instrument is equipped with an automatic gain control (AGC) system.

The pulsed excitation source, a Xenon flash lamp, can be shared among a number of optical channels in a multi-sensor system. The temperature measurement is made by measuring the rate of decay of the fluorescence, as shown in Figure 2. The resultant variation of decay time with temperature is shown in Figure 3.

Measurements can be made typically to $\pm 2^\circ\text{C}$ or better accuracy over most of the working range of

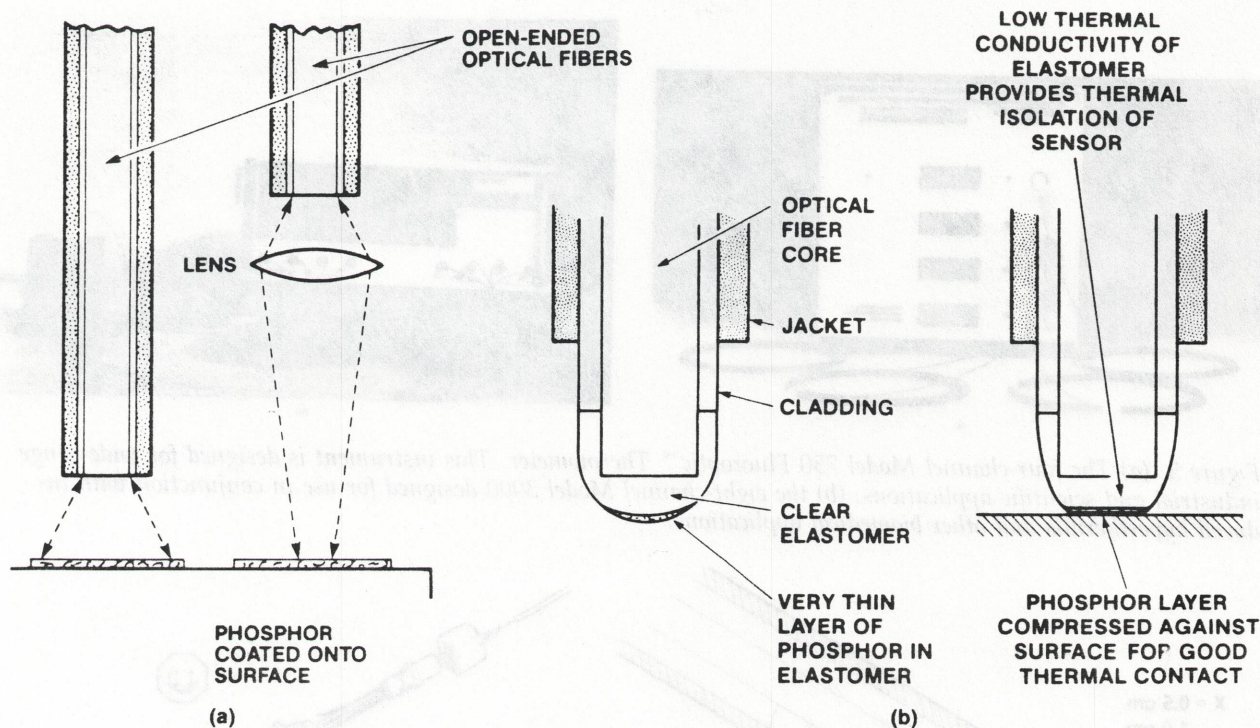


Figure 4. Two different surface temperature measurement techniques: (a) the remote approach in which the phosphor sensor is applied directly to the surface whose temperature is to be measured; (b) a contact probe in which the sensing phosphor layer is on the outer surface of a transparent elastomeric tip which conforms to the surface whose temperature is being measured.

the sensor without calibration. If calibration is performed, accuracy can be improved $\pm 0.2^\circ\text{C}$ or better in the vicinity of the calibration temperature.

Since the characteristics of the phosphor are independent of excitation intensity, the technique lends itself to versatile sensor design. For example, the sensing material can be coated directly onto the surface of interest at a distance from the optics of the system to allow remote measurement of the temperature of the surface (see Figure 4(a)). In addition, a variety of novel contact sensor designs for surface sensing are also feasible. Figure 4(b) illustrates one of these.

Two systems utilizing the new decay time technology are available. A four-channel instrument (see Figure 5(a)) capable of operating from -200°C to 450°C has been developed for industrial and scientific applications [15, 16, 17]. Although single flash precision is of the order of $\pm 0.5^\circ\text{C}$, $\pm 0.1^\circ\text{C}$ precision can be obtained by integrating 20 to 30 flashes over a period of 2 to 3 s.

