Fiber-Optic Instrument for Temperature Measurement

KAZUO KYUMA, SHUICHI TAI, TAKAO SAWADA, AND MASAHIRO NUNOSHITA

***Abstract*—A practical fiber-optic measurement instrument for temperature was constructed consisting of a small sensor responding to optical absorption change in a semiconductor, and a unique signal processing system with two different-wavelength light emitting diodes (LED's). The fiber-optic sensor with a semiconductor chip is quite small, very sensitive, highly reliable, and easy to manufacture at low cost. The most outstanding feature of this system is that it is free from optical-stray-loss. The accuracy of about ±1° and the response time of about 2 s were obtained in the temperature range from −10°C to 300°C.**

I. Introduction

TEMPERATURE is one of the most significant physical variables to supervise and control in high-voltage-power machines. However, inside such operating machines (e.g., transformers, generators, or motors), no conventional electric techniques by thermocouples can be used because of electromagnetic noises or short-circuiting. For such an application, fiber-optic thermometers with optical temperature sensors are most promising.

There are some requirements for putting such fiber-optic thermometers into practical use. In almost all high-voltage-power machines, the capability of measuring the temperature is in the range from −40°C to 250°C with high accuracy. Furthermore, we must detect only the temperature-dependent change of an optical signal, by isolating from the other changes of source intensity, the optical connector loss and the transmission loss of fibers. Other requirements for the sensors are small size, physical hardness, high reliability, reproducibility, long-term stability, low cost, and so on. Some attempts to develop fiber-optic temperature sensors with liquid crystals [1], phosphor [2], or optical fiber itself [3] as a sensing material, have been reported recently. However, there are some technical problems to be solved before putting them into practical use.

In this paper, we propose a unique fiber-optic measurement instrument, constructed of a fiber-optic temperature sensor responding to the optical absorption of a semiconductor and a signal processing system with two different-wavelength light emitting diode (LED) sources [4]. The principle, the outstanding features, the basic performance of our sensor, and its instrument are described in detail as follows.

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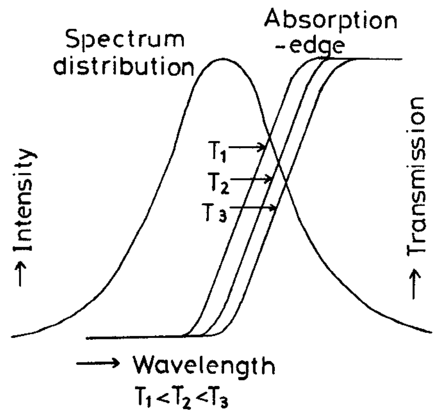


Fig. 1. Basic principle of temperature sensing system.

II. Principle

The principle of our sensing system is shown in Fig. 1. The energy bandgap of most kinds of semiconductors decreases almost linearly with increasing temperature T near room temperature. Hence, the wavelength $\lambda g(T)$ corresponding to their fundamental optical absorption edge shifts towards longer wavelength with T. As shown in Fig. 1, when we employ a light source of a LED with a radiation spectrum coincident with the $\lambda g(T)$ or a selected semiconductor, intensity of the light transmitted through the semiconductor decreases with T.

Fig. 2 shows the schematic configuration of our measuring system. As shown in Fig. 2(b), our sensor is of a quite simple structure, constructed of a thin semiconductor chip sandwiched between two ends of fibers inside a slender stainless pipe. The light of constant intensity is guided by the incoming fiber from the source (LED) to the detector [avalanche photodiode (APD)]. When transmitted through the semiconductor chip, the light is intensity-modulated by temperature. The transmitted light is received by the outgoing fiber and guided to the photodetector. We can take remotely the temperature at the position of the sensor by measuring the output voltage of the detector.

Many combinations of light sources and sensing semiconductors are considered. When a wide measuring range of temperature is required, a LED or halogen lamp source with a wide spectrum distribution is useful. On the other hand, a laser diode or a gas laser source enables us to make a very accurate measurement with high resolution.

