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**OPTICAL REMOTE MEASUREMENT OF TEMPERATURE
IN THE RANGE 0-2000°C**

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ABSTRACT

This report discusses our preliminary investigation of a new optical means of measuring temperature based upon the effect of a birefringent crystal on the state of polarization of a transmitted light beam. The method has some unique attributes: remote nature of measurement, temperature resolution of better than 1°C, and high-temperature operation – up to the melting temperature of the sensor optics (2040°C for sapphire).

PRINCIPLE OF THE METHOD

This temperature measurement method is based upon the effect of a birefringent crystal on the state of polarization of a transmitted light beam. A schematic of an idealized temperature measurement system is shown in Fig. 1. A linearly polarized light wave produced by a laser is directed to a birefringent crystal located in the thermal environment to be monitored.

The orientations are such that there is a 45° angle between the optical polarization vector and the crystal optic axis. In this manner, two orthogonally polarized optical wavefields are created within the crystal, one parallel to the optic axis and one perpendicular. Upon propagation through the crystal, these superpose to create the transmitted light beam, the polarization state of which is generally different than that of the incident one.

As the birefringence or the length of the crystal changes, i.e., due to temperature, the polarization state of the transmitted light beam also changes. The polarizer placed before the photodetector functions as an analyzer, converting these temperature-induced changes into a detectable intensity modulation that can then be displayed.

SENSITIVITY OF THE METHOD

An analysis of this method is most easily done by describing the optical polarization anywhere in the system as a relative retardation of two orthogonal linearly polarized components.

The phase shifts of two orthogonally polarized waves upon propagation through a birefringent crystal of length l are

Fig. 1. Method of remote measurement of temperature.

$$\phi_{\parallel} = 2\pi \frac{\ell}{\lambda_{\parallel}} = 2\pi \frac{\ell f_0}{V_{\parallel}} = 2\pi \frac{\ell n_{\parallel}}{\lambda_0} \quad (1a)$$

and

$$\phi_{\perp} = 2\pi \frac{\ell n_{\perp}}{\lambda_0}, \quad (1b)$$

where λ_0 is the wavelength of the incident light beam, and the pair $n_{\parallel}$, $n_{\perp}$ are the indices of refraction for the polarization parallel and perpendicular to the optic axis, respectively. The differential phase shift is therefore

$$\Delta\phi = \frac{2\pi\ell}{\lambda_0} (n_{\parallel} - n_{\perp}) = \frac{2\pi\ell}{\lambda_0} \Delta n. \quad (2)$$

The transmission through the polarizer is

$$\frac{I}{I_0} = \cos^2 \left[\frac{\Delta\phi}{2} \right] \quad (3)$$

where I_0 is the incident intensity. We have neglected effects that degrade the intensity contrast ratio, such as absorption, scattering, and reflection at interfaces. The photo-detector will produce a current proportional to the polarizer transmission. The signal voltage delivered by the system is therefore expressed by the proportionality relation

$$V \propto \cos^2 \left[\frac{\pi\ell}{\lambda_0} \Delta n \right] \quad (4)$$

by combining Eqs. (2) and (3).

Both the length and birefringence can be expressed as simple polynomial functions of temperature, i.e.,

$$\ell = \ell_0 (1 + k_{\ell} \Delta T) \quad (5a)$$

$$\Delta n = \Delta n_0 (1 + k_{\Delta n} \Delta T), \quad (5b)$$

where ΔT is the temperature change from some reference value and ℓ_0 , Δn_0 are the length and birefringence, respectively, at this reference temperature. Substitution of Eqs. (5) into Eq. (4) yields the temperature dependence of the voltage

$$V \propto \cos^2 \left[\frac{\pi\ell_0\Delta n_0}{\lambda_0} \left(1 + (k_{\ell} + k_{\Delta n})\Delta T + k_{\ell}k_{\Delta n}(\Delta T)^2 \right) \right]. \quad (6)$$

Since our initial interest was in the temperature region greater than 1000°C, we choose single-crystal sapphire as the birefringent temperature sensor. The values for k_ℓ and the pair $k_{\Delta n}$, Δn_0 are given in Refs. 1 and 2, respectively. For the directions normal to the optic axis, these are

$$k_\ell = +7.3 \times 10^{-6}/^\circ\text{C}$$

$$k_{\Delta n} = -1.2 \times 10^{-6}/^\circ\text{C}$$

$$\Delta n_0 = 8 \times 10^{-3} \text{ at } 20^\circ\text{C}.$$

Thus, for sapphire,

$$V \propto \cos^2 \left\{ \frac{8\pi \times 10^{-3} \ell_0}{\lambda_0} \left[1 + 6.1 \times 10^{-6} \Delta T - 8.8 \times 10^{-12} (\Delta T)^2 \right] \right\} \quad (7)$$

until the melting temperature of the sensor optics, 2040°C. At all temperatures up to melting, the term in $(\Delta T)^2$ is always at least three orders of magnitude less than the term in ΔT , therefore, the second order contribution may be neglected. Hence,

$$V \propto \cos^2 \left[\frac{8\pi \times 10^{-3} \ell_0}{\lambda_0} (1 + 6.1 \times 10^{-6} \Delta T) \right]. \quad (8)$$