In addition an eight-channel system has been introduced for medical applications [18, 19], — see Figure 5(b). Primary use is expected to be in medical hyperthermia — the use of controlled heat, in

conjunction with radiation and drugs, for purposes of cancer therapy. Since most of the hyperthermia techniques involve rf or microwave (tumor) heating, artifact-free fiberoptic thermometry techniques are especially attractive. The system utilizes very small needle-implantable or catheter-implantable sensors, either singly or in the form of linear arrays for mapping tumor temperature distributions.

Applications

High Voltage Applications. One obvious area of application of fiberoptic temperature sensors is in the monitoring or testing high voltage equipment. Heat is generated by the flow of electrical current. Under some circumstances this heating can lead to equipment degradation or failure. The electrical characteristics of high voltage components and materials are also frequently strongly temperature sensitive. While there are many high voltage applications, the application to the measurement of winding temperatures in power transformers has received the most attention. Thermocouples obviously cannot be used because of the danger of shorting out the equipment.

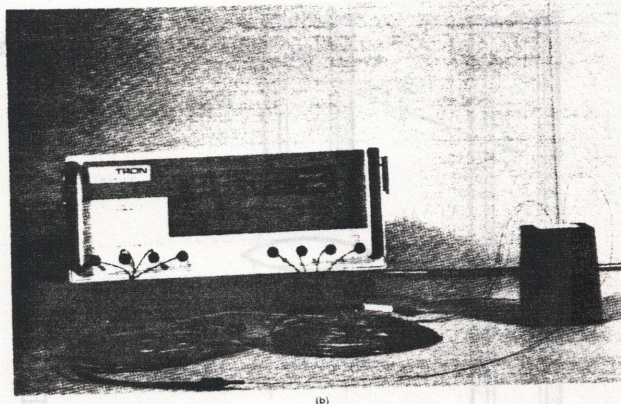
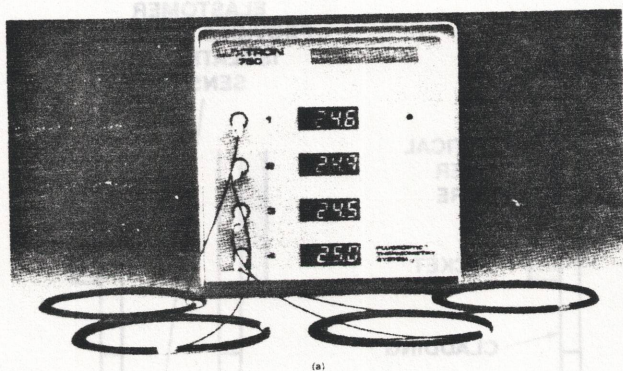


Figure 5. (a) The four-channel Model 750 Fluoroptic™ Thermometer. This instrument is designed for wide-range industrial and scientific applications; (b) the eight-channel Model 3000 designed for use in conjunction with induced hyperthermia and other biomedical applications.

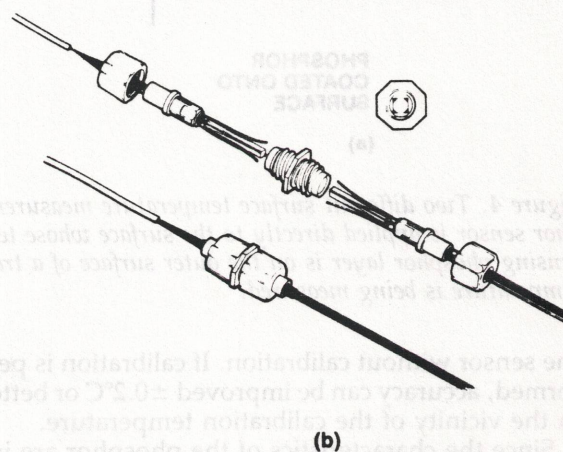
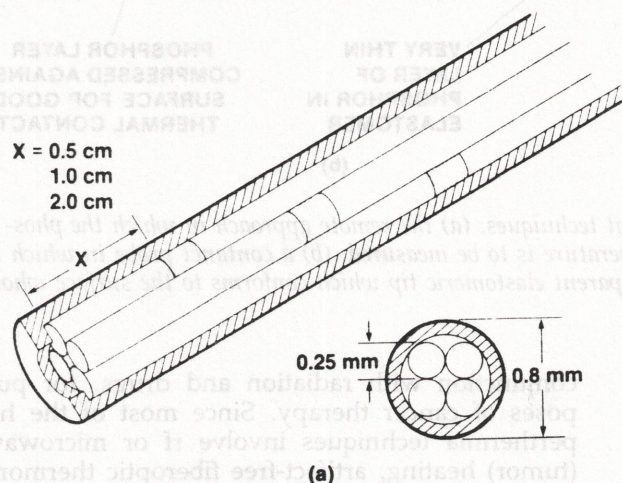


