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Fiber-Optic Systems for Temperature and Vibration Measurements in Industrial Applications

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ABSTRACT

Fiber-optic systems for temperature and vibration measurements have been developed. It is shown that using the principle of wavelength conversion in the sensor, measurement systems, in which only one fiber is used for the connection of the sensor to the instrument, can be realized. The measuring accuracy is practically independent of the properties of the fiber-optic system such as fiber length, fiber diameter and type of connectors used. These properties are very important, reducing installation problems and costs. The adoption of semiconductor technology allows batch fabrication of sensor elements. For the prototype temperature instrument an accuracy of 0·5°C *was obtained in the temperature range* 0 *to* +200°C. *Fiber-optic accelerometers for vibration measurements with a resolution of* 0·05 g *and a dynamic range of* 70 dB *have been realized. The systems have been tested in different industrial environments and have properties that make them suitable for many industrial applications. Advantages of fiber-optic systems are their noise immunity, galvanic isolation and inherent intrinsic safety.*

1. INTRODUCTION

During recent years much interest has been focused on the possibility of using optical phenomena in lightguiding structures for the detection of different physical parameters. Due to the potentially very high sensitivity of interferometric and phase-sensitive detection principles, much of the work on fiber-optic sensors up to now has been devoted to the development of very elaborate and ultra-sensitive systems for the measurement of, for example, rotation and pressure, with applications in gyros and hydrophones.[1]

There are, however, several other well-documented advantages of using optical techniques for the generation and transmission of sensor signals in industrial environments. The optical signal is not affected by electromagnetic interference (EMI) which eliminates the EMI problem of sensor signals, frequently encountered with conventional electrical measurement systems. Furthermore, in a longer perspective, installation of the cabling for the control signals can be greatly simplified, e.g. by utilizing hybrid cables containing optical fibers for control and measurement and where electrical conductors are used for power transmission. The reliable galvanic separation between the sensor and the instrument provided by the optical cable makes it possible to carry out measurements on objects at high potential in a fairly straightforward manner. The dielectric character of the optical cable automatically ensures intrinsically safe measurement systems for use in environments exposed to fire and explosion hazards. Sensors for fiber-optic measurement systems can be constructed out of non-metallic material, be highly miniaturized, compact and of low weight. Thus, measurements using fiber-optic sensors can be carried out with a minimum of disturbance to the object being measured and can often be performed in situations where other techniques have proved inadequate.

In order to benefit from these advantages and to promote the use of fiber-optic sensors in industrial applications it is essential to develop measurement systems with appropriate performance, handling properties and production costs. Looking at a typical fiber-optic system (Fig. 1) for the measurement of the value of a physical parameter in one point, the following conditions should be fulfilled for a practical system:

—the technical performance of the system expressed as measurement range, accuracy, stability, etc., should be adequate for the particular application;
—the optoelectronic system should be compatible with electronics in

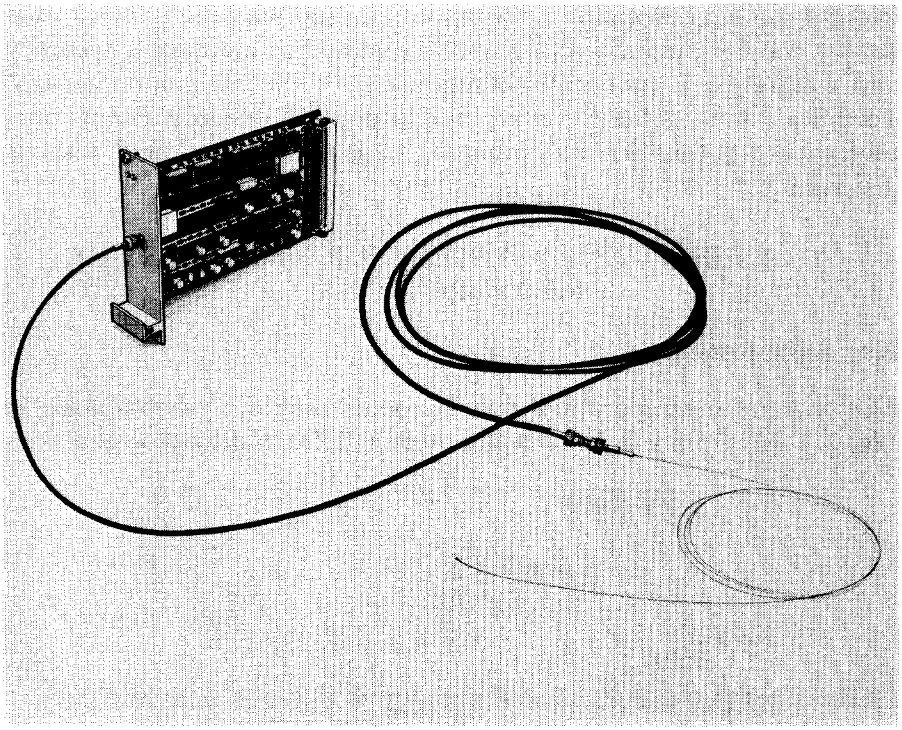

Fig. 1. Typical fiber-optic measurement system for the measurement of a physical parameter in one point. Important parts of the system are: the sensor, the optical cable, optical connectors, optoelectronics and electronics.

terms of such properties as size and power requirements;
—handling and installation should be simple;
—cost-effective technologies should be adopted for the sensor and for the optoelectronics.

