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(54) OPTICAL TEMPERATURE SENSING MEANS

(71) We, LUXTRON CORPORATION, a corporation organised and existing under the laws of the State of California, United States of America, of 2916 Scott Blvd., Santa Clara, CA 95050, United States of America, do hereby declare the invention, for which we pray that a patent may be granted to us, and the method by which it is to be performed, to be particularly described in and by the following statement:—

This invention relates to temperature sensors and sensing means for use in methods and with apparatus for temperature measurement by optical techniques. Such methods and apparatus are described and claimed in our co-pending Application No.: 51006/77 (Serial No. 1,605,116) to which reference is directed. Reference is also directed to our co-pending Application No.: 80.23227 (Serial No. 1,605,117) which describes and claims a device for remotely measuring temperature, comprising a length of optical fibre means; a layer of luminescent material held in optical communication with one end of the optical fibre means, which material is characterised by emitting, when excited, electromagnetic radiation with an intensity that varies as a function of its temperature; means adjacent the other end of the optical fibre means for transmitting electromagnetic radiation through the fibre means, to excite the luminescent material to cause it to emit said radiation; and means also adjacent the other end of the optical fibre means for detecting electromagnetic radiation emitted by the luminescent material.

In the method described in Application No.: 51006/77 a luminescent material adapted to emit, when excited, electromagnetic radiation within optically isolatable bandwidths over at least two distinct wavelength ranges and with relative intensities therein that vary as a known function of the material temperature, is positioned in heat transmissive relation with an object. The material is excited to cause emission from within said at least two wavelength bands and the emission directed optically to a detecting station. At the detecting station, the relative intensities of the emissions from each of said at least two distinct wavelength bands are detected to provide an indication of the temperature of the object.

According to the present invention, a temperature sensor for use in the above method comprises a body and a quantity of luminescent material attached to the body in heat transmissive relation thereto, the luminescent material being characterised by emitting, when excited, electromagnetic radiation within optically isolatable bandwidths over at least two distinct wavelength ranges and with relative intensities therein that vary as a known function of the temperature of the material.

It is acknowledged that the luminescent material defined above is known in the colour television tube art; e.g., as disclosed in British Patent Specifications Nos. 1,375,052; 1,432,733; and 1,452,898. Such materials have also been used in other CRT display tubes; fluorescent lamps; colour correcting envelopes on high pressure mercury lamps; and in X-ray conversion screens. Such articles are not considered to constitute temperature sensors as herein referred to.

The luminescent material is normally a phosphor material and is typically one which has a sharp line of emission at each of said at least two distinct wavelength bands, each of the sharp lines rising from substantially zero emission on either side to a peak line intensity in less than 100 angstroms bandwidth.

In one embodiment of the invention, the body comprises an elongate hollow member closed at one end at which closed end the luminescent material is attached. This member may be adapted to receive an end of an optical fibre along which exciting radiation and/or emitted radiation may be transmitted.

Preferably, the optical fibre is removably coupled to the elongate member. In an alternative embodiment, the body itself comprises an optical film, the luminescent material being attached at one end thereof.

The present invention may also be embodied in the form of particles, of which each comprises the body of a sensor as described above. A plurality of such particles may be dispersed in an optically transparent fluid, enabling the temperature of the material to be determined by optical methods.

The invention will now be described by way of example and with reference to the accompanying drawings wherein:

Figure 1 is a block diagram illustrating in general the basic concept of the present invention;

Figure 2 are curves that illustrate the fluorescent emission spectrum at two different temperatures of an europium-doped lanthanum oxysulfide phosphor when excited by ultraviolet radiation;

Figure 3 are curves that illustrate the intensity of specific strong emission lines from certain rare earth oxysulfide phosphors when excited by suitable radiation; or

Figure 3A is a sample excitation spectrum curve for a rare earth oxysulfide at a single radiation output line;

Figure 4 schematically illustrates one specific form of the present invention wherein the temperature of the surface of a wind tunnel model is remotely measured;

Figure 5 shows one specific form of an an optical detector 103 of the temperature measuring system of Figure 4;

Figure 6 shows another specific form of an optical detector 103 of the temperature measurement system of Figure 4;

Figure 7 schematically illustrates a large electrical power transformer utilising one aspect of the present invention for remotely measuring spot temperature thereof;

Figure 8 shows a phosphor temperature sensor and optical system therefor as one form of the temperature measurement system of Figure 7;

Figure 8A illustrates a modification of the temperature measurement system of Figure 8;

Figure 9 shows a variation in the temperature measurement system of Figure 8;

Figure 10 shows yet another variation of the temperature measurement system of Figure 8;

Figure 11 illustrates a rotating device with its internal temperature being measured according to another aspect of the present invention;

Figure 12 illustrates a moving belt with its temperature being measured according to another aspect of the present invention;

Figure 13 illustrates another aspect of the present invention wherein the temperature of fluid flow is measured;

Figure 14 illustrates the present invention applied to a system including a removable temperature probe sleeve; and

Figure 15 illustrates the present invention in an application monitoring an internal temperature of a biological specimen that is under heat treatment.

Referring to Figure 1, the basic features of all of the various aspects of the present invention are illustrated. Within some environment 1 is positioned a solid object 20 having a phosphor coating 40 over at least a portion thereof. The phosphor is characterized by emitting, when excited, electromagnetic radiation within separable bandwidths at two or more distinct wavelengths and with relative intensities in those bands that vary as a known function of the temperature of the phosphor 40. Thus, the temperature of the phosphor 40 is detected that is the same as or related to that of the object 20, and in some application of the environment 1 as well.

Such luminescent emission of the phosphor 40 in the form of electromagnetic radiation 41, generally in or near the visible spectrum, is excited by a source 60 over a path 61. The source could be radioactive material, a source of cathode rays, an ultraviolet electromagnetic energy source, or any other remote source producing efficient fluorescence depending upon the particular type of phosphor utilized in the preferred forms of the present invention. The relative intensities of two distinct wavelength bands within the emitted radiation 41 contains the desired temperature information.