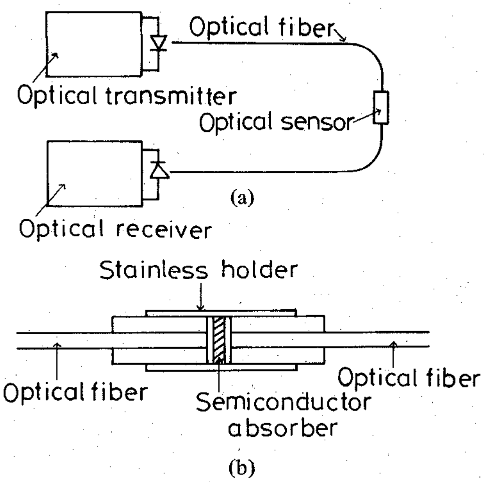


Fig. 2. (a) Schematic diagram of the fiber-optic measurement instrument for temperature. (b) Configuration of the fiber-optic temperature sensor.

III. CHARACTERISTICS

In our experiments, an AlGaAs LED, having about 880 nm center wavelength and 150 nm spectrum distribution width, was used as the light source. Advantages of this choice are that transmission loss of optical fibers is very small near the wavelength of 880 nm, and that much optical power is stably coupled into the fiber by using the LED-to-fiber coupler. The temperature and driving current of the source are controlled by an external feedback circuit to keep both intensity and spectrum constant. Two kinds of semiconductors, polycrystalline CdTe and semi-insulating GaAs, were examined as the sensing material. Either of their polished chips of 1 mm^2 area was sandwiched between two ends of fibers in the stainless tube of 1.8 mm diameter. The thickness of the chips was 0.5 mm for CdTe, and 0.2 mm for GaAs. Fig. 3 shows the outside view of our sensor. From our preliminary experiments, it was shown that the combination of the AlGaAs LED and either semiconductor chip is quite proper because their $\lambda g(T)$ lies just within the LED's spectrum width for the temperature range to be measured. The $d\lambda g/dT$ was found to be about 0.31 nm/deg for CdTe, and 0.35 nm/deg for GaAs. Therefore, we expect to measure the temperatures more than 400°C for both semiconductors when using the LED of 150 nm spectrum width.

In Figs. 4 and 5, the relative output power, which is proportional to the output voltage of the detector, is plotted against the temperature from −10°C to 300°C. The output signal processed by a log amplifier is also shown in the same figures. These curves were obtained by attaching the sensors to an electric heater while monitoring the changed temperatures with a thermocouple. The maximum temperature measured by our sensor was limited to 300°C by the melting point of the Teflon jacket of the fibers. The accuracy of our sensing device is mainly dependent upon the loss changes due to mechanical discrepancy or plastic flow of resin. However, the measurement error was less than ±3°C in the temperature range examined for both semiconductors. As seen from these figures, the GaAs sensor is more sensitive than the CdTe sensor in the lower

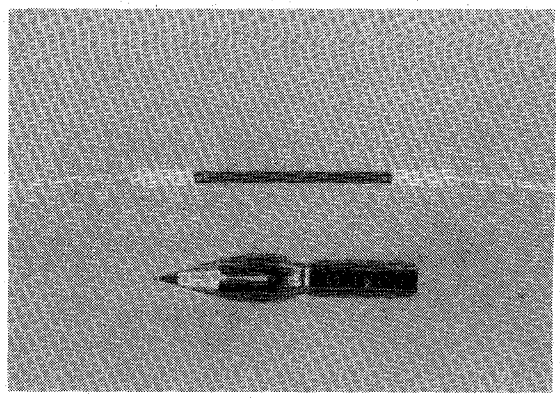


Fig. 3. Outside view of the sensor.

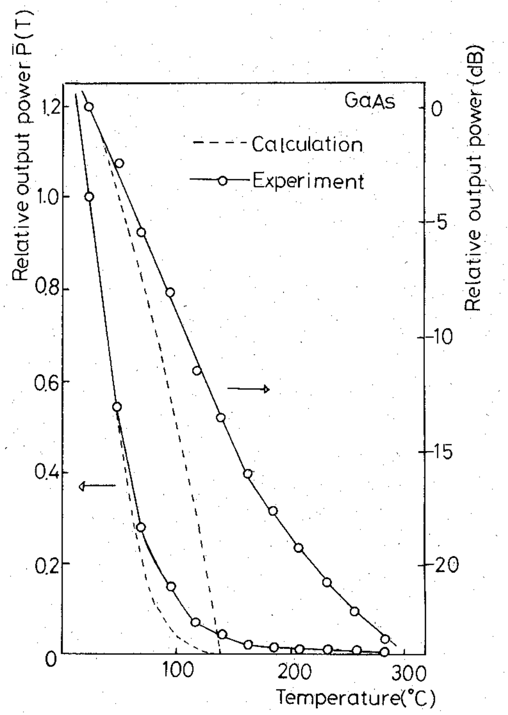


Fig. 4. Relative output power as a function of temperature for the GaAs sensor.