In this paper, fiber-optic systems for temperature and vibration measurements, which fulfill these requirements, are presented. By using a technique of wavelength conversion of the optical signal in the sensor, systems have been developed in which only one optical fiber is needed for the connection between the sensor and the measuring equipment. This greatly facilitates installation and handling problems and reduces costs.

Optical cables and connectors compatible with the ones developed for optical communication systems can be used with the systems. It is shown that the system performance expressed as measuring accuracy and calibration is practically independent of the fiber-optic system. Technical data obtained from measurements on instrument prototypes are presented and practical experience from field tests is discussed.

2. A FIBER-OPTIC SYSTEM FOR TEMPERATURE MEASUREMENTS

2.1. Basic principles

The system for temperature measurements is shown schematically in Fig. 2. Light from a light-emitting diode (LED) in the optoelectronics

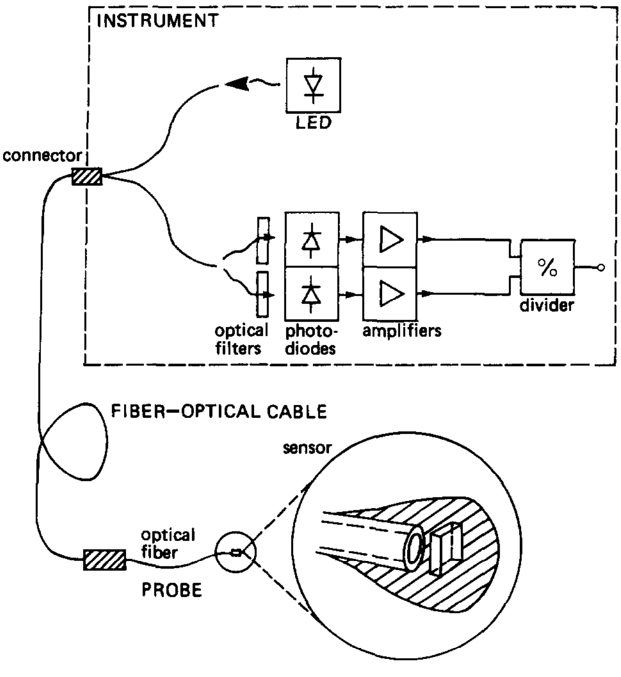

Fig. 2. A fiber-optic system for temperature measurement. An LED in the optoelectronics excites the photoluminiscence of the sensor crystal via optical couplers and one optical fiber. The photoluminescence is detected with a two terminal wavelength demultiplexing detector in the optoelectronics. The resulting signals are converted to an output signal corresponding to the temperature of the sensor by the electronics.

of the instrument is transmitted to the sensor crystal via an optical coupler and an optical fiber. The light impinging on the sensor is absorbed and re-emitted as light with another wavelength spectrum in a process called photoluminescence. The sensor is a semiconductor structure of aluminium gallium arsenide developed to give a high quantum efficiency for the optical conversion process. The re-emitted light, the wavelength spectrum of which is determined uniquely by the temperature of the sensor, is led back to the measuring equipment with the same optical fiber as the exciting light and is detected by a wavelength demultiplexing detector. The detector output signals are fed to the electronics and an output signal corresponding to the temperature of the sensor is formed. The system thus created is very insensitive to changes in the attenuation in the fiber-optic system. In Fig. 3 typical emission spectra and spectral response curves for the optical and optoelectronic components in the system are shown.