The emitted radiation 41 is gathered by an optical system 20 and directed in a form 81 onto an optical filter and radiation detector block 100. The block 100 contains filters to isolate each of the two bands or lines of interest wtihin the radiation 81 that contain the temperature information. After isolation, the intensity of each of these bands or lines is detected which results in two separate electrical signals in lines 101 and 102, one signal proportional to the intensity of the radiation in one of the two bands and the other signal proportional to the intensity of the radiation in the other of the two bands of interest.

These electrical signals are then applied to an electronic signal processing circuit 120. In a preferred form, the signal processing circuits 120 take a ratio of the signals in the lines 101 and 102 by the use of routinely available circuitry. This electronic ratio signal is then applied to a signal processor within the block 120. The signal processor is an analog or digital device which contains the relationship of the ratio of the two line intensities as a function of temperature for the particular phosphor 40 utilized. This func-

tion is obtained by calibration data for the particular phosphor 40. The output of the signal processor in a line 121 is thence representative of the temperature of the phosphor 40.

The signal in the line 121 is applied to a read out device 140 which displays the temperature of the phosphor 40. The device 140 could be any one of a number of known read out devices, such as a digital or analog display of the temperature over some defined range. The device 140 could even be as elaborate as a color encoded television picture wherein each color represents a narrow temperature range on the object. It could also be a television picture stored on disc or tape.

Preferred Phosphor Materials and Characteristics

The fundamental characteristics of a phosphor material for use in the present invention is that when properly excited it emits radiation in at least two different wavelength ranges that are optically isolatable from one another, and further that the intensity variations of the radiation within each of these at least two wavelength ranges as a function of the phosphor temperature are known and different from one another. A phosphor material is preferred that is further characterized by its radiation emission in each of these at least two wavelength bands being sharp lines that rise from substantially zero emission on either side to a maximum line intensity, all in less than 100 angstroms. The lines are easy to isolate and have their own defined bandwidth. But mixtures of broadband emitters, such as of more conventional non-rare earth phosphors, are also usable so long as two different wavelength ranges of emission of the two materials can be separated sufficiently from one another so that an intensity ratio can be taken, and as long as the temperature dependences for thermal quenching are sufficiently different from the two phosphors.

For a practical temperature measuring device, the phosphor material selected should also emit radiation in the visible or near visible regon of the spectrum since this is the easiest radiation to detect with available detectors, and since radiation in this region is readily transmitted by glass or quartz, windows, fibers, lenses, etc. It is also desirable that the phosphor material selected be an efficient emitter of such radiation in response to some useful and practical form of excitation of the phosphor material. The particular phosphor material or mixture of phosphor materials is also desirably chosen so that the relative change of intensity of emission of radiation within the two wavelength ranges is a maximum within the temperature range to be measured. The phosphor material should also be durable, stable and be capable of reproducing essentially the same results from batch to batch. In the case of fiber optic transmission of the phosphor emission, as described in specific embodiments hereinafter, a sharp line emitting phosphor is desirably selected with the lines having wavelengths near one another so that any wavelength dependent attenuation of the fiber optic will not significantly affect the measured results at a position remote from the phosphor, thereby eliminating or reducing the necessity for intensity compensation that might be necessary if fibers of varying lengths were used.

The composition of a phosphor material capable of providing the characteristics outlined above may be represented very generally by the generic chemical compound description $A_xB_yC_z$, wherein A represents one or more anion elements, B represents one or more cation elements, together forming an appropriate non-metallic host compound, and C represents one or more activator elements that are compatable with the host material. x and y are small integers and z is typically in the range of a few hundredths or less.

There are a large number of known existing phosphor compounds from which those satisfying the fundamental characteristics discussed above may be selected by a trial and error process. A preferred group of elements from which the activator element C is chosen is any of the rare earth elements having an unfilled f-electron shell, all of which have sharp isolatable radiation line emissions of 10 angstroms bandwidth or less. Certain of these rare earth elements having comparatively strong visible or near visible emission are preferred for convenience of detecting, and they are, typically in the trivalent form: praseodymium (Pr), samarium (Sm), europium (Eu), terbium (Tb), dysprosium (Dy), holmium (Ho), erbium (Er) and thulium (Tm). Other non-rare earth activators having a characteristic of sharp line emission which might be potentally useful in the present invention would include uranium (U) and chromium (Cr^{3+}). The activator element is combined with a compatable host material with a concentration of something less than 10 atom percent relative to the other anions present, and more usually less than 1 atom percent, depending on the particular activator elements and host compounds chosen.

A specific class of compositions which might be included in the phosphor layer 40 is a rare earth phosphor having the composition $(RE)_2O_2S:X$, wherein RE is one element selected from the group consisting of lanthanum (La), gadolinium (Gd) and yttrium (Y), and X is one doping element selected from the group of rare earth elements listed in the preceding paragraph having a concentration in the range of 0.01 to 10.0 atom percent as a substitute for the RE element. A more

usual portion of that concentration range will be less than 1.0 atom percent and in some cases less than 0.1 atom percent. The concentration is selected for the particular emission characteristics desired for a given application.

Such a phosphor compound may be suspended in a nitrocellulose binder for application in environments having temperatures of less than about 120° F, and in a silicate binder for higher temperature applications.

A specific example of such a material for the phosphor layer 40 of Figure 1 that is very good for many applications is europium-doped lanthanum oxysulfide ($La_2O_2S:Eu$) where europium is present in the range of one atom percent down to 0.1 atom percent as a substitute for lanthanum. The curves 42 and 43 of Figure 2 provide, for two separate phosphor temperatures, the intensity of its emission as a function of wavelength. The phosphor was in the form of a finely crystalline powder and was excited by electrons. The emitted radiation was analyzed with a scanning monochronmeter followed by a photo-multiplier detector. The particular material for which Figure 2 illustrates the luminescent emission spectrum is lanthanum oxysulfied with 0.1 atom percent of europium substituted for lanthanum.

