Evaluation of Optical Fiber Macrobendings in Temperature Sensor Dedicated for Power Transformer Monitoring

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Abstract: Optical fiber sensing techniques are recognized as very promising in diagnostic and condition monitoring of power transformers. According to the IEC standard 60076-2, the winding hot-spot temperature can be designated with the optical fiber sensor. In this paper, the investigation of the influence of macrobending of the optical fiber temperature sensor on the sensing performance is presented. The obtained results prove that the optical fiber sensor wrapped six times around the 14 mm cylinder still provides temperature sensing abilities.

Keywords: GaAs sensor, temperature, power transformer, optical fiber, monitoring

1. Introduction

Power transformers are the key elements in a power system network. The increasing renewable electricity market results in challenges in such system and power transformers. A failure of power transformer can lead to serious consequential losses, therefore, monitoring of the transformer condition and power lines is essential in order to obtain reliable power supply network [1–4]. Degradation of transformers is caused by ageing process and corrosion, which leads to deterioration of transformer performance [5, 6].

Moisture of insulation and temperature inside the transformer, which is higher than maximum operating temperature, accelerate the transformer aging process [7–9]. Therefore, different methods are used for transformer condition monitoring [2, 10, 11], where conventional tests use electrical or chemical sensors. However, in real-time measurements, these methods have limitations due to high electromagnetic interference or high time consumption [12].

To overcome these problems, fiber optic-based sensors have emerged in transformer condition monitoring. Optical fibers are small, immune to electromagnetic interference and they can operate in harsh conditions. Additionally, they provide in site diagnostics, have good sensitivity and stability [13] and provide temperature measurements ability [14]. Therefore, many fiber optic approaches have been utilized to monitor the transformers performance [15–18]. Such approach has been also standardized. IEC standard 60076-2 [19] describes the application of optical fiber sensor for the direct measurement of the winding hot-spot temperature. The sensor consists of optical fiber ended with the gallium arsenide (GaAs) crystal and micromirror. The temperature fluctuations change the property of GaAs crystal and the absorbed by the crystal wavelengths are shifted. However, the utilization of optical fiber sensors can be affected by numerous factors e.g. macrobending of optical fiber or pressure applied on the optical fiber sensor, which can lead to additional losses in optical path or even to a damage of the optical fiber sensor.

Since the intensity of absorbed light by the GaAs crystal is low and the macrobending decreases further the intensity of the signal, it is possible that temperature sensing ability will be lost. In this paper, the investigation of macrobending influence on sensing performance is shown. Experimental results proved that despite the significant macrobending of optical fiber, it is possible to perform temperature measurements.

2. Theory

The operation principle of the optical fiber sensor is based on the light absorption/transmission of GaAs crystal. Some incoming wavelengths are transmitted through the GaAs crystal and reflected back by a mirror placed behind the crystal, and some are absorbed, as shown in Fig. 1. A wavelength which can be absorbed (Fig. 1) by a semiconductor with a band gap energy E_g can be calculated from Eq. (1). In GaAs crystal, the energy E_g depends on the temperature as shown in Eq. (2) [20]:

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$$\lambda_g\left[\mu\text{m}\right] = \frac{1.24}{E_g\left[\text{eV}\right]}, \qquad (1)$$

$$E_g\left(T\right) = E_g\left(0\right) - \frac{\alpha \cdot T^2}{\beta + T}, \qquad (2)$$

where for GaAs crystal at normal pressure, the $E_g(0) = 1.519$ eV, $\alpha = 0.541 \cdot 10^{-3}$ eV/K, $\beta = 204$ K.

Therefore, when the temperature of the crystal decreases, shorter wavelengths are absorbed by the GaAs crystal, and when the crystal temperature increases, the transmission spectrum shifts towards higher wavelengths. The spectrum of the back reflected light is analyzed by a spectrometer, which enables the observation of the spectrum shift and relate it to a temperature change.

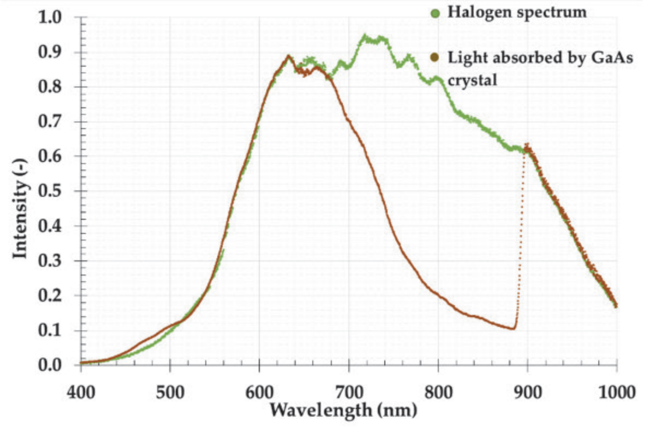

Fig. 1. Comparison of a broadband halogen spectrum and a spectrum of the light partially absorbed by GaAs crystal
Rys. 1. Porównanie spektrum lampy halogenowej przed i po absorbcji przez kryształ GaAs