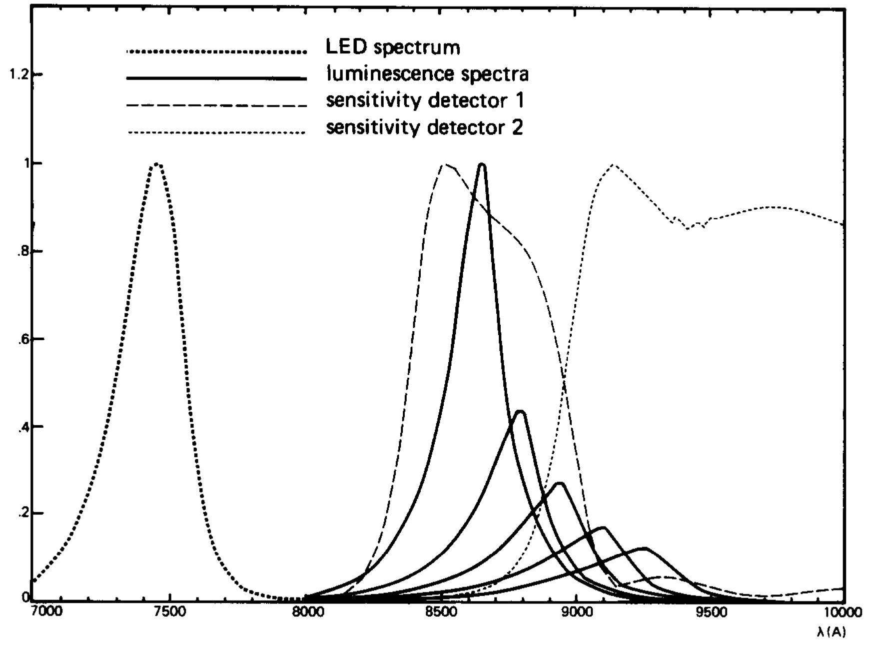

Fig. 3. Spectral curves for the optical and optoelectronic components in the system as determined by experiment.

2.2. The sensor

The sensor structure was developed using GaAs technology. The sensor material was developed to have a high quantum efficiency for the photoluminescence process and to have a well-defined photoluminescence spectrum in order to facilitate the manufacturing of temperature probes with reproducible properties.

It is well known[2] that the recombination of excited carriers at the surface of a GaAs crystal tends to reduce the quantum efficiency for the photoluminescence process in bulk crystals. It has also been experimentally verified[2] that using heterostructures, in which an active layer of GaAs is surrounded by confinement layers of $Al_xGa_{1-x}As$, gives a material with high quantum efficiency at room temperature.

The sensor material for the fiber-optic temperature measurement system was developed using such heterostructure techniques and has

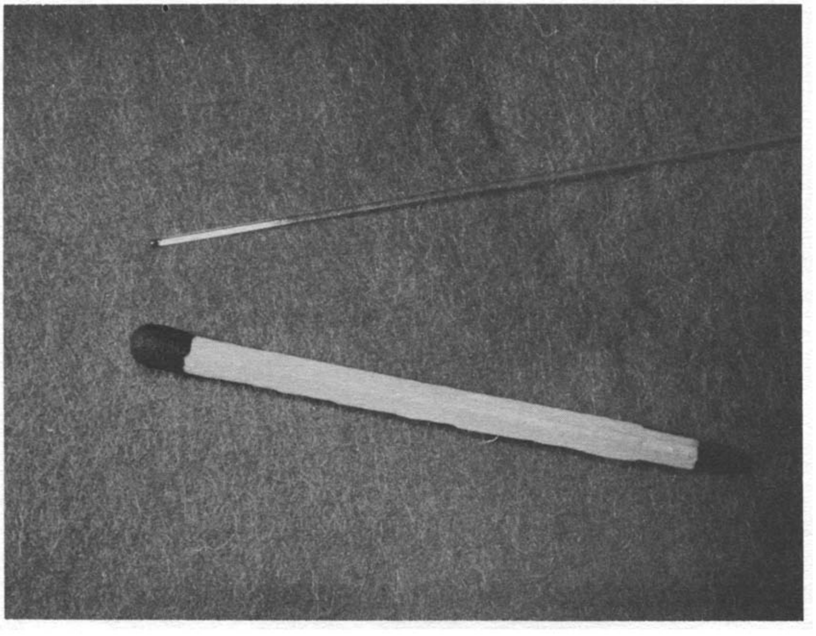

Fig. 4. Picture showing a temperature sensor, fabricated by mounting the semiconductor crystal (with dimensions $0{\cdot}1\times0{\cdot}2\times0{\cdot}2\ mm^3$) directly onto an optical fiber using a silicone compound. The fiber used is an all silica fiber with 100 μm core diameter. The total outer diameter of the fiber with primary coating is about 0·5 mm.

an internal quantum efficiency of above 50% at room temperature. Photoluminescence spectra from the sensor obtained at temperatures in the interval 0 to +200°C are shown in Fig. 3. The decrease in intensity of the spectra in this temperature region corresponds to a decrease in the quantum efficiency by about a factor of 4 which is believed to be due to the self-absorption effects of the luminescence in the material. Further details of the development of the sensor materials is given in ref. 3.

In Figs 4 and 5 two examples of temperature sensors are shown. The sensor shown in Fig. 4 is manufactured by attaching the semiconductor crystal to the optical fiber using a silicone compound with suitable optical, mechanical and thermal properties. This extremely small primary sensor element provides a good basis for the further development of temperature probes for applications where, for example, higher mechanical strength or chemical resistance is needed. The temperature probe shown in Fig. 5 can be used, for example, in highly corrosive atmospheres. The semiconductor crystal is embedded in a silicone resin and the probe is hermetically sealed from the environment using a glass capillary tube fused directly to the optical fiber.