Curve 42 of Figure 2 shows the emission spectra of such a material at 295° K which is room temperature. The curve 43 of Figure 2 shows the emission spectra for the material at 77° K, the extremely cold temperature of liquid nitrogen. It will be noted that the spectral characteristics of the emission are much different at these two temperatures and these changes continue to occur as the phosphor is raised above room temperature.

Narrow wavelength fluorescent lines which are particularly useful for temperature measurement, as marked on the curves of Figure 2, are located at approximately 4680 angstroms, 5379 angstroms, 5861 angstroms (actually a doublet) and 6157 angstroms. The relative intensities of these lines change as a function of temperature of the phosphor and it is these relative intensities that give the temperature information in the various forms of the present invention.

The relative intensities of at least two of suitable narrow bandwidth spectral lines are determined, in the preferred forms of the invention, by taking the ratio of the detected intensities of two of the lines. The two lines must thus be non-overlapping and separated enough in wavelength so that their intensities may be measured independently. Referring to Figure 3, the intensities of the four spectral lines identified on Figure 2 are drawn as a function of temperature of the phosphor (curves 51, 53 and 54). Additionally, curve 44 of Figure 3 shows a ratio of the two spectral lines 52 and 51 respectively at 5379 angstroms and 4680 angstroms as a function of temperature. It is such a characteristic as illustrated by the curve 44 that permits accurate, pre-calibrated temperature measurement by taking a ratio of two spectral lines. Similarly, if the other two lines 52 and 51 respectively at 6157 angstroms and 5861 angstroms are ratioed, the characteristics of the resulting ratio as a function of temperature is given in curve 45. As can be seen from Figure 3, the ratio represented by the curve 44 varies strongly within a temperature range of from −75° C to +50° C. The second ratio indicated by the curve 45, on the other hand, varies strongly with temperature over the range of from about 50° C to 300° C. Therefore, the particular fluorescent emission spectral lines of the phosphor that are utilized depend upon the expected temperature range to be monitored.

Referring to Figure 3, the intensities of two spectral lines for europium-doped gadolinium oxysulfide ($Gd_2O_2S:Eu$) as a function of temperature of the phosphor are shown as emission lines 55 (at 4680 angstroms) and 56 (5379 angstroms). Europium is present with 0.1 atom percent of europium substituted for gadolinium.

The intensity of the 4680 angstrom emission line of europium-doped yttrium oxysulfide ($Y_2O_2S:Eu$) is shown by curve 57 of Figure 3, where europium is present with 0.1 atom percent of europium substituted for yttrium. The intensity of the 5379 angstrom of the $Y_2O_2S:Eu$ line is shown by curve 58. A line useful for referencing (ratioing) in $Y_2O_2S:Eu$ is the 6157 angstrom line represented by curve 59. The curves 55, 56, 57 and 58 show usable temperature dependent emission intensity characteristics in different temperature ranges than those spanned by the lanthanum material exhibiting curves 51 and 52. These additional oxysulfide materials are most usable over the rapidly changing portions of their curves when referenced to a line such as the 6157 angstrom line. The differences with useful temperature ranges of these materials are significant when selecting an optimum material for a specific application. The 4680 angstrom line 55 of gadolinium oxysulfide, for example, has particular advantages for medical temperature measurement since especially rapid changes occur with good signal strength over the range of human body temperatures.

It will be noted from Figure 3 that each of the gadolinium, lanthanum and yttrium oxysulfide materials illustrated has the same doping, namely 0.1 atom percent of europium. However, experiments with materials of widely different doping levels of europium indicate that the temperature dependences are not significantly affected by doping level. The temperature characteristics of the material are, as can be seen, very dependent upon the

phosphor host material, as well as on the choice of activator ion, thus permitting optimization of the temperature characteristics for a particular application by selection of the proper host material.

Referring to Figure 3A, a typical light intensity output characteristic is illustrated from the rare earth oxysulfide phosphors discussed above. This is the emission intensity at a particular wavelength line, as a function of wavelength of the phosphor exciting radiation. It can be seen that the most intensity is obtained when the phosphor is excited with ultraviolet radiation. Ultraviolet radiation is preferred, therefore, for exciting the phosphor in most cases. But some optical systems that might be used to transmit exciting radiation have considerable losses t ultraviolet radiation when compared to losse in the visible range. A long length of optica fiber, such as one over 100 meters in lengt would be such a system. When the losses ar great enough, it may be preferable to excit the phosphor with visible radiation, such a at either the blue or green excitation bands shown on Figure 3A. Even though the resulting excitation efficiency may be lower for visible than ultraviolet radiaton, the improved visible transmission of a long optical fiber can make up for this difference.

In order to adequately detect and measure these spectral line ratios without interference from adjacent emission lines, the fluorescent radiation 41 and 81 of Figure 1 must first be passed, as part of the block 100, through an optical filter such as a monochrometer or interference filter set chosen to isolate the selected wavelength ranges in which the spectral lines of interest fall. It can be seen from the characteristics of the phosphor illustrated in Figure 2 that for the 4680 angstrom, 5861 angstrom and 6157 angstrom lines, a bandpass filter in the order of 50 angstrom wide is adequate for separation. In addition to separation, it may also be desirable to correct the measured lines intensities within the block 100 for any strong background radiation which may be present, such as that from room light or day light. For that purpose, it may be desirable in certain circumstances to additionally measure the intensity of radiation as seen through the utilized monochrometer or filter when tuned to a spectral region near the fluorescent lines but where no fluorescent radiation is expected. An example using the phosphor whose characteristics are illustrated in Figure 2 is in the region of from 6000 to 6100 angstroms. Alternatively, the background can be determined by turning off the excitation source and looking through the two filters. Any background radiation so measured can then be subtracted from the 5861 and 6157 angstrom line intensities that are measured to yield a more correct ratio for temperature measurement purposes.