Figure 6. (a) Four-sensor linear array probe for the Model 3000. This small diameter probe allows thermal mapping of tumor temperatures with minimum number of probe implants; (b) Novel low-cost connector for use with the four-sensor probe.

Historically, thermal behavior of medium and large power transformers has been determined by simulation rather than measurement. A portion of the transformer current is passed through a resistor located in the oil being circulated through the transformer but external to the high voltage environment. From the rise in temperature or increase in resistance of the resistor, the temperature of the winding is estimated according to a preconceived model. The transformer is then operated within certain established guidelines based on this simulated temperature.

There are several reasons for being interested in measuring true winding temperatures. First, this allows the direct monitoring of transformer performance over time and thereby the detection of over-

heating and gradual deterioration. Second, the thermal behavior of the transformer can be certified, *i.e.*, it can be shown to meet thermal design specifications during factory testing. Third, and probably most important, if the true temperature of the warmest region of the winding is monitored, the transformer can be overloaded safely when necessary. Thus, the full overload capacity of the system may be utilized through knowledge of true winding temperatures.

The key requirements, other than a range of -30°C to $+250^{\circ}\text{C}$ and an accuracy of $\pm 2^{\circ}\text{C}$ are: (1) the proper design of a probe to withstand 20 years or more of constant vibration plus the effects of hot transformer oil; (2) a system with which data can be taken remotely without need for

maintenance or recalibration over long periods of time; and (3) for portable use, an instrument which can be connected to pre-installed probes and immediately take data without need for calibration.

Several transformer instrumentation projects have been undertaken. These have shown that fiberoptic probes can be installed safely and that valuable data can be obtained from operating transformers. These studies have also pointed to improvements needed in probe installation procedures and hardware. These are now being refined to allow more routine utilization of the technology [21].

Uses with Microwave Heating. Microwave power is being used increasingly in industry for a wide range of heating processes ranging from drying and food processing (cooking and meat tempering) to the forming and bonding of plastics, wood products, and composite materials. Most materials, including dielectrics, can be heated with microwaves. This technique is ideal for either continuous or batch processing. It has the advantage of faster and more uniform heating. However, since the part is heated in free space with an antenna-like applicator rather than in a conventional furnace or autoclave, there is no well-defined reference temperature with which the product comes into equilibrium. Hence, there is frequently a need for a microwave-immune temperature sensor.

One example of the need for such a microwave-immune sensor is for use in conjunction with the development of microwavable foods and, more recently, of active packaging for such foods [22]. While it is possible to measure surface temperatures of foods by infrared imaging (thermography) of the food after it is removed from the microwave oven, it is only through the use of fiberoptic probes that an actual time history of food temperatures can be obtained during the microwave cooking process for regions internal to the food. Although heavily sheathed thermistor probes are sometimes used for home microwave cooking, they are neither fast nor accurate enough for research purposes. In addition, they perturb the heating fields substantially thereby altering the effects being measured.

A second example of use of a microwave-immune sensor is in the fabrication of composite materials. In many cases, these materials are cured using rf or microwave power. Many parameters need to be controlled. For example, an epoxy-bonded part being cured by microwaves may experience a different degree of heating depending upon the exact composition of the epoxy (including moisture content), the applicator design and position relative to the part being heated, and the effi-

ciency of coupling of power from the rf generator into the applicator. In addition, the curing process is typically exothermic, making continuous temperature control even more difficult without measurement. As a result, it may be impossible to pre-set all process parameters, and the temperature of each part may have to be measured continuously during fabrication.

Induced Hyperthermia. Recently, induced hyperthermia has been added to the armamentarium of cancer therapy techniques. It is found that heating of a cancer tumor to a temperature of 42.5°C makes the tumor more sensitive to ionizing radiation. Thus, the combined use of heat and radiation can produce a marked improvement in response at a lower radiation dose level and with reduced side effects. Heat also shows promise of synergism when used in combination with chemotherapy.