Using these and similar techniques, temperature probes with highly reproducible properties (corresponding to a temperature error in the output signal of less than 1°C) can be manufactured.

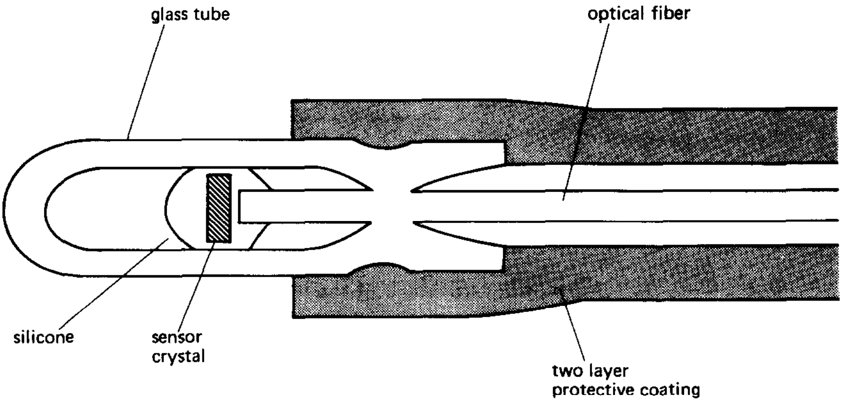

Fig. 5. Temperature probe in which the semiconductor crystal is hermetically sealed inside a glass capillary tube. The semiconductor crystal is embedded in a soft transparent material (e.g. silicone).

2.3. The optoelectronic system

The optoelectronics for the system can be realized in a variety of ways. In Fig. 6 one solution is shown where graded index rod lenses and interference filters are used to obtain two wavelength-dependent beam splitters. Light from a standard commercial LED with a peak wavelength of about 750 nm (cf. Fig. 3) is guided in an optical fiber to a system of graded index rod lenses (GRIN). An optical filter (IF 1) is used to suppress the radiation from the LED in the long wavelength region. One of the optical filters in the GRIN system (IF 2) acts as a dichroic mirror having a high reflectivity for light of wavelengths shorter than about 800 nm (cf. Fig. 3), while the other optical filter (IF 3) is designed with a change in reflectivity at about 900 nm. The module thus assures that the light emitted from the LED is fed out into the fiber system to the sensor and that the returned light from the sensor is wavelength divided between the two photodiodes PD1 and PD2. Using these techniques, small, compact optoelectronic systems can be constructed. The actual size of the module used for the fiber-optic temperature instrument is $1{\cdot}5 \times 2{\cdot}5 \times 3\ \mathrm{cm}^3$ including the means for thermal stabilisation. Figure 7 shows the relationship between the output signals from the optoelectronic system and the temperature of the sensor.

The quotient S_2/S_1 between the two output signals is a monotoni-

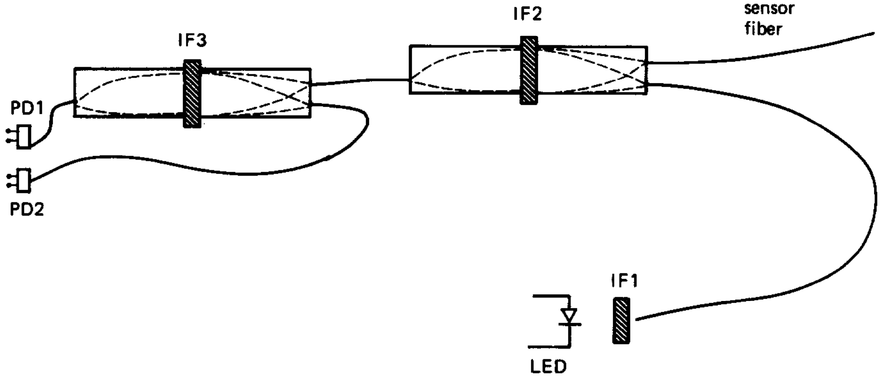

Fig. 6. Optoelectronic system of the fiber-optic temperature sensor. The system is constructed using graded index rod lenses (GRIN) and interference filters (IF). A standard LED and photodiodes are used.