A physical mixture of phosphor compounds can also be utilized, as an alternative, in order to obtain desired temperature characteristics. The intensity of one emission line from one compound of the mixture, for instance, can be compared with the line intensity of another compound in order to provide optimum measuring characteristics over a given temperature range. Alternatively, two emission lines from each of two phosphor compositions can be utilized, the lines from one compound compared over one temperature range and the lines from the other compound being compared over an adjacent temperature range. For example, a terbium doped lanthanum, gadolinium or yttrium oxysulfide may be used as one compound in combination with an europium-doped lanthanum, gadolinium or yttrium oxysulfide as the other compound.

The phosphor materials mentioned above have an advantage of being relatively inert and stable. The emission lines of the phosphor are in the visible or near visible region and thus transmission through long air paths, through water and other liquids, or through long optical fibers, or through glass or quartz optics, is possible. Such a phosphor differs from more conventional phosphors in that it emits very sharp line output spectra that can be readily optically isolated from each other, and the temperature dependence of line intensities at a particular wavelength is very strong relative to that at other wavelengths over a given temperature range of practical interest. Other phosphor materials having these characteristics can be utilized as part of the technique and structure of the various aspects of the present invention, as well.

Remote Non-Contact Surface Temperature Measurements

Referring to Figure 4, an object 21 within an environment 2 has its outside surface painted with phosphor material 46. By monitoring the emission of the phosphor, when properly excited, the surface temperature of the object 21 can be monitored from a remote distance and without contacting the object 21.

In the particular example shown in Figure 4, the object 21 is an aerodynamic model positioned in an environment 2 that is a test wind tunnel. The surface temperature being monitored on the model 21 provides information as to the effect of the air flow in heating the model surface.

The phosphor painted on the surface of the model 21 is excited to luminescence by illumination from ultraviolet lamps 62 and 63. In some situations, an ultraviolet laser

might be used as well, particularly for measurement of selected object points. The ultraviolet output of the lamps 62 and 63 are passed, respectively, through windows 64 and 65 that are transparent to ultraviolet energy so that it might pass into the wind tunnel 2 and onto the model 21. Another window 82 permits emitted radiation from the phosphor on the surface of the model 21 to be gathered by an optical system, represented by lenses 83 and 84. The collected radiation 85 is then directed onto a filter and detector system 103. The filter and detector 103 is similar to the filter and detector 100 previously described with respect to Figure 1.

Referring to Figure 5, details of one form of the filter and detector 103 are illustrated. A filter wheel 104 is positioned in the path of the radiation 85 from the phosphor. The wheel 104 has at least two different filters 105 and 106 spaced on different areas of the wheel 104 so that as it is rotated by the motor 112 the filters 105 and 106 are alternately passed through the beam 85. The filters 105 and 106 are designed to be narrow bandpass filters to select out two different spectral lines of the phosphor being utilized.

The two selected phosphor emission lines are thus applied in time sequence to a detector 107 whose output is applied to an electronic circuit 108. The detector could be a photomultiplier or a silicon photo-diode which would give only an average of the intensity of the particular selected lines over the entire object 21 or the detector 107 could be some other device, such as an image dissector or a television camera, that would convert the optical image of the object 21 as viewed by the selected emission lines into a two dimensional intensity plot. The use of the latter type detectors has an advantage of permitting temperature detection on each point of the object 21 separately. The electronics 108 receives a synchronous signal from the detector 111 which tells it which of the two filters 105 and 106 are in front of the detector 107 at any instant. This permits the electronics 108 to develop the two signals 109 and 110 representative, respectively, of the intensities of the two selected emission lines of the phosphor.

Figure 6 shows another form of the filter and detector 103 of Figure 4. In the form of Figure 6, a beam splitter or dichroic mirror 90 is positioned in the path of the phosphor fluorescent emission beam 85 so that known fractions of the intensity of the beam goes in each of two directions. One direction is through a filter 115 and onto a single detector 116 to develop an electrical signal 110'. The other path is through a filter 113 onto a second detector 114 to develop a signal 109'. Each of the filters 113 and 115 are selected to permit one or the other of two selected emission spectral lines to pass therethrough and onto their respective detectors. The output signals in the lines 109 and 110 of Figures 4 and 5, and 109' and 110' of Figure 6, are applied to appropriate signal processing and readout circuits as described with respect to blocks 120 and 140 of Figure 1. The read-out device would depend, of course, upon the type of detector used, being a television display system or video storage medium if the detector 107 is a television camera.

Remote Point Temperature Measurement

There are many applications of large machinery and apparatus wherein it is desired to monitor the temperature at one or more points within the apparatus while it is operating. Large machinery is especially expensive. It is very inconvenient and expensive when it breaks down due to local overheating. If such local overheating can be detected before any damage is done, then the cause of it can be determined, thus avoiding more costly shutdowns of the equipment. Monitoring the overall or average temperature of the equipment, by monitoring the temperature of water or oil coolant, for instance, does not provide the necessary information in most instances because the overheating could be raising the temperature of a small part of the machinery to an excessive and damaging level without raising the average temperature any detectable amount.

One such piece of equipment wherein there has been a long need for such point temperature measurement is in large electrical power transformers, some of which are capable of handling several megawatts of electrical power. Destruction of such a large piece of equipment is not only extremely costly but can significantly disrupt a large portion of an electric power company's distribution system. The problem has not been satisfactorily solved before since electrical transformers, as is the case with other high voltage electrical equipment, cannot tolerate any electrical conductors within the equipment that will disturb the electric and magnetic fields or cause a potential for short circuits. Therefore, there is a need for a non-metallic local point temperature sensor that can be used inside of electrical power transformers or other types of large electrical equipment.