3. Measurement setup and test procedures

In order to evaluate the optical fiber sensor, the measurement stand is built as shown in Fig. 2 and Fig. 4. As the light source, the broadband halogen lamp (1) is used. Light is introduced through the lens (2) to the glass optical fiber from Thorlabs (3) and optical circulator WMC2L1F from Thorlabs (5). Optical circulator (5) distributes the light to the optical fiber (4) ended with GaAs temperature sensor (shown in Fig. 3), and delivers the back-reflected light through optical fiber (3) to the spectrometer CCS200/M from Thorlabs (6). The spectrometer (6) is connected to a computer (7) to perform data analysis. GaAs sensor is immersed in oil (9), which was kept in a glass vessel. The vessel is placed on a hot plate Stuart EW-04805-29 (8). In order to monitor the oil temperature, the Extech SDL200 thermometer (10) with a thermocouple type K (11) is placed in oil next to the used sensor (Fig. 4c).

Tests are conducted five times: from the room temperature equal to ~22 °C up to 100 °C, with the not bended optical fiber. After that, the optical fiber with the GaAs sensor (4) was wrapped six times around the metal cylinder (12) with the diameter 14 mm, as shown in Fig. 4b, and the tests are repeated.

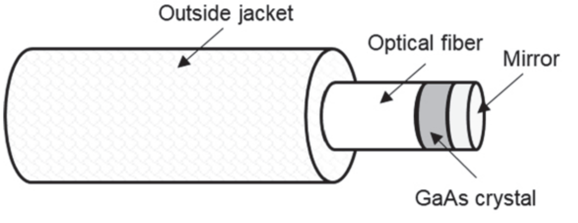

Fig. 3. Construction of the optical fiber temperature sensor with a GaAs crystal
Rys. 3. Konstrukcja światłowodowego czujnika temperatury z kryształem GaAs

Fig. 2. The diagram of measurement setup
Rys. 2. Schemat układu pomiarowego

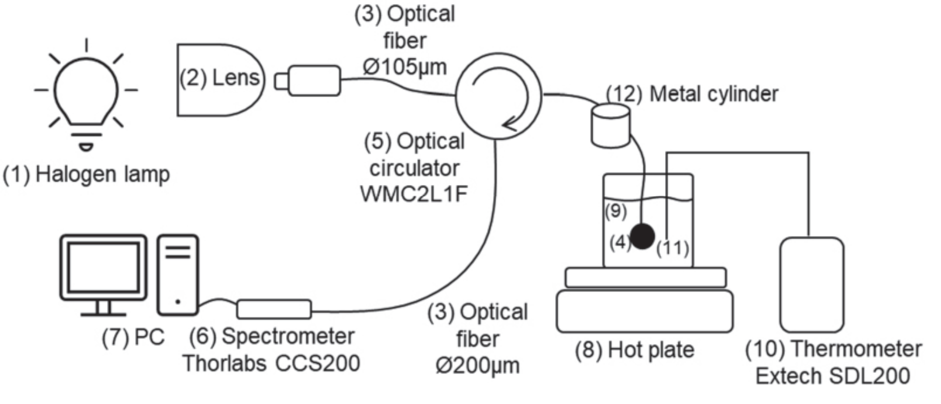

Table 1. Results test for the optical fiber sensor before macrobending
Tabela 1. Wyniki testu przed makrozgięciem światłowodu

Parameter	Test number				
	1	2	3	4	5
Temp. range (°C)	21.6–89.5	22.3–92.7	22–92.9	22.6–103	23–97.4
Temp. coefficient (nm/°C)	0.3564	0.3656	0.3569	0.363	0.3432
Linearity R^2	0.9938	0.9919	0.9992	0.9965	0.9965

