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A Novel Fibre Optic Stress/Strain Sensor, Using the Near-Infrared SPATE Effect (FONI-SPATE)

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Abstract

A new fibre optic stress/strain sensor, utilising near-infrared SPATE, is reported which is suitable for monitoring hot materials. The fibre is merely arranged to collect the grey body emission from a heated metal sample. When the sample is subject to transient stresses, the radiation is modulated because of the adiabatic changes in the temperature of the material surface. The modulation of the light is monitored, via a silica optical fibre, using a near- infrared GaInAs photo-detector. This is also believed to be the first demonstration of SPATE in the near infrared region of the spectrum.

Introduction

The technique called SPATE (Stress Pattern Analysis by Thermal Emission)(1,2) has found considerable success for the monitoring of vibration in mechanical structures, engines etc. The method relies on the adiabatic heating and cooling that occurs in a cyclically stressed sample, which results, in turn, in a transient variation of the infrared emission from the surface. The temperature change, ΔT, that results from the stress is given(2) by:-

$$\Delta T = -T \cdot \frac{\alpha}{C\rho} \Delta(\sigma_1 + \sigma_2)$$

where T is the absolute temperature, α is the thermal expansion coefficient, C is the specific heat at constant stress, ρ is the density and $\Delta(\sigma_1 + \sigma_2)$ is the sum of the transient changes in the principal stresses in the surface region. Clearly, the strain is related to the stress via the elastic constants of the material. Like an ideal gas, the temperature of the specimen reduces during expansion and increases during compression.

For conventional SPATE systems, the thermal changes are observed using an infrared thermal-imaging camera and the video signal is processed to observe changes in the infrared emission. These changes occur synchronously with the vibrational frequency of the specimen. However, if the material is heated above 200°C, there is a significant emission tail in the near infrared region 2.0 → 2.5 μm, where short lengths ($\sim$1 metre) of silica fibre are still reasonably transparent. In addition, high performance "extended" GaInAs detectors can be used to detect low levels of radiation in this region. With our new method, surface strain sensing becomes possible, using a probe which is remoted via a silica fibre cable. In addition, the probe may potentially be embedded in a material (or pushed into a narrow-bore hole in a specimen) in order to measure strain at internal surfaces. Thus, although not readily capable of providing a 2-dimensional display, as possible with conventional SPATE, we have formed a new flexible probe, which is capable of measuring in less accessible places.

Theory

The spectral radiance, R, of a grey body, at a temperature, T, is given by(3):-

$$R = \frac{2c^2h}{\lambda^5} \frac{d\lambda}{e^{\frac{hc}{\lambda KT}} - 1} \bullet \epsilon$$

where C = velocity of light, h = Plank's constant, λ = wavelength, $d\lambda$ is the wavelength interval, K is the gas constant and ϵ is the surface emissivity. If an optical fibre, of area A, is placed in a position such that a strained specimen totally fills its acceptance cone, a power P_r is collected, where:-

$$P_r = \int\int\int R \,.\, \cos\theta \,.\, dA \,.\, d\Omega \,.\, d\lambda$$

For small collection angles, it can be simply shown that:-

$$P_r \simeq \pi^2 . a^2 . (N.A)^2 \int_{\lambda_1}^{\lambda_2} R d\lambda$$

where N.A is the numerical aperture of the fibre and a is the fibre radius. This power, P_r, is the same as that which would be collected if the fibre were to be butted against the specimen (i.e. the spacing from the sample is not critical when calculating the collected power).

Provided $T \leq 800°K$ and $\lambda \leq 2.5\mu m$, then $e^{\frac{hc}{\lambda KT}} \gg 1$, and the equation for the collected light can be more simply evaluated to give the power, P_r, as a function of the temperature, T, and the change in power ΔP_r as a function of change in temperature, ΔT. From equation (1), the optical intensity modulation index $\Delta P_r/P_r$ can then be related to the stress. The constant of proportionality depends both on the material properties and the temperature of the sample. However, the former are normally known for common materials and the temperature can be inferred from the total optical power received, as this is a highly sensitive function of temperature(4). Strain can, of course, be deduced from the stress if the elastic properties of the material are known.