Referring to Figure 7, such a transformer is very generally illustrated. A thick steel outer shell 7 contains a transformer core 6 having windings 4 and 5 therearound. The entire core and windings are submersed in an oil bath 3 for insulation and cooling. In order to monitor the temperature of a given spot on the interior of such a transformer, a single sensor 22 is provided in accordance with another aspect of the present invention. The sensor 22 is connected to one end of a long optical fiber bundle 86. The sensor 22

may be constructed without any metal parts at all and is optically connected by the fiber bundle 86 to an appropriate filter and detector system 100', an electric signal processing circuit 120' and a direct temperature read-out device 140'.

Referring to Figure 8, the temperature sensor 22 is shown in cross section wherein it contains a phosphor material 87 in optical communication with one end of the optical fiber bundle 86. This end of the optical fibers and the phosphor are all sealed together by an appropriate glass or ceramic material to form a probe which may be inserted into a transformer or other machinery. The probe is subjected to the temperature to be measured and the phosphor, being part of that probe, responds as described hereinbefore with relative changes in the intensity of its spectral output lines as a function of temperature.

The output of the phosphor 47 is obtained at an opposite end of the fiber bundle 86 by a lens 87 which directs the emission radiation through a beam splitter or dichroic mirror 88, through another lens 89, and thence to a system already described with respect to Figure 6, including a beam splitter or dichroic mirror 90, two filters 113 and 115 and two radiation detectors 114 and 116.

In order to excite the phosphor 47 to emit the desired lines, the embodiment of Figure 8 employs an ultraviolet light source 66 whose output is directed by a lens 67, passed through a broadband ultraviolet filter 68 which blocks all but the ultraviolet light and then onto the beam splitter or dichroic mirror 88. The element 88 is designed to transmit visible light but reflect ultraviolet light so that the optical configuration shown in Figure 8 utilizes such a characteristic to advantage. The ultraviolet radiation is reflected by the element 88, directed through the lens 87 into the optical fiber bundle 86 and transmitted through it to the phosphor material 47 to excite its luminescent emission which provides the temperature information in a coded form, as described above.

Referring to Figure 8A, a modification of the system of Figure 8 is shown wherein a probe 27 of a type similar to probe 22 of Figure 8 is excited by connection through a fiber optic 86' to an excitation source 60'. The radiation from the phosphor within the probe 27 is carried by a separate fiber optic 86'' to the appropriate filters and detectors 100''. The fiber optics 86' and 86'' may be a single optical fiber each, or may be a bundle of fibers. The use of the separate fiber optics 86' and 86'' has a principal advantage of providing optical isolation between the phosphor excitation radiation and radiation given off by the phosphor. Excitation radiation as well as possible low level fluorescence from the optical fiber itself is thus kept clear of the detectors 100''. The result is less optical background noise and improved accuracy. The excitation source 60' and detector 100'' may also be more easily physically isolated using the bifurcation scheme.

Figure 9 shows a variation of the probe and detecting system of Figure 8 wherein a probe 23 includes a phosphor material 48 attached to one end of an optical fiber bundle 91. Encapsulated within the probe 23 in this embodiment is a radioactive material 69 which is selected to excite, for a number of years, the phosphor material 48. The emission of the phosphor material 48 is transmitted through the optical fiber bundle 91, through a lens 92 and onto a beam splitter, filter and detector system as described previously with respect to Figures 6 and 8. The radioactive material 69, used in place of the ultraviolet source 66 of Figure 8, may be, for example, an isotope of nickel, such as $_{63}Ni$, having a half life of 92 years. This material emits electrons but does not emit gamarays. This probe 23 and communicating optical fiber bundle 91 still may maintain the desirable charactersitic of having no metallic component if the $_{63}Ni$ is in the form of an oxide or other non-metallic compound.

Figure 10 shows a variation of either of the probe assemblies of Figures 8 and 9 wherein a single optical fiber bundle 92 provides optical communication with a plurality of separate probes, such as the probes 24, 25 and 26, which can be positioned at different locations within a power transformer or other apparatus. At one end of the optical fiber bundle 92, a few of the fibers are connected with each of the individual probes 24, 25 and 26. At the opposite end of the fiber bundle 92, the opposite ends of the same optical fibers are connected to individual filters and detectors. That is, the probe 24 is in optical communication with only the filter and detector block 117, the probe 25 only with the filter and detector block 118, and so forth. Alternatively, the separate probes can be scanned at the output end of the fiber optic bundle by a single detector in a controlled and predetermined fashion.

Obviously, the specific types of equipment where such temperature probes have a high degree of utility are numerous. An electric power generating nuclear reactor is another place where the invention can be used with great advantage to measure temperature of remote, inaccessible positions.

Other Applications

The techniques of the present invention lend themselves to optical commutation. They may be applied without physical contact and are immune to electrical noise. A specific application of optical commutation is on a rotating device 200 as shown in Figure 11. This device could be a motor, turbine or generator. The phosphor containing probe

22 is embedded in the rotating part 200 as are an optical fiber input bundle 201 and an output bundle 203. The optical fiber bundles terminate at an external circumference of the wheel or rotating part 200. This permits the non-rotatable fixed positioning of an exciting radiation source, such as an ultraviolet source 205, and phosphor emission receiving optics 207 adjacent thereto. At one position, for a short instance, in each rotation of the rotating part 200, the ultraviolet source and the phosphor emission radiation optics 207 will be aligned with their respective optical fiber bundles 201 and 203. At that instant, the temperature of the part at the position of the embedded phosphor containing probe 22 is measured. The optical system 207 is connected with an appropriate filter and detector 209 of one of the types discussed with respect to other of the embodiments above.

The same technique can be utilized, as shown in Figure 12, for a moving belt 211. This optical temperature measurement technique can be seen to have considerable advantages since no physical connection of wires or other devices are required between the moving part and the fixed measuring equipment. As an alternative to the particular optical technique shown in Figures 11 and 12, the rotating part 200 and the belt 211 could also be painted with a phosphor paint as discussed with respect to Figure 4.