More precisely, there is also an amplitude modulation of this periodicity in temperature due to the vanishing of the birefringence with increasing temperature, i.e., $k_{\Delta n} < 0$. This amplitude modulation takes the form of a slow, monotonically decreasing with temperature function, which we denote as $f(\Delta T)$. The voltage is more accurately represented as

$$V = f(\Delta T) \cdot \cos^2 \left(\frac{8\pi \times 10^{-3} \ell_0}{\lambda_0} (1 + 6.1 \times 10^{-6} \Delta T) \right). \quad (9)$$

Since, precise information about ΔT is contained in the periodic term, further description of $f(\Delta T)$ is unnecessary except to note the effect on the amplitude of the periodic term near the melting temperature.

DESCRIPTION OF PRELIMINARY EXPERIMENTS

An experiment was set up exactly as shown in Fig. 1. Lacking a readily available sapphire crystal, we used a ruby laser rod. This rod was placed in an oven in order

1. W. M. Yim and R. J. Paff, J. Appl. Phys. **45**, 1456 (1974).
2. M. A. Jeppersen, J. Opt. Soc. Am. **48**, 629 (1958).

that the temperature could be varied over a wide range. The temperature was independently monitored with an optical pyrometer and a thermocouple.

The experimental parameters were:

$$l_0 = 75 \text{ mm},$$

$$\lambda_0 = 6.328 \times 10^{-4} \text{ mm (He-Ne laser),}$$

$$20^\circ \leq \Delta T \leq 1300^\circ\text{C (the temperature limit of the oven).}$$

Substituting in Eq. (8), these parameters predict a voltage which varies as

$$V \propto \cos^2 \left[2979 + \left(\frac{\pi}{172.9} \right) \Delta T \right].$$

The predicted periodicity is about $173^\circ\text{C}/\text{cycle}$; however, the periodicity observed over the range $1050^\circ\text{--}1250^\circ\text{C}$ was approximately $7^\circ\text{C}/\text{cycle}$. We believe that this deviation from prediction may be due to thermally varying stresses in the crystal. To check this possibility, we plan to use stress-relieved sapphire crystals, and they are on order at this time. In many circumstances, this greater sensitivity would be very useful. Therefore, once this phenomenon is identified, we may be able to design for sensitivities greater than that predicted by the theory above.

APPLICATIONS

The results of the preliminary experiments are sufficiently encouraging that we now consider applications. The initial motivation for this development was the desirability of having alternative temperature measurement systems for in situ coal gasification experiments.

Field application requires a more sophisticated apparatus than that shown in Fig. 1 in order to simplify alignment, increase reliability, and obtain data unambiguously. A step in that direction is shown in Fig. 2. This system also offers increased sensitivity for a given crystal length because the TIR (total internal reflection) end doubles the effective optical path within the crystal.

Increased degrees of sophistication are possible, such as the use of split-field techniques developed for fringe-counting interferometry to indicate whether the temperature is increasing or decreasing.

ADVANTAGES AND LIMITATIONS OF THE METHOD

The advantages of the method are:

- Remote nature of the measurement. Using diffraction-limited lasers and optics, the temperature at the crystal can be measured at very great distances, either in turbulent environments using graded-index fiber optics (which preserve polarization properties), or through vacuum lines of sight.

Fig. 2. Apparatus configuration for field applications.

- High resolution. Our preliminary demonstration experiment exhibited a temperature resolution of about 1°C (this assumes $1/10$ cycle definition, which is not unreasonable). This sensitivity should be easily doubled by using a TIR crystal, and doubled again by decreasing the wavelength (i.e., Argon-ion laser instead of He-Ne). In conjunction with sophisticated electronics, millidegree resolution seems feasible.
- High temperature operation. The upper temperature range is limited only by the melting temperature of the optics.
- Optical simplicity. The scheme can be designed to be alignment insensitive. It lends itself to array-type measurements where one laser can illuminate a number of crystals with high signal-to-noise ratio since fast response is not necessary.

The primary disadvantages include:

- The necessity of a relatively tranquil line of sight between analyzer optics and the birefringent crystal.
- The system response-time limitation imposed by the thermal-diffusion time constant of the crystal.

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