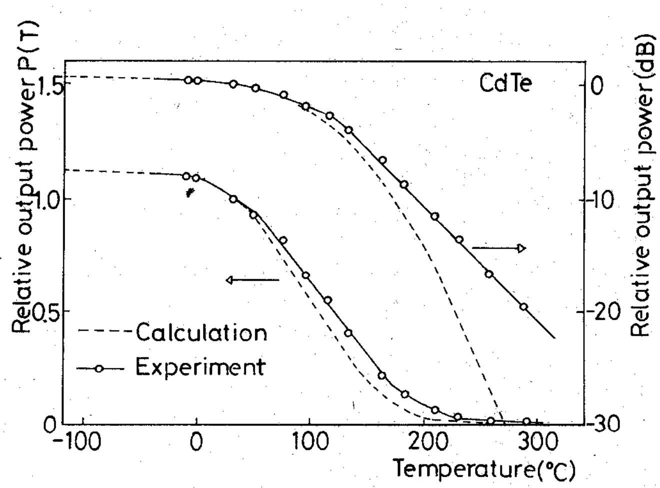


Fig. 5. Relative output power as a function of temperature for the CdTe sensor.

temperature region because the $\lambda g(T)$ of GaAs is found out at a longer wavelength. The dotted lines in the figures are the theoretical curves obtained by assuming that the radiation spectrum of an LED has a normal distribution.

The temperature response time was determined by measuring the time constant of the output voltage when the sensor was quickly replaced between a 0°C water bath and another boiling water bath. From the output voltage waveform shown in Fig. 6, the time constant of about 2 s was obtained.

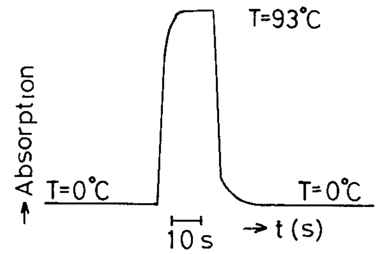


Fig. 6. Temperature response characteristic of the sensor.

IV. Measurement Instrument with Higher Accuracy

In the previous section, we described that our sensor and its instrument have a quite simple structure. Although our sensor has high sensitivity and fast response time constant in the temperature range of our interest, higher accuracy in the practical measurements is required. In the sensor system based on the light-intensity-modulation by temperature, changes of the optical signals by the transmission loss of fibers, the optical connector loss, or the coupling loss between the fibers via the sensing material are confused with the temperature-dependent signals.

In order to get rid of these confusions, we developed a unique signal processing system with two different-wavelength LED's. This schematic diagram is illustrated in Fig. 7. This instrument consists of the above mentioned fiber-optic sensor and an electronic circuit. The electronic circuit contains two optical transmitters, an optical receiver, and a signal processing circuit. As shown in Fig. 7, a pair of optical dual pulses of different wavelengths λ_1 ($\simeq$0.88 μm) and λ_2 ($\simeq$1.27 μm) are guided from both the AlGaAs LED and the InGaAsP LED to a detector through the fiber-optic sensor and optical fibers. An optical coupler is used to couple both different-wavelength light pulses into the incoming fiber. Each optical pulse has a width of 10 ms and a duty cycle of 3 percent. The interval between the light pulses is 20 ms. The absorption of the light of λ_1 by the sensor is changed as a function of temperature. On the other hand, the semiconductors such as CdTe and GaAs are almost transparent for the light of λ_2, which we use here as a reference signal pulse. Electric output pulses obtained from the Ge APD are applied to sample-hold-circuits to get the dc signals proportional to the pulse height. The sample-hold amplifiers are gated on for a short time of about 1 ms when the transmitted light is present. The sampling pulses for these amplifiers are delayed from each optical sensing pulse by approximately 4 ms. After converting to the dc signals, the output signal of the temperature-dependent light (λ_1) is normalized by that of the reference light (λ_2) with an electric divider. The divider output is dependent only upon the band-edge shift of the semiconducter.