Referring to Figure 13, yet another application of the basic concept of the present invention is shown wherein the temperature of a moving stream of fluid 215 passing through a pipe 217. A window 219 is provided in the wall of the pipe 217 and characterized by transmitting ultraviolet and visible radiation without significant attenuation. An electromagnetic energy source 221 in the ultraviolet spectrum illuminates the interior of the pipe through the window 219. The fluid stream 215 is provided with a plurality of phosphor coated particles 223 that have a size and density consistent with the type of fluid 215 and flow to be expected so that they remain distributed within the fluid stream 215. The radiation from the ultraviolet source 221 causes the phosphor coating on the particles 223 to luminesce and this luminescence is gathered by an optical system 225 which collects and transmits the phosphor radiation to an appropriate detector 227. By detecting and ratioing the intensities of two phosphor emission lines of interest, the temperature of the fluid stream 215 is determined since the particles have been given a chance to reach a temperature equilibrium with that of the fluid stream 215.

Other particular applications will become apparent from this description. The probe and optical fiber embodiment can be applied to point temperature measurement in humans and animals, for example.

A further application is illustrated in Figure 14. The end of an optical fiber bundle 301 is capped with a disposable temperature sensing sleeve 303. The sleeve 303 is formed of a cylindrical base portion 305 that is carried at the end of the optical fiber 301. One end of the cylindrical base 305 is capped with a thin, heat conductive cap 307 such as, for example, one made of metal. On an inside surface of the cap 307 is a phosphor coating 309. At the other end of the fiber optics 301 (not shown) is an excitation source and detecting system. The end of the optic fiber 301 with the sleeve 305 is immersed in the environment for which a temperature is desired to be taken, such as a human or animal cavity, or liquid baths.

The advantage is that the sleeve 303 may be discarded after a single use, thus preventing cross contamination from occurring in sequential temperature measurements. A significant advantage of using the present invention for this type of measurement is that it has a very low thermal mass, resulting in the temperature indicating phosphor 309 reaching a steady state value of the temperature of its surroundings very quickly. Except for the cap 307, the remaining plastic materials affect very little heat transfer from the surroundings to the phosphor 309. The other advantages described above concerning the phosphor, optical fiber structure generally are present here as well.

Yet another application is utilizing the probe and optical fiber embodiment of the present invention generally to measure the temperature at a point within humans and animals. A potential application is illustrated in Figure 15 wherein a human or animal body 311 contains a cancerous tumor schematically shown at 313. A technique presently being explored for treating the tumor, called hyperthermia, involves irradiating the tumor 313 by means of energy 315 from a source 317, the result being induced heating. However, the success of this technique for treating the tumor 313 is dependent upon maintaining the tumor at a specific, well controlled elevated temperature.

Therefore, a means of monitoring and controlling the temperature of the tumor 313 is to surgically implant a minute, nonprotruding temperature probe 319 of the type discussed principally with respect to Figure 9. A fiber optic 321 communicates between the temperature probe 319 and excitation and detection apparatus 323. For this application, of course, the size of the temperature probe 319 and cross-sectional dimension of the optical fiber 321 needs to be as small as possible. The optical fiber can be limited to one or two fibers and the temperature probe 319 can be formed by coating the phosphor and a thin encapsulating material

directly onto the end of the optical fibers. The temperature of the tumor 313 can then be monitored and the intensity of radiation from the source 317 adjusted to maintain the optimum temperature for treatment.

The techniques of the present invention also have application for point temperature measurements in chemical and food processing systems. The advantage of an optical fiber and temperature probe system as described herein in such applications is that they are chemically inert, have a very fast response time, provide electrical isolation, can be permanently calibrated, are of low cost, are sterilizable and can even be used in large moving machinery. These sensors can also be used to measure the temperature of food undergoing microwave cooking, an application where a thermocouple or any other metallic temperature measuring apparatus cannot be used.

A particular further application that takes advantage of the fact that a direct physical contact need not be maintained with an object under measurement is in food processing where a dot of phosphor can be placed on each package to be cooked and the temperature thereof monitored by monitoring the emissions of the phosphor when excited in the manner discussed above.

The optical fiber technique of the present invention permits point temperature measurements to be made at a long distance from the detection and excitation apparatus. The use of such techniques for monitoring temperatures at various points in an industrial plant can easily involve optical fiber runs in excess of 100 meters and even many times that. For such long runs, it may be preferable to use excitation radiation within the visible spectrum with a rare earth phosphor acting as the temperature indicating device. The particular excitation radiation that would be sent down the long optical fiber and the phosphor composition for such an application have been discussed earlier with respect to Figure 3A.

The technique can also be broadly applied to imaging thermography wherein an object scene is imaged onto a phosphor screen and the emissions detected through filters by a television camera to measure the relative intensity of two emission lines and thence the temperature of the image, the latter being proportioned to the temperature of the object scene. In yet another approach to thermal imaging, the phosphor screen could be mounted within a vacuum tube, illuminated from one side by the thermal image, via a suitable infrared-transmitting window and substrate, and excited from the other side by an electron beam scanned in raster fashion. In this instance the thermal image could be reconstructed using a single pair of optical point detectors suitably filtered with the resultant line intensity ratio thence used to modulate the intensity of the electron beam of a cathode ray display tube which is also scanned in raster fashion in synchronism with the exciting electron beam.

WHAT WE CLAIM IS:—

1. A temperature sensor comprising a body and a quantity of luminescent material attached to the body in heat transmissive relation thereto, the luminescent material being characterised by emitting, when excited, electromagnetic radiation within optically isolatable bandwidths over at least two distinct wavelength ranges and with relative intensities therein that vary as a known functon of the temperature of the material.