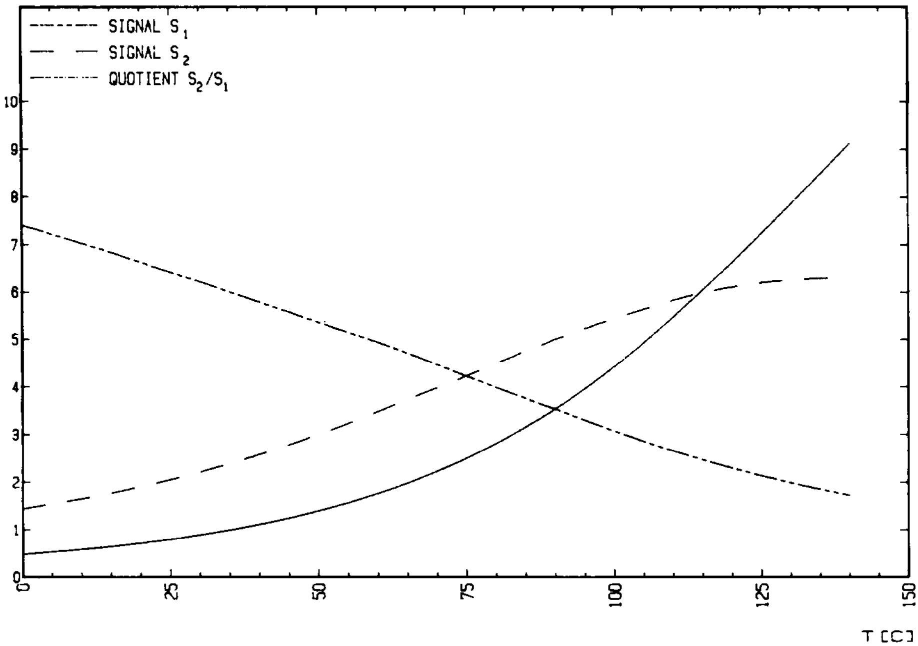

Fig. 7. Output signals from the optoelectronic system as a function of the temperature of the sensor. S_1 and S_2 are the output signals from PD 1 and PD 2 respectively. The quotient S_2/S_1 giving the basis for the temperature determination is also shown.

cally increasing function of the temperature of the sensor and is used in the electronics to give this temperature.

2.4. Electronics of the system

The electronics of the system is shown schematically in Fig. 8. The analog part of the system works with chopped signals to give good suppression of noise and consists of drive circuits for the LED and amplifiers and phase sensitive detectors for the signals from the photodiodes. A microprocessor controls the drive current of the LED to give signal levels independent of attenuation in the optoelectronic system. The microprocessor also forms the quotient between the two signals from the photodiodes, linearizes it and gives a temperature value. Normally a set of pre-programmed calibration constants are used by the processor. In cases where higher accuracy is needed, the

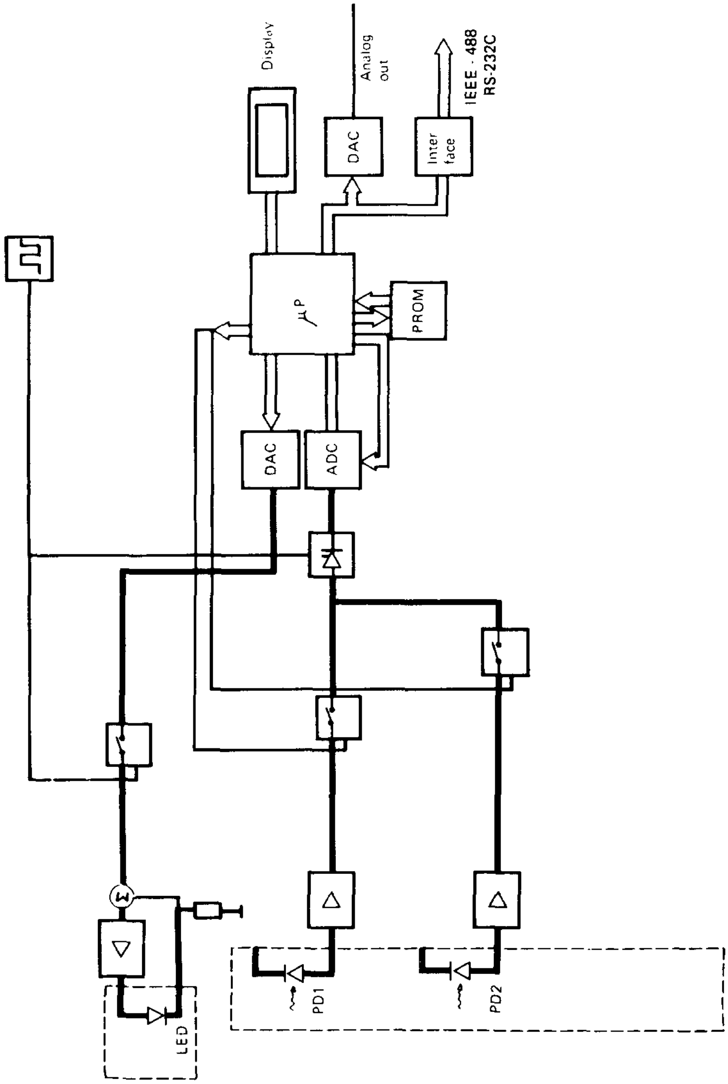

Fig. 8. Block diagram of the electronic system of the fiber-optic temperature instrument. A processor is used to correlate the output signal from the optoelectronic system with the temperature of the sensor. The processor also controls other functions of the system such as the drive current of the LED. To increase the accuracy of the measurement, the system can be equipped with an oven for automatic temperature calibration.

system also has auto-calibration facilities using a calibrated oven, the temperature of which is controlled by the processor.