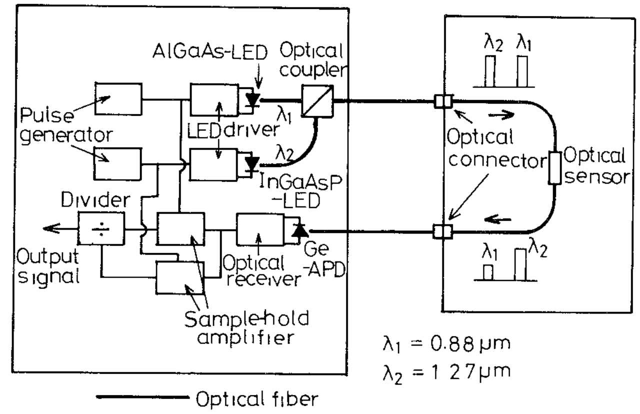


Fig. 7. Schematic of the optical temperature measurement system using two different-wavelength LED's.

In Fig. 8, variations of the divider output voltage V_o, the temperature-dependent signal voltage V_s, and the reference signal V_r are plotted as a function of the output connector loss. The change of V_o is less than 1 dB for the connector loss up to 20 dB. This means that we can get the measurement accuracy within ±1°C in the range from −10°C to 300°C without recalibrating the system, even if fluctuation of the optical signal intensity is above ±20 percent. The accuracy within ±1°C was obtained in the same temperature range once the system was set up.

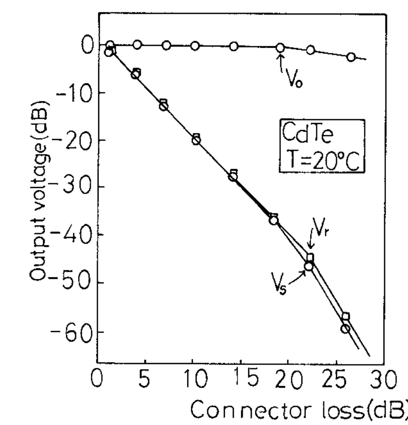


Fig. 8. Changes of output voltage as a function of connector loss.

V. Conclusion

A practical fiber-optic instrument for measuring temperatures with a new type of fiber-optic temperature sensor was developed. This sensor has a quite simple structure and is easy to manufacture at low cost. For the system with an AlGaAs LED, the accuracy within ±3°C was obtained in the temperature range from −10°C to 300°C. The response time constant was about 2 s. These performances are sufficient to use in the temperature measurement inside high-voltage electric-power machines.

Furthermore, we developed a more accurate measurement instrument which requires no correction in the fields tested and in which a unique signal processing technique with two different-wavelength LED's is used. The accuracy of this type of instrument was about ±1°C in the same temperature range.

We will employ our thermometer to measure the temperature of dynamic electric-power machines in the near future.

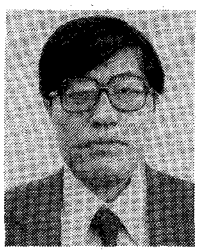
References

[1] T. H. Windhorn and C. A. Cain, "Optically active binary liquid crystal thermometer," *IEEE Trans. Biomed. Eng.*, vol. BME-26, pp. 148-152, 1979.

[2] Gnostic Concepts Inc, *Fiber Optics for Sensor Applications*. 1980, pp. 310-313.

[3] G. B. Hocker, "Fiber-optic sensing of pressure and temperature," *Appl. Opt.*, vol. 18, no. 9, pp. 1445-1448, 1979.

[4] K. Kyuma, S. Tai, T. Matsui, T. Sawada, and M. Nunoshita, "Fiber-optic measurement instrument for temperature," in *Tech. Dig. CLEO'81*, 1981, pp. 102-103.



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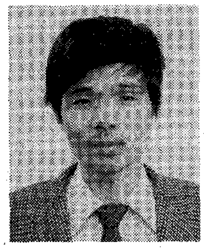

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