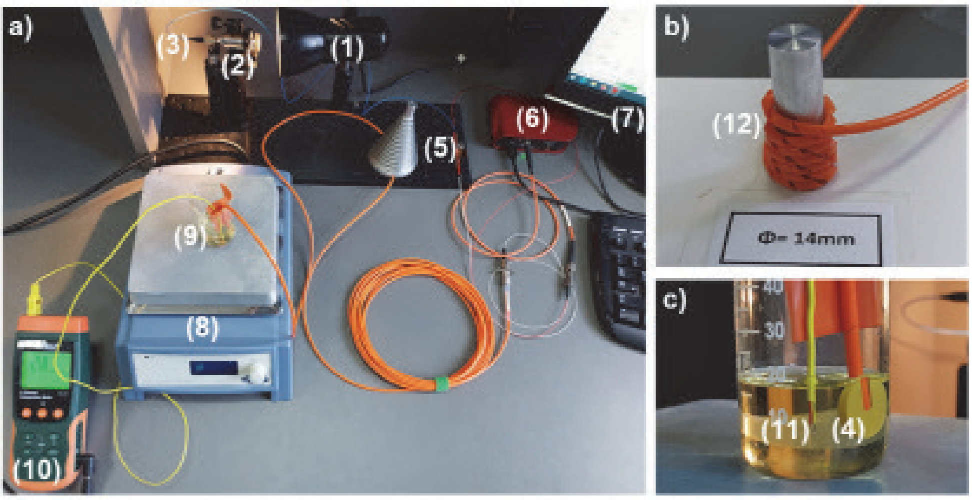

Fig. 4. (a) Measurement setup, (b) macrobending on optical fiber sensor, and (c) thermocouple and optical fiber sensor placed in oil
Rys. 4. (a) Stanowisko pomiarowe, (b) makrozgięcia światłowodu i (c) termopara wraz z czujnikiem światłowodowym zanurzone w oleju

4. Results

In Figure 5, the shift of the absorbed spectrum caused by GaAs crystal temperature rise is shown. The temperature increase causes drop of the difference between the intensity levels of the absorbed and transmitted light. In addition, spectrum shifts towards higher wavelengths, as expected. In order to determine the optical fiber sensor temperature, the central wavelength of the rising slope is monitored. This wavelength shift in time and temperature increase is shown in Fig. 6a. The initial inertia in temperature increase is caused by the oil and glass vessel heat capacity. Tests are repeated five times (Fig. 6b), and for each test the temperature coefficient of the optical fiber sensor is calculated. Collected data are given in Tab. 1, and they prove the linear operation of the investigated sensor in the investigated temperature range with average temperature coefficient equal to 0.3570 nm/°C.

The spectrum of reflected back light after each wrap (from 1 to 6), when the optical fiber is bent around the cylinder is given in Fig. 7. After the sixth turn, the intetsity of the transmisted

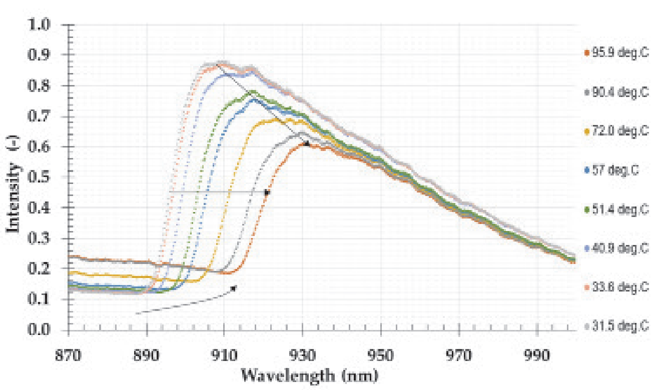

Fig. 5. The spectrum of the back-reflected light before macrobending the optical fiber
Rys. 5. Spektrum światła po przejściu przez czujnik bez wprowadzonych makrozgięć

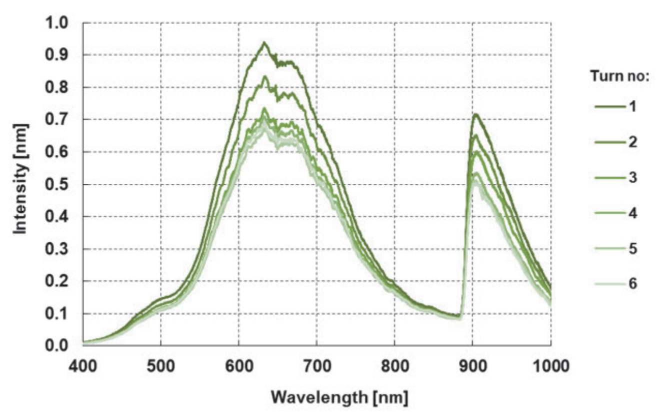

Fig. 7. The spectrum of the back-reflected light after macrobending the optical fiber, showing the impact of the turns quantity
Rys. 7. Spektrum światła po przejściu przez czujnik z wprowadzonymi makrozgięciami

