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ACCURATE OPTICAL TEMPERATURE MEASUREMENT USING LIQUID CRYSTAL SENSOR

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1. Introduction

Recent works have shown that given tumors and diseases could be detected by local temperature measurements.
It was also ascertained and experimentally proved that a "temperature gap" exists in which healthy cells survive, whereas abnormal cells belonging to a tumorous system or affected by given diseases are destroyed.
Nowadays, in thermotherapy, the most efficient way to bring the required heat in a given area of the body is to use a beam of microwaves.
However, it is necessary to follow the local evolution of temperature and to adapt the microwave power level to the one required to keep the heating between the limits of the "temperature gap". Overheating may destroy healthy cells. Underheating makes the therapy unefficient and, maybe, aggravates the case.
Unfortunately, usual devices which can be used for temperature measurement at a given point make use of a temperature-to-electric current relationship and the presence of metallic conductors strongly react to a microwave field by self-heating.
In other words such sensors are directly heated by the microwave beam and give a signal which corresponds to their own temperature instead of that of the tissues in which they are inserted.
This is one of the main reasons why thermotherapy was very difficult to apply safely.
It is the purpose of the "optical temperature analyzer" instrumentation presented here to propose a system using probes totally insensitive to an electromagnetic field and thus to allow an accurate temperature measurement of the tissues, even in the presence of a strong microwave beam and without interfering with it.

2. Basic principle of dielectric temperature probes

The medical and prospective aspects of hyperthermical therapy using liquid crystal probes are described in Dr. Gautherie's paper :
"Actualités et prospective de l'utilisation de l'hyperthermie hyperfréquence en thérapeutique cancérologique, Paris 1979, Vol. 60, p. 685-689"
and the scientific solution to temperature measurements is given in Mr. Samsel, Pellaux and Gautherie's communication to the present Meeting :
"Development and evaluation of a new device for non-interfering thermal dosimetry during microwave heating for cancer therapy".

The purpose of the present paper is to describe the technical solution used in the practical instrumentation presented at this Second Annual Meeting of the Bioelectromagnetics Society.

The temperature sensor is a thin silica-glass fiber used as a light conductor. The extremity of the portion which will be introduced in the tissues to be thermally treated is covered with a thin layer of a cholestric liquid crystal compound.

The interesting property of such a compound is to react to a temperature change by a change in colour. Thus to a given colour corresponds a given temperature.

More generally, the wavelength reflected by the liquid crystal is a function of temperature.

One possible solution is to illuminate the liquid crystal (LC) with white light and to measure the wavelength at which the reflected light reaches a maximum of intensity.

For practical reasons, it is easier to use a rotating monochromator as a light source producing a wavelength which is linearly scanned between two limits : in our case, between 400 and 700 nanometers (nm), this covering approximately the visible range from violet to red.

As said before, the liquid crystal compound has a colour depending on the temperature. Thus, when illuminated with a continuousely varying wavelength the LC-sensor will have a response as shown in fig. 1a, 1b and 1c for three temperatures.

The monochromator is of the Ebret type (fig. 2). The light source L has an almost continuous spectrum between 400 and 700 nm. A part of the beam passes through a first slit S1 and is reflected on a rotating diffraction grating. After a second reflection on the mirror M, the light passes through a second slit S2 and is focused on the input of one to four optical light guides W1 to W4 by a microscope objective O. These light guides are connected to the LC temperature sensors via four optical connectors located on the front panel.

It can be shown that the wavelength is a direct function of the diffraction grating angle. This means that, knowing the exact angular position of the grating implies that the wavelength at this position is known.
A servo-system is used to monitor the grating revolution speed and the associated electronics delivers a succession of pulses, each of them corresponding to 1 nm. A marker unit gives a pulse of higher amplitude at any desired initial value, in our case, 400 nm.
The light focused on the optical fiber travels along it, reaches the LC layer and is reflected. A "Y-junction" sends the reflected light on a photo-detector (PD) giving an electrical output proportionnal to the intensity of the optical signal.
An electronic computing unit C establishes the correlation between the monochromator signal (wavelength) and the peak of the reflected light and computes the corresponding temperature. The result is displayed on an LED read-out with a resolution of one tenth of a degree centigrade.

3. Colour to temperature relationship

According to the above mentionned papers, the relationship relating colour to temperature is an hyperbolic function defined by

$$(T-To)^{\alpha} \cdot (Xo + \lambda)^{\beta} = C$$

In a restricted range, this function can be reduced to

$$(T-To)(Xo+\lambda) = C \qquad (\alpha \text{ and } \beta \cong 1)$$

Thus

$$T = To + \frac{C}{Xo + \lambda}$$

where To, Xo and C are constants depending on the LC compound and λ is the wavelength or, more precisely, the number of nanometers from a given origin (here, 400 nm).