Since local or regional tumor heating is most frequently accomplished with rf or microwave energy, the same problems of measuring temperature exist for hyperthermia as for other applications of microwave power. Measurement is required for control since too much heat will kill surrounding normal tissue and too little will not produce the desired therapeutic result in the tumor. Accuracy, ease of calibration, and stability of calibration are all important.

The new medical system can handle up to eight individual sensors or two four-sensor arrays simultaneously [19, 20]. The four-sensor arrays (see Figure 6a), which are useful for thermal mapping, are made from non-fragile 250 micron plastic fibers contained in a Teflon outer sheath. The four-sensor array has a diameter of less than 0.9 mm and can fit into a specially designed 19-gauge needle-implantable catheter. While calibration is required to obtain the desired $\pm 0.1^\circ\text{C}$ accuracy, the calibration can be made quickly by measurement at one known temperature anywhere in the range of interest.

Electronics Fabrication. Temperature measurements in electrically hostile environments are difficult by conventional techniques. Add to this the problems of making a good surface temperature measurement in a vacuum and one has some feel for the difficulties encountered in measuring temperatures during electronics fabrication. Similar fabrication processes are utilized in the manufacture of integrated circuits, microwave circuits, magnetic recording media, and optical components. During these fabrication processes, the part is frequently in a vacuum chamber rather than in a furnace. As a result, all knowledge of temperature is lost. And yet temperature measurement and control

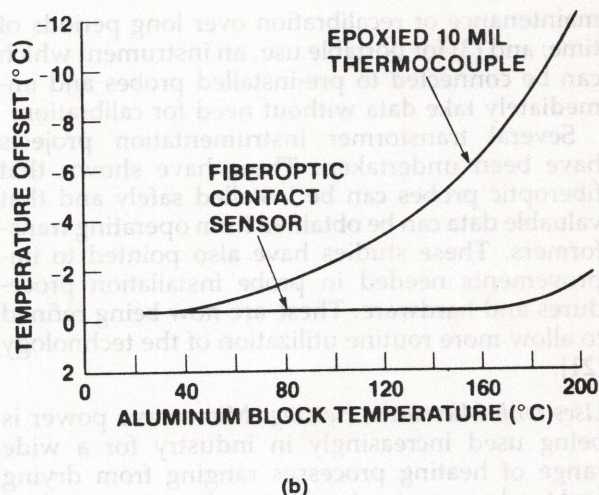
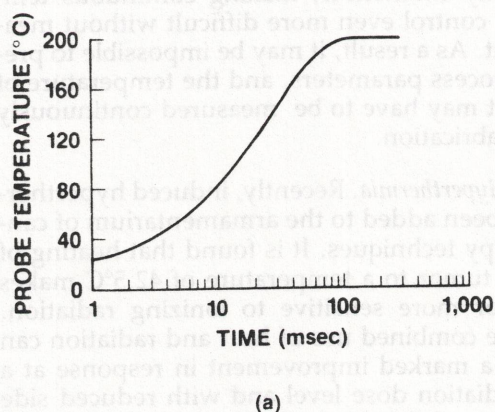


Figure 7. (a) Speed of response of elastomer-tipped probe when touched to a 200°C surface; (b) offset of temperature reading obtained with elastomer-tipped surface probe touched lightly to the surface as compared with that of a thermocouple of similar dimension epoxied to the surface.

are often important to both product quality and throughput.

Dry etching in a plasma is rapidly replacing wet chemical etching of semiconductor materials. During plasma etching, if photoresist is present on the wafer, it can be damaged if the temperature becomes too high. In addition, the results of the etching process — trench shape, etch rate, uniformity, and reproducibility — all depend on wafer temperature.

The potential for photoresist damage is also present during ion implantation — the doping of silicon by direct ion bombardment. With the push for higher throughput, the danger of photoresist damage is increased.

Finally, the critical properties of electronic coatings also depend strongly on substrate temperatures. Hence, the measurement of temperature during deposition is desirable. The technology is applicable in both rf sputtering and in plasma-assisted chemical vapor disposition.

Even if thermocouples or thermistors could be used in these applications — and they cannot because of the electrically hostile nature of the environment — they would be a poor choice for surface measurements. It would be difficult to achieve good thermal contact without epoxying the sensor to the surface. In addition, there would be considerable perturbation of the surface temperature because of the thermal mass of the sensing device and the thermal conductivity of its leads. In contrast, the optical sensor is inherently small and the thermal conductivity of the fiber is low.