From the above formulae, the ratio of the optical intensity modulation index, $\Delta P_r/P_r$, to the stress, $\Delta(\sigma_1 + \sigma_2)$, has been calculated, as a function of absolute temperature, T. This linear relationship is shown graphically in Fig. 1 for two temperatures. For these curves, we have assumed that the fibre/detector light-receiving combination has a uniform response up to a long wavelength cut-off at 2·5 μm. (A vertical band-edge has been assumed at this wavelength).

Experiment

In order to test our new method, we mounted a stainless steel (type 304) test coupon in an Instron 8501, servo-hydraulic, testing machine and arranged for it also to be electrically heated using a low-voltage, high-current source. The coupon was subjected to a mean longitudinal stress of 3·5 KN, plus a cyclical (sinusoidal, F = 20 Hz) longitudinal stress component of up to 5·0 KN p-p. A fibre-bundle cable, with 16 silica-cored fibres (Heraeus Fluosil, type SWU 1.1 ; core ϕ = 200 μm, N.A. = 0·23) was used to guide light to an Epitaxx GaInAs photodetector (long-λ cut-off at 2.6 μm). The bundle was larger than the detector, and, because of this, tests showed it coupled only 5 times as much optical power to the detector as did a single fibre of the same type. The apparatus is shown in Fig 2(a). Fig. 2(b) shows the response from the sensor (upper curve) when the coupon was subjected to a cyclic stress of 5·0 KN p-p. The lower curve shows the stress, as indicated by the Instron load cell output. The middle curve is a pre-filtered version of the optical signal, which was passed through a filter having a 10 Hz → 50 Hz bandpass characteristic. The upper middle curves were subjected to multiple averaging (4096 averages) on a Philips PM3392 digital oscilloscope, in order to improve the signal/noise ratio.

Our measurements show that the detected signal (top curve) followed the sinusoidal stress signal (bottom curve) in terms of waveform, phase and polarity. The response was also found to be linear with applied stress, as shown by the two curves in Fig. 3, taken at temperatures of 676 K and 710 K. The observed optical modulation index was 0·52%, corresponding to a scale factor of $4{\cdot}3.10^{-6}\%\ KN^{-1}\ m^{2}$, with the sample heated to 710°K. This corresponds to the theoretically expected value of $3{\cdot}9.10^{-6}\%\ KN^{-1}m^{2}$, using values of $\alpha = 18.10^{-6}\ K^{-1}$, $C = 5.10^{2}\ J.Kg^{-1}K^{-1}$, $\rho = 8.10^{3}\ Kg.m^{-3}$ in equation 1.

In order to use the method for stress/strain sensing at these temperatures, it is necessary to take a least 128 averages of the signal, in synchronism with the applied stress signal. However, the optical signal strength, and hence the signal/noise ratio, is expected to increase dramatically if the temperature of the test coupon were to be increased, or if fibres and detectors having a longer-wavelength IR response were to be used. For example, if the stressed sample were at 1000°K, the radiated signal would be 10^{3} times greater, even when using the same silica fibre.

Conclusions

We have, for the first time, demonstrated the feasibility of constructing a simple fibre-remoted stress/strain sensor, using infrared emission from hot samples. In addition, we believe this is the first demonstration of the use of the SPATE method in the near infrared region of the spectrum. The method could have a number of practical applications for monitoring strain in naturally-hot structures (e.g. engine components, turbine blades, etc), where the use of conventional sensors may prove difficult, and it may be particularly advantageous for measurement in relatively-inaccessible areas.

References

1. Mountain D.S., Webber J.M.B., "Stress pattern analysis by thermal emission (SPATE)" Proc. SPIE vol 164 (1978) pp 189-196.

2. Stanley P., "Thermoelastic stress analysis: progress and prospects", 9th International Conference on Experimental Mechanics, August 1990, Copenhagen, Denmark.

3. Kingslake R., "Applied Optics and Optical Engineering", vol IV, chapter 8, Academic Press (1967), ISBN 0-2-406604-7.

4. Dakin J.P., Kahn D.A., "A novel fibre optic temperature probe" Optical & Quantum Electronics 9 (1977) pp 540-544.

Figures

1. Relationship (theoretical) between the optical intensity modulation index, $\Delta P_r / P_r$, and the material stress, $\Delta(\sigma_1 + \sigma_2)$ at two temperatures (Our calculation assumes a fibre/detector response cut-off at 2.5μm).

2(a) Apparatus for testing the FONI-SPATE system, using INSTRON servo-hydraulic, testing machine.