2. A temperature sensor according to Claim 1 wherein the luminescent material is a phosphor material.

3. A sensor according to Claim 2 wherein the phosphor has a sharp line of emission within each of said at least two distinct wavelength bands, each of the sharp lines rising from substantially zero emission on either side to a peak line intensity in less than 100 angstroms bandwidth.

4. A sensor according to Claim 2 or Claim 3 wherein the luminescent material comprises a phosphor composition (RE) $_2O_2S:X$, wherein RE is an element selected from the group consisting of lanthanum, gadolinium and yttrium, and wherein x is a doping element with a concentration of from 0.01 to 1.0 atom percent and is selected from the group consisting of europium, terbium, praseodymium, samarium, dysprosium, holmium, erbium and thulium.

5. A temperature sensor according to any preceding Claim wherein the body comprises an elongate hollow member closed at one end at which closed end the luminescent material is attached.

6. A temperature sensor according to Claim 5 wherein the open end of the member receives an optical fibre.

7. A temperature sensor according to Claim 5 or Claim 6 wherein the body is removably coupled to an optical fibre.

8. A temperature sensor according to any of Claims 1 to 4 wherein the body is a length of optical fibre with the quantity of luminescent material attached to an end thereof.

9. A sensor according to any of Claims 1 to 4 wherein the body is a container.

10. A sensor according to Claim 9 wherein the body is a food container.

11. A temperature sensor substantially as described herein with reference to and as illustrated by the accompanying drawings.

12. A clinical thermometer including a temperature sensor according to any of Claims 1 to 7 and 10.

13. Temperature sensing means comprising a plurality of sensors according to any of

Claims 1 to 4 wherein each body is a separate particle.

14. An optically transparent fluid having dispersed therein temperature sensing means according to Claim 13.

15. Temperature sensing means according to Claim 13 and substantially as herein described.

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1605118 COMPLETE SPECIFICATION
6 SHEETS *This drawing is a reproduction of the Original on a reduced scale*
Sheet 1

FIG. 1

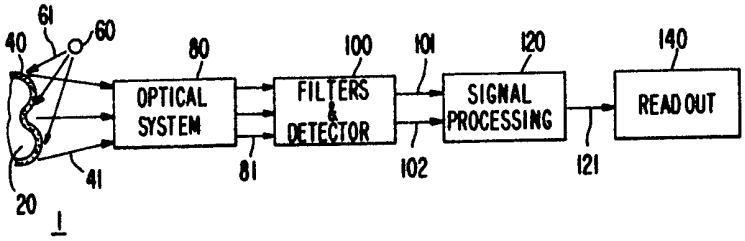
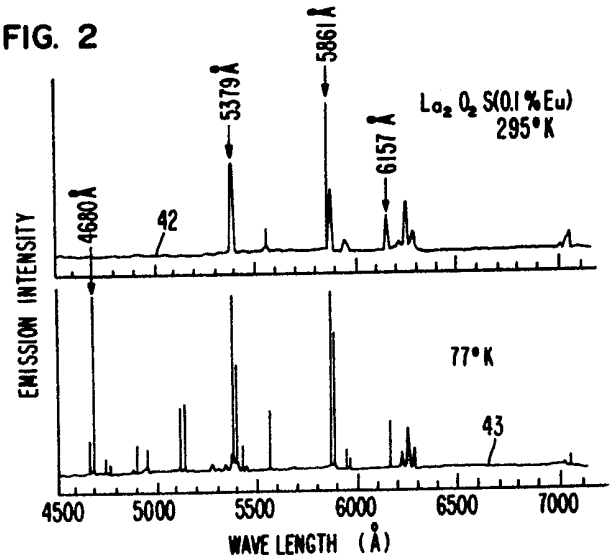


FIG. 2



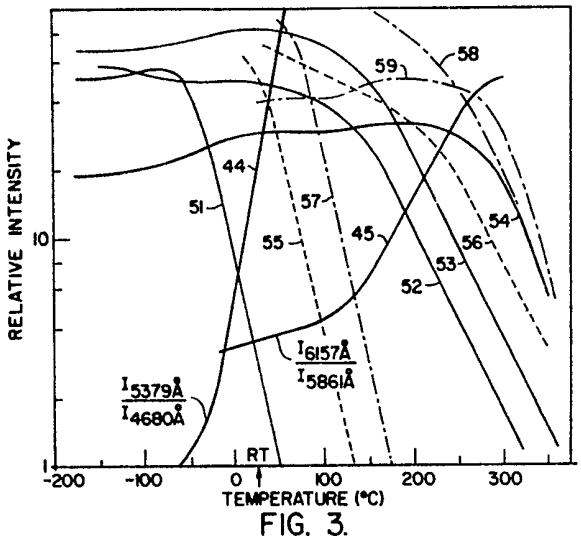
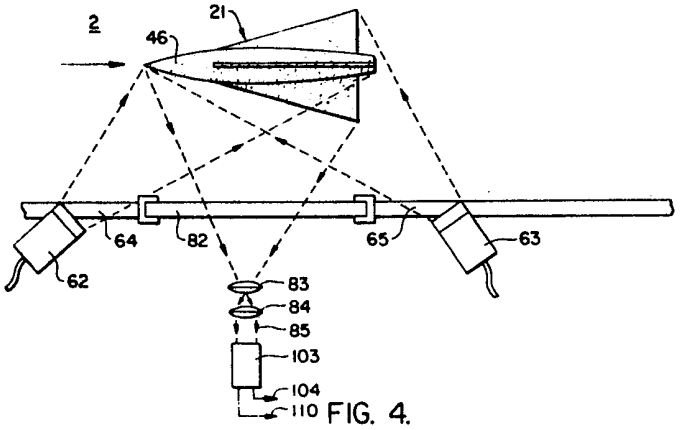

RELATIVE INTENSITY
10
1
-200
-100
0
RT
100
200
300
TEMPERATURE (°C)
58
59
44
57
51
55
45
54
56
53
52
$\frac{I_{6157Å}}{I_{5861Å}}$
$\frac{I_{5379Å}}{I_{4680Å}}$

FIG. 3.