2.5. Performance of the system

The fiber-optic temperature measurement system was designed for the temperature interval 0 to +200°C. An optical fiber with a core diameter of 100 μm was adopted as suitable for industrial applications. For the first prototype instrument an accuracy of about 1°C and a resolution of 0·1°C has been obtained. A long-term stability better than about 0·5°C has been measured during a test period of 2 months.

With an all silica optical fiber of standard telecommunication quality, fiber lengths up to 500 m can be inserted between the sensor and the instrument with a change in calibration of less than 1°C. (Sumitomo semi-step index fiber was used in the experiments.) With longer fiber lengths it is possible to calibrate with the fiber inserted to obtain full accuracy. The use of connectors to the fiber-optic cable has also been shown to give little effect on the accuracy of the measurement. (Four connectors from Stratos have been used in the tests, giving less than 1°C change in the calibration.)

Due to the small dimensions of the temperature sensors obtainable, the technique potentially allows sensors with a very short response time to be constructed. Figure 9 shows a measurement of the temperature response characteristic of the system, with an unen-

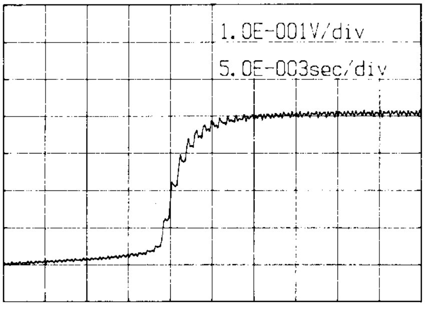

Fig. 9. Temperature response characteristics of the system. The curve was obtained by inserting the sensor into a water bath. The response time of the system (0–90%) was found to be about 5 ms.

capsulated sensor element. The curve was obtained by quickly inserting the sensor in a water bath. A time constant for the response shorter than about 5 ms was obtained.

3. A FIBER-OPTIC SYSTEM FOR VIBRATION MEASUREMENTS

3.1. Basic principles

The system for vibration measurements is shown schematically in Fig. 10. The sensor modulates the light reflected back into the optical fiber. The variations in the intensity of the returned light are detected by the optoelectronics in the instrument and are used as a measure of the quantity being measured, the acceleration at the sensor. In order to correct the received signal modulation, for a variable attenuation in the fiber-optic system, a reference signal must be provided.

This can be accomplished with a conversion of wavelengths in the sensor, in which a fixed portion of the impinging light is converted to light of other wavelengths. These are selectively detected by the optoelectronics in the instrument. By taking the ratio of the two signals thus obtained an output signal proportional to the value of the acceleration at the sensor can be created. This signal is highly insensitive to factors such as the length and quality of the optical fiber and type of optical connectors used.

3.2. The sensor structure

Sensors, working according to the principles described above, can be realized in many ways, using different technical solutions and technologies. A sensor element in which semiconductor technology has been adopted for the fabrication process is shown in Fig. 11. A cantilever beam is fabricated in GaAs-$Al_xGa_{1-x}As$ using epitaxial crystal growth techniques and selective chemical etching. Further details of the technology are given in ref. 4. The techniques allow batch processing of micro-mechanical structures with well-defined geometrical and mechanical properties. (The sensor element shown in Fig. 11 has a thickness of about 5 μm and a length of 1·28 mm.) In recent years much progress has been reported in the development of

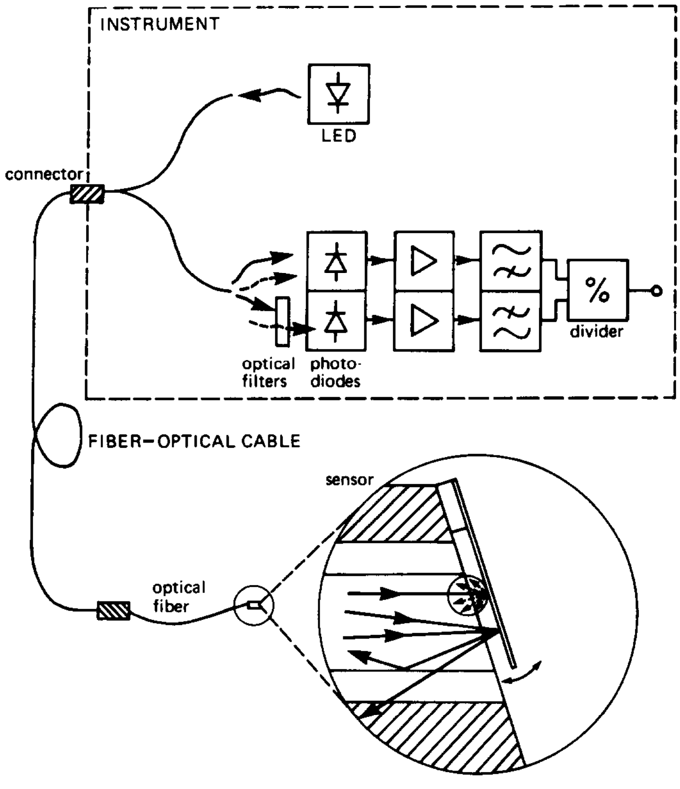

Fig. 10. A fiber-optic system for vibration monitoring by means of acceleration measurement. Light from an LED in the instrument is reflected back into the optical fiber at the sensor, the reflexion being modulated by the acceleration of the sensor. The modulation of the returned light is detected in the optoelectronics as a measure of the acceleration. A reference signal is created by a wavelength conversion process in the sensor.