2(b) Signals on Philips PM3392 oscilloscope. Upper track is detected A.C optical signal component (averaged 4096 times) and lower trace is signal from load cell. The middle trace was the detected signal passed through a 10 Hz → 50 Hz filter, prior to averaging.

3. Experimental variation of optical modulation index $\Delta P_r / P_r$ with applied unidirectional stress $\Delta(\sigma_1)$ at two temperatures.

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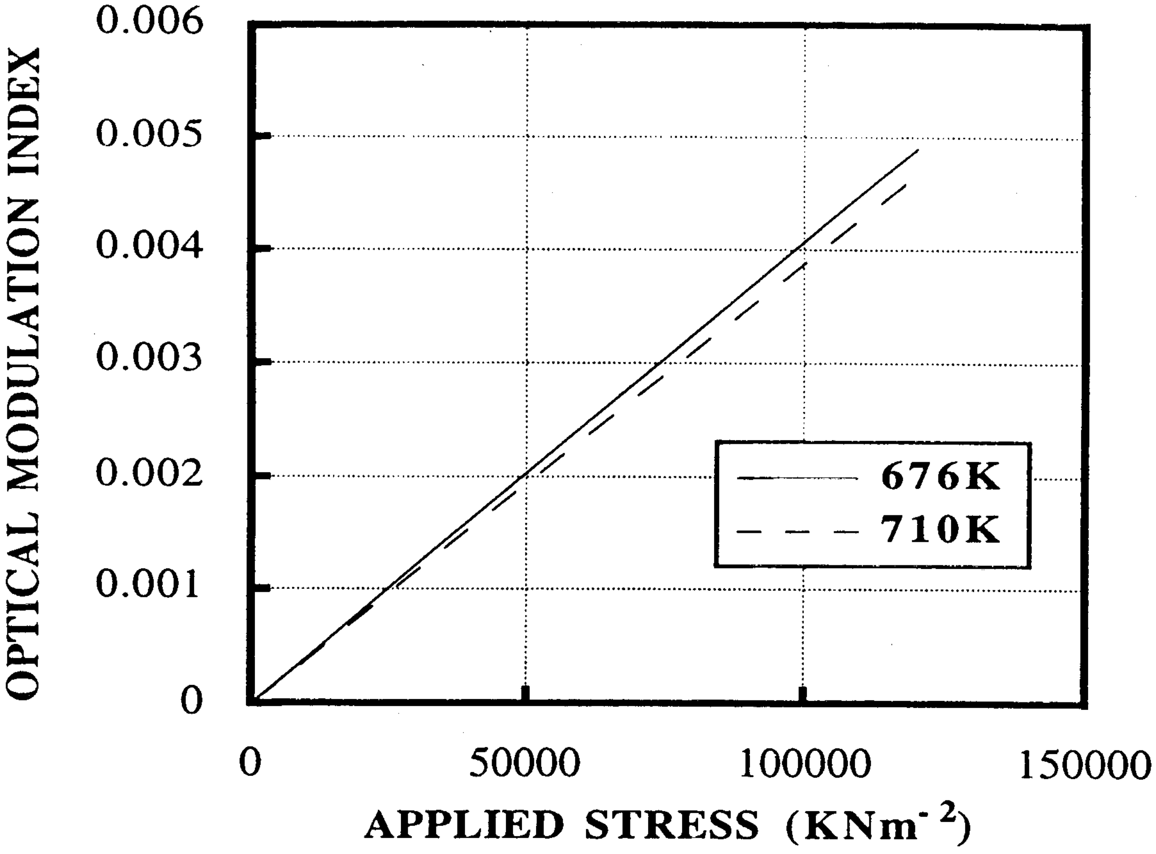
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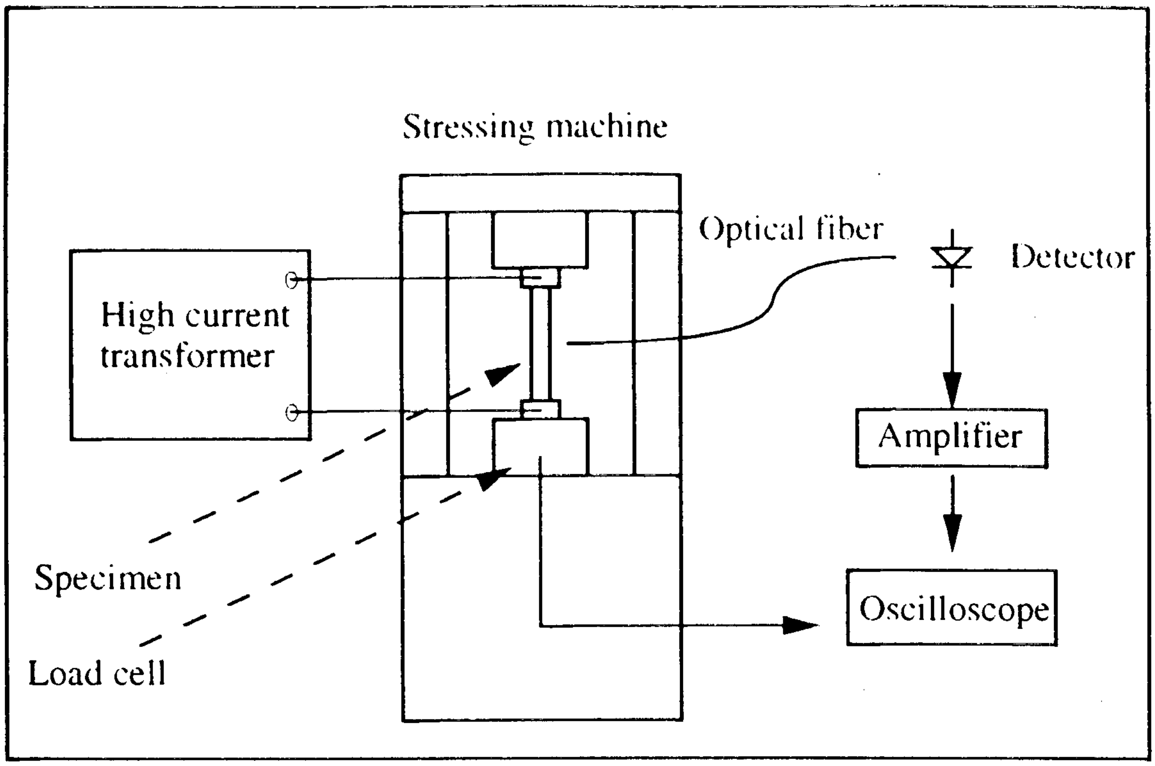