4. Detection of the reflected light

As explained before,the light issuing from the monochromator travels through an optical fiber, is reflected by the liquid crystal and fed to an optical detector. The light intensity at this point being very low, a photo-multiplier has been chosen as detector, with the advantage of a fast response time (a solution using solid-state detectors is being studied).
After amplification, the output signal of the detector is the one shown in fig. 1.
The diffraction network is rotated at a speed of 10 revolutions per second. It is thus possible to make as much as 10 measurements per second.

5. Electronic unit

Each probe is connected to an electronic module having the following functions :

- signal detection and amplification as described under point 4,
- processing of the signal given by the monochromator, i.e. detection of the pulse corresponding to the initial wavelength (usualy 400 nm) and shaping of the nanometric pulses,
- processing of the reflected light signal including improvement of the signal-to-noise ratio, possibility of choosing a level at which the signal is to be considered (rejection of parasitic reflections),
- computer section taking into account the probe constants C, Xo, To and computing the temperature corresponding to the number of nanometric pulses received when the return light peak is detected,
- if set on "CALIBRATE", the unit gives the result of the equation

  $$T = To + \frac{C}{Xo}$$

  thus allowing calculation of the constants (C, To and Xo) of an unkown probe,
- supervising section giving alarm outputs if :
  a) the nanometric pulses fail
  b) the colour signal is not correctly received
  c) a maximum allowed temperature Tmax is exceeded.

These signals are available on electrical outputs allowing actuation of optical or acoustical alarms.
These failures are also visible on the temperature display :
- if everything is normal, the display is continuous
- in case of a monochromator pulse failure, the display flashes slowly (three times per second)
- if the maximum temperature Tmax is exceeded, the display flashes at a higher rate (10 times per second).

Finally, a potentiometer allows one to adjust the repetition rate of each probe in order to choose the optimum between measurement speed and display readability. The range covers from 10 measurements per second to one measurement every 10 seconds.

6. Instrument description

The whole system is contained in a single cabinet 50 cm long, 35 cm high, and 46 cm wide.
The monochromator with its light source is mounted on the rear and the front panel is divided into six units. Four of them are allocated to the mounting of one to four electronic units for the temperature probes.
The three probes constants : C, Xo and To as well as the maximum temperature Tmax at which alarm will be switched on are simply dialed on four sets of thumbwheels on the front plate of each probe unit.
Usually, two probes are inserted into the tumor and two in the neighbouring healthy tissues in order to be sure that a safe temperature is not exceeded there.
The fifth unit contains the monochromator monitor and marker, including a set of thumbwheels for choosing the wavelength at which the scanning begins.
The sixth unit is fitted with four optical connectors for the LC-probes, and the mains switch.

7. Acknowledgment

This instrument was developped by CIPOSA Ltd, Bienne, Switzerland, thanks to the researches conducted at the Louis Pasteur University of Strasbourg, by Professor Coche in the field of temperature sensitive liquid crystals, Dr. Gautherie and Mr. Samsel for the medical aspects.