process technology for micro-mechanical structures in silicon, for different sensor applications.[5] In this case, the possibility of integrating electronic circuitry and mechanical elements is an important aspect for further development. In the case of fiber-optic sensors, controlling mechanical and optical properties makes it possible to develop 'integrated structures' capable of processing optical signals. The beam shown in Fig. 11 is one example of such a structure. It consists of a double heterostructure of GaAs-AlGaAs of similar design to the structure described in Section 2.2 for the temperature

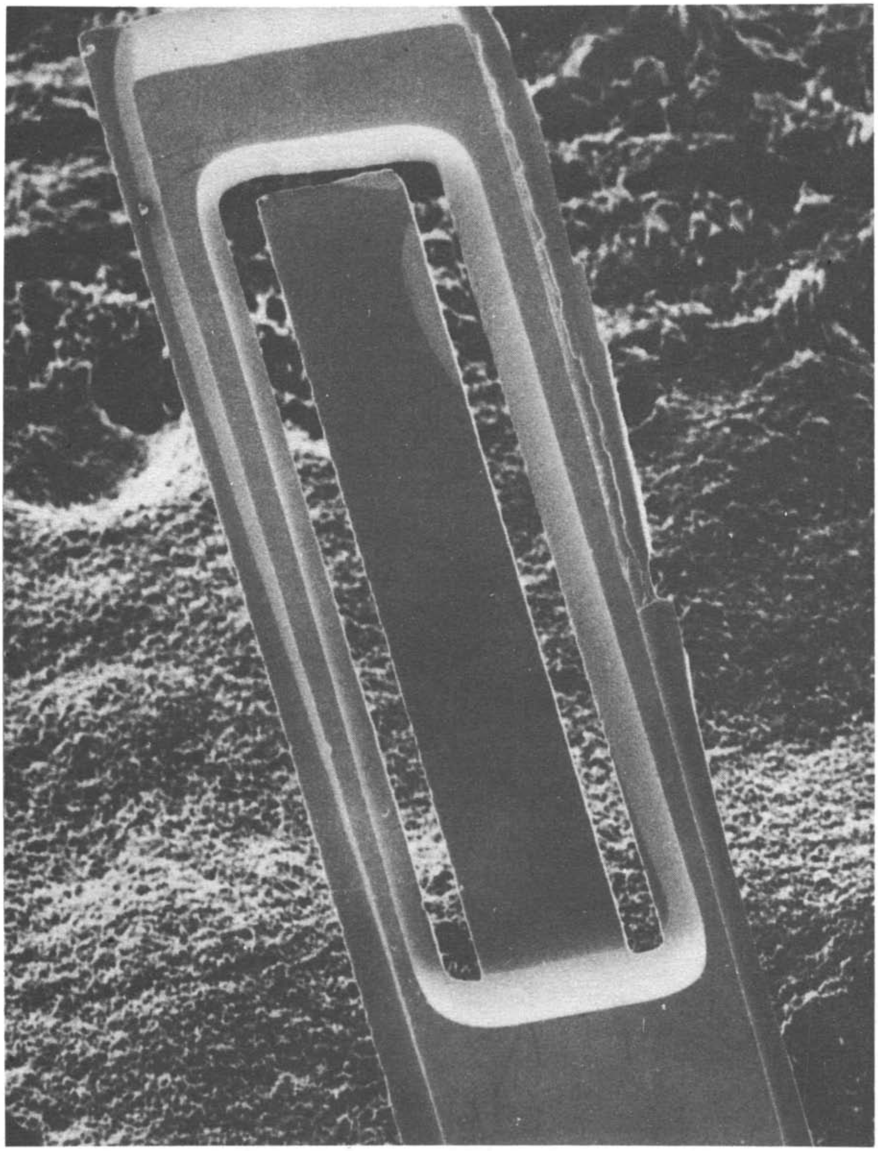

Fig. 11. SEM micrograph of the sensor element for the fiber-optic accelerometer. The cantilever beam is fabricated of GaAs–AlGaAs, using epitaxial crystal growth techniques and selective chemical etching. The beam has a thickness of approximately 5 μm and a length of 1·28 mm.