2
21
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83
84
85
103
104
110

FIG. 4.

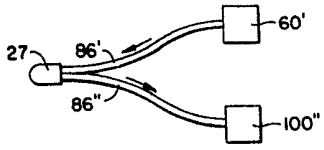


FIG. 8A.

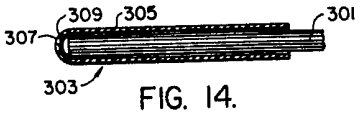


FIG. 14.

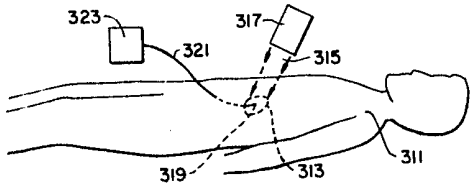


FIG. 15.

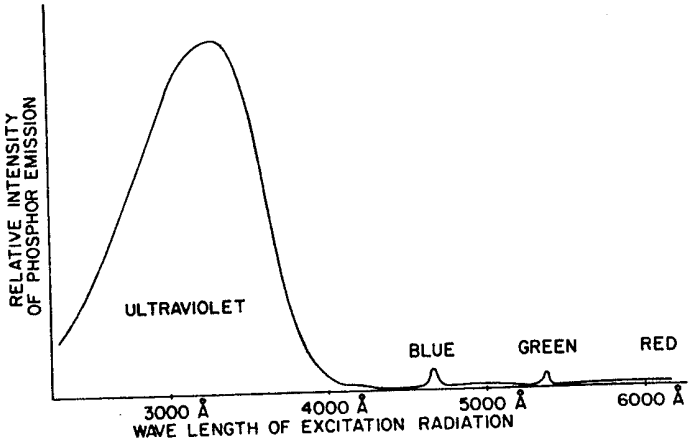


FIG. 3A.

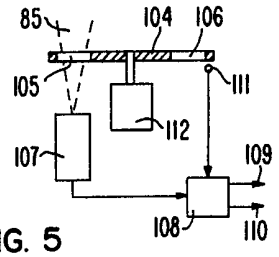


FIG. 5

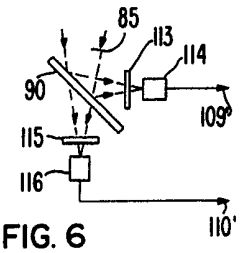


FIG. 6

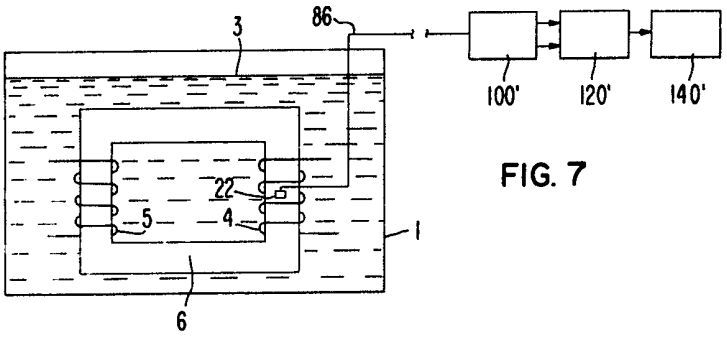


FIG. 7

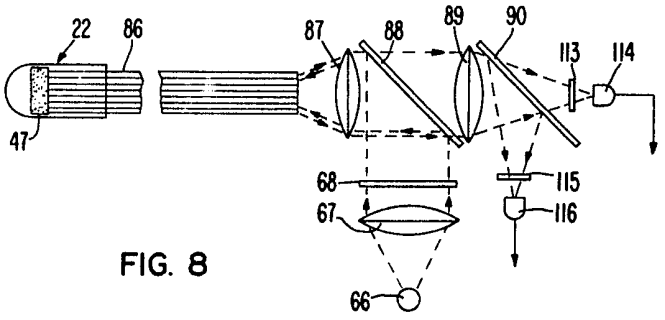


FIG. 8

FIG. 9

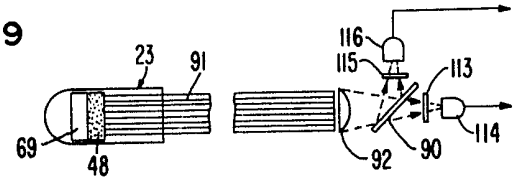


FIG. 10

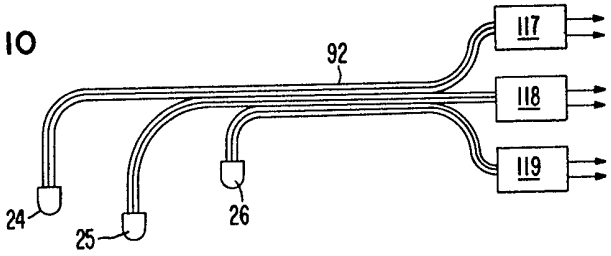
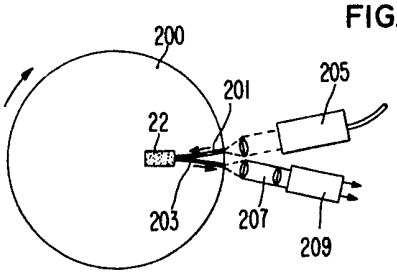


FIG. 11



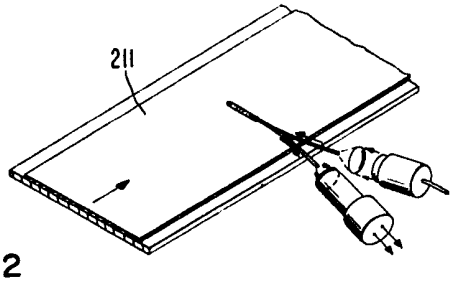


FIG. 12

FIG. 13