Intensity referencing in an extrinsic optical fiber temperature sensor
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Abstract
Optical fiber sensors based on intensity measurement require some form of intensity referencing to avoid errors arising from parasitic losses. Known techniques of referencing such as balanced bridge, divided beam systems or two-wavelength referencing are not suitable for low-cost applications since they use relatively complicated optical components such as multiple LED sources, couplers, filters etc. In this work a novel method of referencing in an extrinsic optical fiber sensor system utilizing temperature dependence of absorption edge in a semiconductor crystal is described. The sensor system comprises a single LED source and no optical fiber junctions. The emission spectrum of an LED depends on its temperature. The reference is provided by controlling the temperature of an LED source and transmission measurements with different emission spectra. The entire process is controlled by a microprocessor unit. Performance of a sensor system is investigated and it is shown that the losses in connectors may be compensated for.

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Keywords: extrinsic optical fiber sensor; intensity referencing; temperature measurement; absorption edge; semiconductor; hot-spot measurement

1. Introduction
In some specific applications e.g. power transformer monitoring [1] or magnetic resonance imaging [2] fiber optic sensors are used for temperature measurements since they do not interfere with close proximity electromagnetic fields. Conventional fiber-optic temperature sensors are based on one of three methods: fluorescence decay time, Fabry-Perot interferometry or the shift of the absorption edge in semiconductor crystals [3]. These systems are not low cost, since they comprise relatively complicated optical components like interferometer, couplers, spectrometer, filter etc. The motivation of this work is to realize a low-cost fiber-optic temperature sensor for the above mentioned applications. Optical fiber sensors based on intensity measurement require some form of intensity referencing to avoid errors arising from parasitic losses [4]. We demonstrate a novel method of referencing in an extrinsic optical
fiber system utilizing temperature dependence of absorption edge in a semiconductor crystal. The system comprises a single LED source and no optical fiber junctions.

**Nomenclature**

- $I_0$: forward drive current of the LED
- $\lambda$: wavelength
- $\lambda_p$: peak wavelength of the LED spectrum
- $dP/d\lambda$: spectral power distribution of the LED
- $R$: responsivity of the photo-detector
- $t_{\text{InP}}$: transmission factor of the sensitive element (indium phosphide prism)
- $T_a$: ambient temperature to be measured
- $T_b$: temperature of the diode function block
- $T_{\text{LED}}$: temperature of the LED

2. Working principle

The concept of a sensor [5] is shown in Figure 1. Light from an LED ($\lambda_p \approx 950$ nm at room temperature) is guided through the input optical fiber into the sensor head. There it is coupled into an indium phosphide (InP) prism, deflected twice and coupled into the output fiber. The transmitted light power is reduced with the growing temperature of the InP-prism $T_a$. Due to the tiny prism dimensions a novel manufacturing method bridging fine mechanics and microsystems technology is required [6].

As this fiber-optic sensor is based on intensity measurement, parasitic losses must be compensated for. The block diagram of a sensor system is shown in Figure 2. The temperature of the diode function block is maintained a constant level above the surrounding temperature. This is achieved by heating the diode function block with the power transistor. In the stationary regime $I_0$ is constant, $T_b$ and $T_{\text{LED}}$ are equal. The monitoring photodiode controls the intensity emitted by the LED.

3. Compensation of parasitic losses

The emission spectrum of an LED source depends on its temperature $T_{\text{LED}}$. It is known that $\lambda_p$ increases with the growing $T_{\text{LED}}$ [7]. For the LED used in this work $d\lambda_p/dT_a = 0.22$ nm/K. The ratio $R_{1/2}$ of two photocurrents taken at two different temperatures $T_{B1}$, $T_{B2}$ is independent of losses $d$:

$$R_{1/2}(T_a) = \frac{\int_{0}^{\infty} R(\lambda, T_{B1}) \cdot t_{\text{InP}}(\lambda, T_a) \cdot \left| dP(T_{\text{LED1}})/d\lambda \right| \cdot d\lambda}{\int_{0}^{\infty} R(\lambda, T_{B2}) \cdot t_{\text{InP}}(\lambda, T_a) \cdot \left| dP(T_{\text{LED2}})/d\lambda \right| \cdot d\lambda}.$$  \hspace{1cm} (1)

It is assumed that the losses in a fiber-optic system are not significantly wavelength dependent and may be taken into account by damping coefficient $d$. 

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notice that for given values of $T_{B1}$ and $T_{B2}$, $R_{1/2}$ is not a monotonic function of $T_a$ in the required range of temperatures $(-50^\circ C \leq T_a \leq 150^\circ C)$.

4. Transient operation regime

Non-monotonic behaviour of $R_{1/2}$ with $T_a$ is a disadvantage, since it limits the range where the temperature may be determined unambiguously. Modelling shows that for given material parameters one has to increase the temperature of the LED in order to get a monotonic behaviour of $R_{1/2}$ in the required temperature range. Continuous operation of an LED at elevated temperatures decreases its expected operating lifetime. To overcome this limitation transient operation regime is introduced. The LED is loaded by higher current pulse $I_0(t)$ and heated itself due to power dissipation. The measurements have been performed as follows. The initial LED temperature was set to 70°C. Then the LED was self-heated by sending a current pulse of $I_0 = 500$ mA during 2 seconds. The amplified output voltages of a photo-diode $U_{ph}$ and a monitoring diode $U_{mon}$ have been measured at the beginning and the end of the current pulse. In order to eliminate transient oscillations averaged values as given below were calculated:

$$
\overline{U}_{out2} = \frac{\sum_{i=1}^{20} U_{ph,i}}{25}; \quad \overline{U}_{out1} = \frac{\sum_{i=179}^{200} U_{ph,i}}{25}; \quad \overline{U}_{mon2} = \frac{\sum_{i=1}^{20} U_{mon,i}}{25}; \quad \overline{U}_{mon1} = \frac{\sum_{i=170}^{194} U_{mon,i}}{25}.
$$

(2)

The sampling rate was 100 Hz. The resulting ratio $R_{1/2, meas}$ is given by

$$
R_{1/2, meas} = \frac{\overline{U}_{out1}/\overline{U}_{mon1}}{\overline{U}_{out2}/\overline{U}_{mon2}}.
$$

(3)
Fig. 3. Comparison between experiment and simulation: (a) stationary regime, $I_0 = 80 \text{ mA}, T_{B1} = 60^\circ \text{C}, T_{B2} = 30^\circ \text{C}$; (b) transient regime. Parameters of measurements and simulations are described in the text.

The transient LED temperatures $T_{LED1}$ and $T_{LED2}$ cannot be measured directly. Figure 3b compares the measurement results with simulation. A good agreement is seen. The fit is achieved for $T_{LED1} = 160^\circ \text{C}$ and $T_{LED2} = 140^\circ \text{C}$. The obtained dependence $R_{1/2}(T_a)$ is monotonic in the entire working range.

Performance of the sensor system has been investigated under realistic conditions. The losses into fiber connectors have been introduced by pulling the connecting ferrules out of the diode block. Compensation for the connector losses (as large as 4 dB) has been proven experimentally. Finally we verified the results of temperature measurement on a surface of a standard working 50 KVA transformer with an infrared camera. Excellent agreement has been demonstrated and no interference with electromagnetic fields has been observed.

Acknowledgements

Financial support by the Bavarian State Ministry of Sciences, Research and the Arts within the priority research program “Miniaturized Sensor Systems with Emphasis on Applications in Medical Engineering, Biotechnology, Automotive and Automation Engineering” is gratefully acknowledged.

References