There are two fundamentally different approaches to making good surface measurements with a

phosphor sensor [17, 18]. In the first, the phosphor is coated onto the surface of interest. The measurement is then made remotely using the fiber at a distance with or without an auxiliary lens — Figure 4a. This technique allows good measurements over the full range of the instrument.

In the second approach, the sensing layer forms a very thin coating on the outer surface of an elastomer-tipped probe — Figure 4b. As the probe contacts the surface, say the back side of a wafer being etched, the elastomer deforms bringing the phosphor layer into good contact with the wafer. The elastomer's low thermal conductivity isolates the sensing layer thermally. Sensor response is very fast (equilibrium of the sensor with the surface is observed to occur in 100 ms or less) and accuracy is good up to 200°C. The response and accuracy of the elastomer-tipped probe are shown in Figure 7.

Electronics Testing. There is also considerable interest in the thermal testing of operating electronic components and circuits whether for thermal design verification, as a quality control tool or for screening of high reliability devices. While such testing is not done normally in a vacuum chamber as with device fabrication, a fast, convenient surface temperature measurement technique is nonetheless of just as much interest. Furthermore, the fact that the fiberoptic probe is safe in terms of device shorting and is minimally perturbed by rf fields is a major plus, especially where high voltages or microwave fields are likely to be encountered.

There is a need for reduced sensor size in some of the IC and microwave circuit applications and to

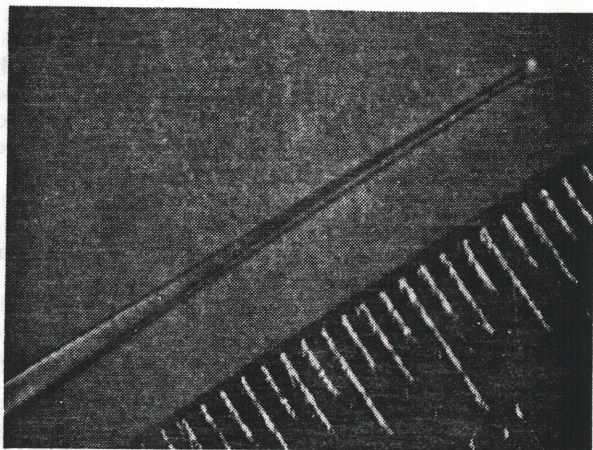


Figure 8. Probe with 1-mil sensing tip fabricated using a tapered silica fiber.

this end the limits of small area sensing are being explored. It has recently proven possible to build contact sensors (Figure 8) with diameters in the 1 to 2 mil range [23]. However, more sensitivity will be required to make remote measurements on micron-sized areas possible. Various approaches to increasing sensitivity are now under investigation.

High Magnetic Field (Magnetic Resonance) Applications. Magnetic resonance imaging (MRI) is rapidly coming into its own as an important medical diagnostic tool. Temperature is important both as a measure of rf power delivered to the patient and because the relaxation times of interest are temperature dependent. Here, in addition to being subject to the imposed rf environment, the patient is positioned in the core of a large superconducting magnet. Hence, a temperature probe for this application needs to be both rf-immune and unaffected by the high magnetic field. Fortunately,

with the decay time technology, no magnetic field effects have been observed in experiments in fields of up to 12 Tesla. Fields are substantially smaller than this in typical MRI applications.

Temperature is also of interest in magnetic resonance spectrometry, particularly when studying biological or biochemical samples. In nuclear magnetic resonance (NMR) spectrometry, samples can be heated strongly by proton decoupling fields. In the process, labile biochemical molecules may be altered in structure and living organisms can be killed. Kinetics studies, as of enzymes, also require a precise knowledge of temperature. Presently, sample temperatures are not measured during NMR spectrometry, but rather nitrogen gas is heated or cooled and then passed over the sample holder. The sample tube, being glass, is a poor conductor of heat, so the sample is not always effectively controlled in temperature and rapid heating by rf fields may not be detected.

There are also applications in electron spin resonance (ESR) spectrometry where the sample volume is much smaller. Here, the potential for highly localized heating by the incident microwave fields is in fact even greater.

Conclusions

The practicality of phosphor-based fiberoptic temperature measurement has been demonstrated. The new technology opens up many previously inaccessible areas of application as well as providing significant improvements for certain important measurements such as of surface temperatures. The potential of the technology, which allows both non-contact measurement and the development of precise yet inexpensive sensors, has yet to be fully realized.

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