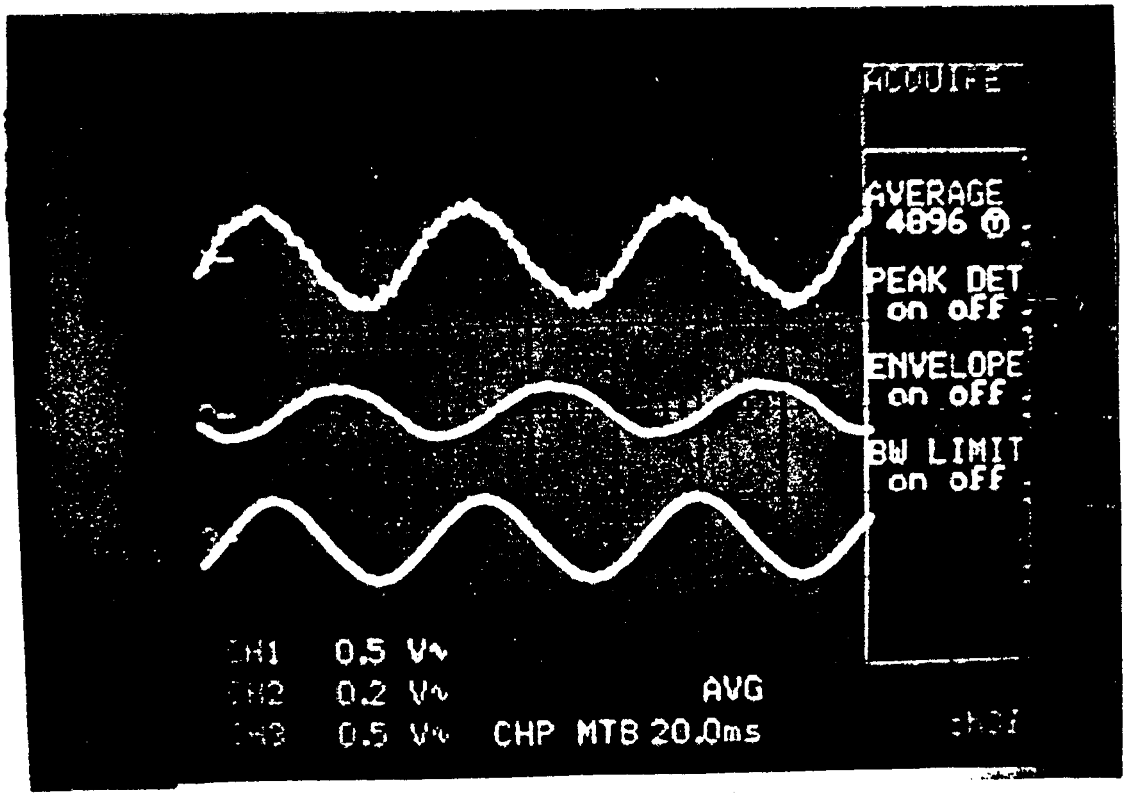

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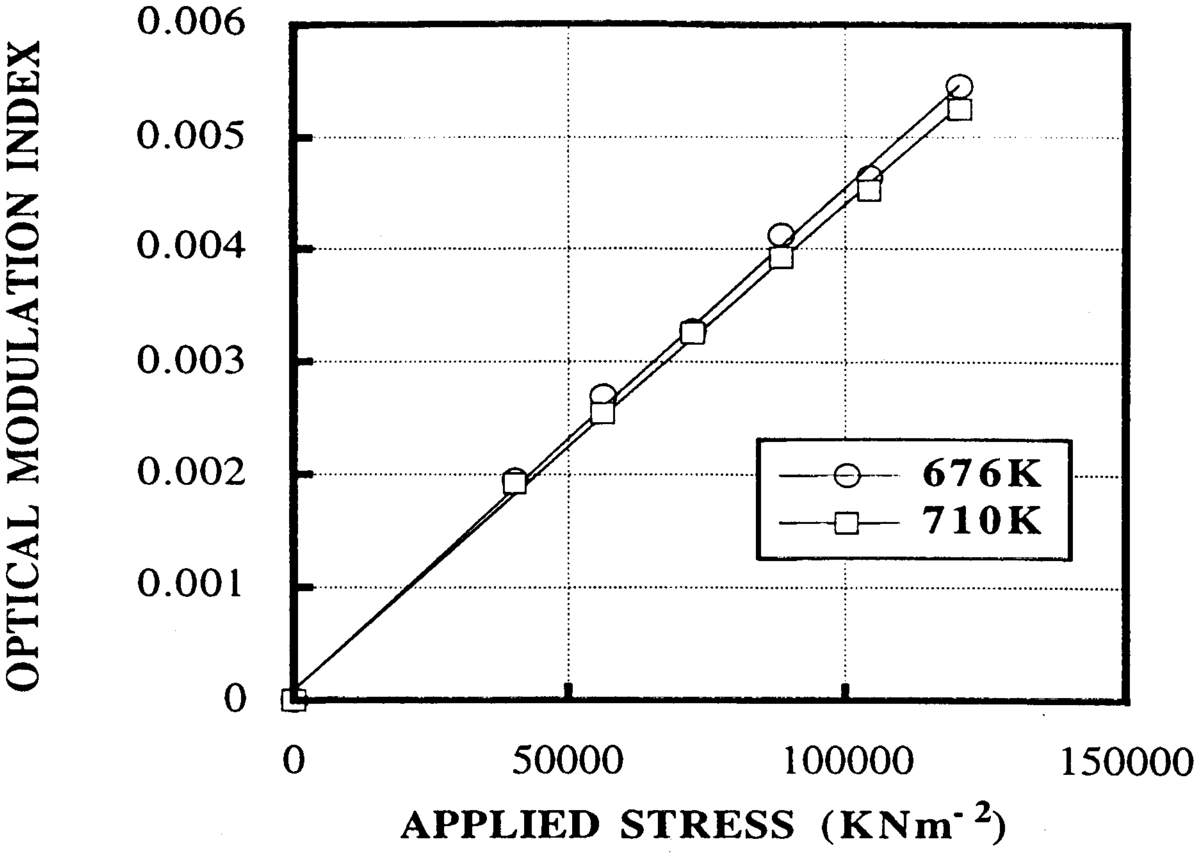
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