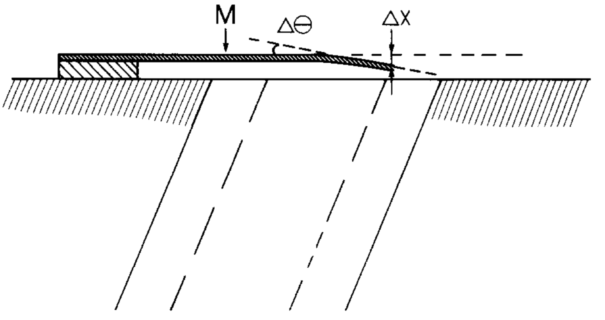

Fig. 12. Schematic diagram of the fiber-optic vibration sensor. The light modulation of the sensor is determined primarily by the change in angle ϕ of the beam.

instrument. A fixed fraction of the incoming light is absorbed by the beam and re-emitted as photoluminescence in another wavelength region. This process has a well-defined dependence of temperature and, furthermore, the luminescent light re-emitted into the fiber has a negligibly small dependence on the vibration of the beam. The optical signal thus created is detected by the optoelectronics in the instrument and used as a reference signal. On the other hand, the reflected signal modulation of the sensor is basically dependent on the change in the angle and the distance of the beam with respect to the end surface of the optical fiber (cf. Fig. 12). The modulation index m can be expressed in terms of the displacement x and the 'bending angle' $\Delta\theta$, as

$$m = A\Delta x + B\Delta\theta = C \cdot \frac{M}{k} \cdot a \tag{1}$$

The resonance frequency, f_r, of the system is given by

$$f_r = \frac{1}{2\pi}\sqrt{\frac{k}{M}} \tag{2}$$

M is the applied mass, a is the acceleration and k is a spring constant depending on the geometry and elastic constants, A, B and C are proportionality constants, depending mainly on the geometry. The ratio A/B is also a function of the numerical aperture of the fiber. In designs used so far, the $B\Delta\theta$ term dominates.

From eqns (1) and (2) it is clear that trade-offs can be made between the efficiency of the light modulation, as expressed by the modulation index m and the resonance frequency f_r. The modulation index m can be controlled independently of f_r by varying the mass M and its point of application along the beam. Thus sensitivity can be increased at the expense of higher strain in the stressed portions of the beam. In our experiments, the applied mass has consisted of glass spheres placed in various positions along integrated beam structures as shown in Fig. 11. In the final design, the mass is advantageously integrated with the structure.

3.3. Performance of the system

The prototype system was developed using a 200 μm core, step index fiber with a numerical aperture (N.A.) = 0·3. The maximum sensitivity that can be obtained for the system is determined by the modulation efficiency of the beam and the noise generated in the optoelectronics. The upper limit of the modulation is determined by non-linear effects occurring at large displacements and ultimately by the maximum allowable strain of the material. With one geometrical design, a resolution of 0·05 g has been achieved with a resonance frequency of about 2 kHz. The dynamic range of the instrument is typically 70 dB. These results were obtained using a standard LED as the light source in the optoelectronics. Increasing the power inserted into the fiber system, for example by using a semiconductor laser, the sensitivity and dynamic range are expected to increase by about 20 dB.

4. APPLICATIONS

The fiber-optic instruments for temperature and acceleration measurements described in this paper have been extensively used and field tested in applications related to electric power equipment.

Fiber-optic temperature probes with mechanical and chemical properties that make them suitable for use in the environment typical of high power transformers have been developed. The temperature of hot spots in the transformer windings during initial transformer load tests have been measured with these probes.

The temperature at different locations in electrical motors has been measured, both in the stator windings and in the rotor. The fiber-optic accelerometer was developed primarily to provide a simple means to monitor vibrations of mechanical parts at high electric potential, e.g. in turbo generators.

Due to the advantages of fiber-optic sensors, which were briefly discussed in the Introduction, it is very probable that the vast majority of applications are to be found in other areas. Preliminary tests with the fiber-optic temperature instrument have been carried out in microwave ovens, in which the temperature of the object being heated has been measured. Another application area where the use of fiber-optic instruments would be advantageous due to the inherent safety is in the petrochemical and chemical industries. For example, temperature measurements of the electrodes in electrochemical cells can be easily and safely performed using fiber-optic instrumentation.

5. CONCLUSION

The fiber-optic measurement systems presented in this paper have technical performance handling and installation properties which make them suitable for industrial applications. The use of one single optical fiber for the connection between the sensor and the instrument greatly facilitates installation and reduces cost. The instruments provide a unique relationship between the output signals and the input parameters independent of the installation and properties of the fiber-optic system. More specifically, the accuracy of the measurement is virtually unaffected by factors such as the diameter and the length of the optical fiber (up to 500 m if standard telecommunication fiber is used) and the type of the optical connectors used. Semiconductor technology has been adopted for the sensors providing possibilities of batch processing, of small, compact sensor elements. The systems have been tested in different industrial environments.

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