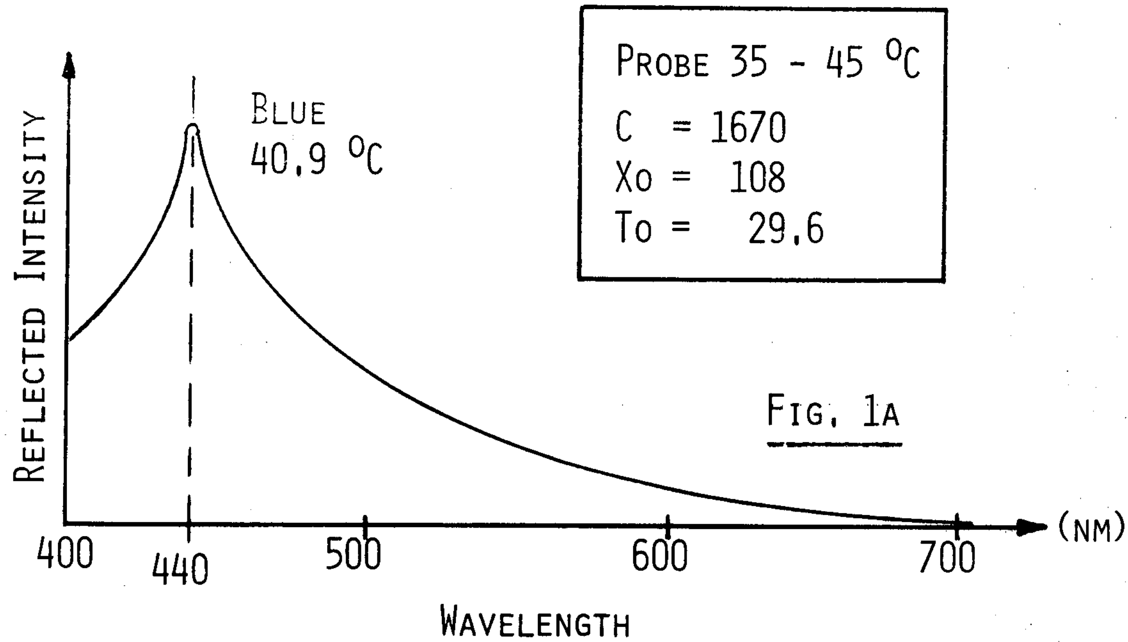

FIG. 1A

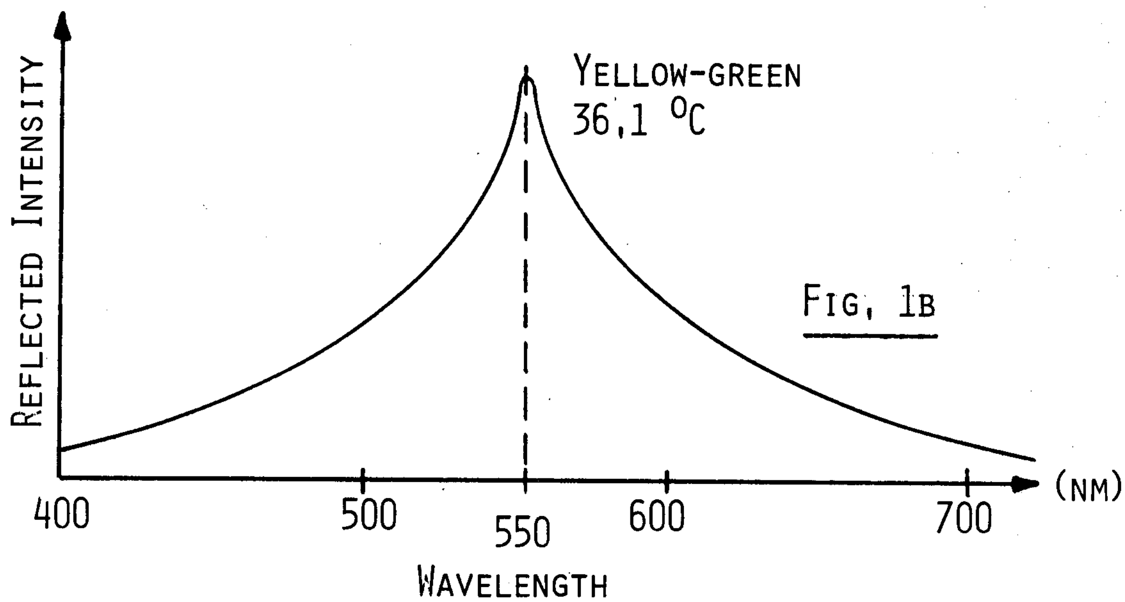

FIG. 1B

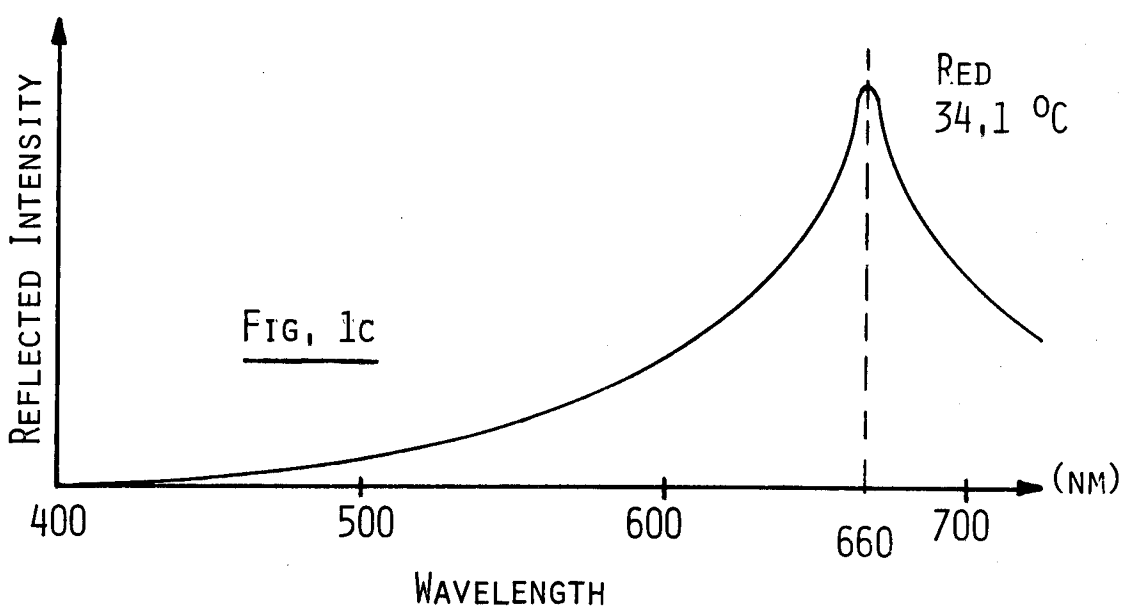

FIG. 1C

Optical Temperature Analyzer

Functional diagram