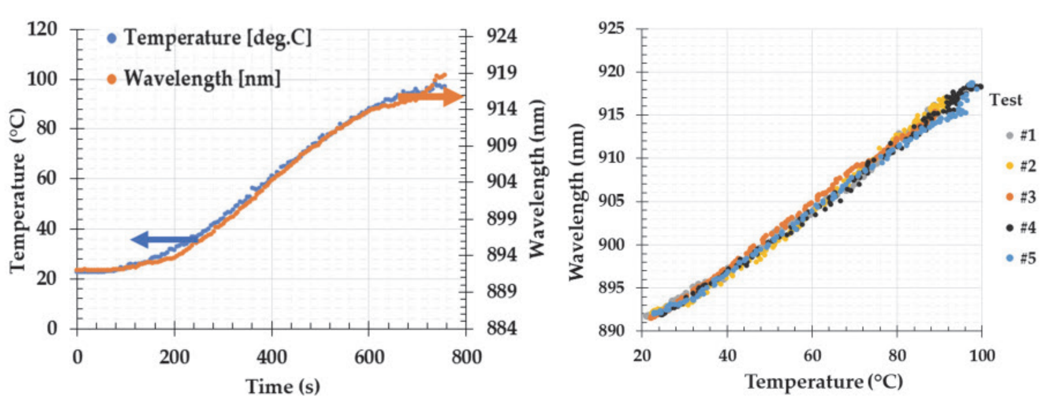

Fig. 6. (a) Temperature and wavelength shift in time, (b) wavelength shifts in five tests, for the optical fiber sensor before macrobending
Rys. 6. (a) Zmiana temperatury i długości fali w czasie, (b) zmiana długości fali podczas pięciu testów bez wprowadzonych makrozgięć na światłowodzie

Table 2. Results test for the optical fiber sensor after macrobending
Tabela 2. Wyniki testów dla czujnika z wprowadzonymi makrozgięciami

Parameter	Test number				
	1	2	3	4	5
Temp. range (°C)	23.2–99.5	23.3–97.7	23.9–98.9	23.3–99.6	23.4–98.4
Temp. coefficient (nm/°C)	0.3273	0.3361	0.3289	0.3163	0.3269
Linearity R^2	0.9965	0.9924	0.9982	0.9965	0.9973

light (around 910 nm) dropped by 30 %. Since this is the worst case, it is decided to continue tests only with such bent optical fiber. The influnce of temperature change on the spectrum is investigated, and the collected data are shown in Fig. 8. Based on these results, it can be stated that the monitoring of the spectrum shift is still possible.

As presented in Fig. 9a, the temperature and wavelength shifts are linear in time. Tests with optical fiber after macrobending are repeated five times, and the collected data are shown in Fig. 9b. Convergent data prove, that despite the macrobending, the optical fiber sensor can still provide accurate temperature measurements. The average temperature coefficient calculated from these tests is equal to 0.3271 nm/°C (see Tab. 2).

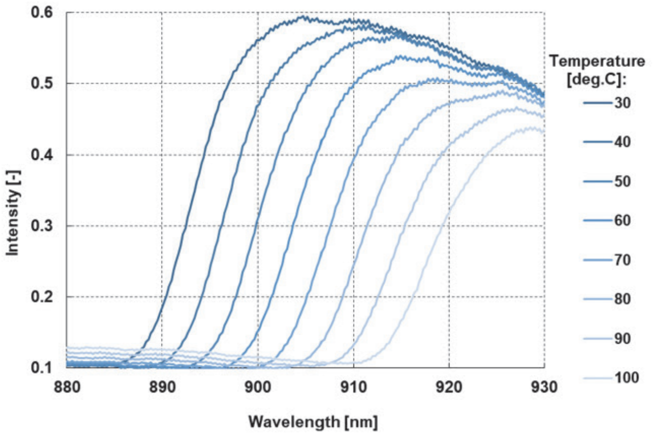

Fig. 8. The back-reflected light spectrum shift caused by the temperature increase after macrobending the optical fiber six times
Rys. 8. Zmiana spektrum światła odbitego pod wpływem wzrostu temperatury dla czujnika z sześcioma nawinięciami światłowodu na cylinder

5. Conclusion

Power transformers are the key elements of electric grid. In site diagnostic of the transformers performance is possible due to application of optical fiber sensors, since they can operate despite high voltages presence. Integration of optical fiber sensors inside the power transformer should be carried out carefully since glass optical fiber can be destroyed easily if it would be crushed by e.g. massive transformer sheets.

In this paper, the influence of optical fiber macrobending on sensor performance is investigated. It is determined that the intensity of the spectrum dropped by 30 % after wrapping the optical fiber six times around the cylinder. However, the difference between power levels of absorbed and transmitted light is sufficient to provide temperature sensing and the average temperature coefficient of the investigated sensor is equal to 0.3271 nm/°C in the temperature range ~23 °C – 98.5 °C. This value is smaller by 8.4 % in comparison to the temperature coefficient calculated for the optical fiber without macrobending.

Obtained data prove that the optical fiber temperature sensors can be practical and profitable, and they can operate despite the incorrect distribution inside a power transformer.

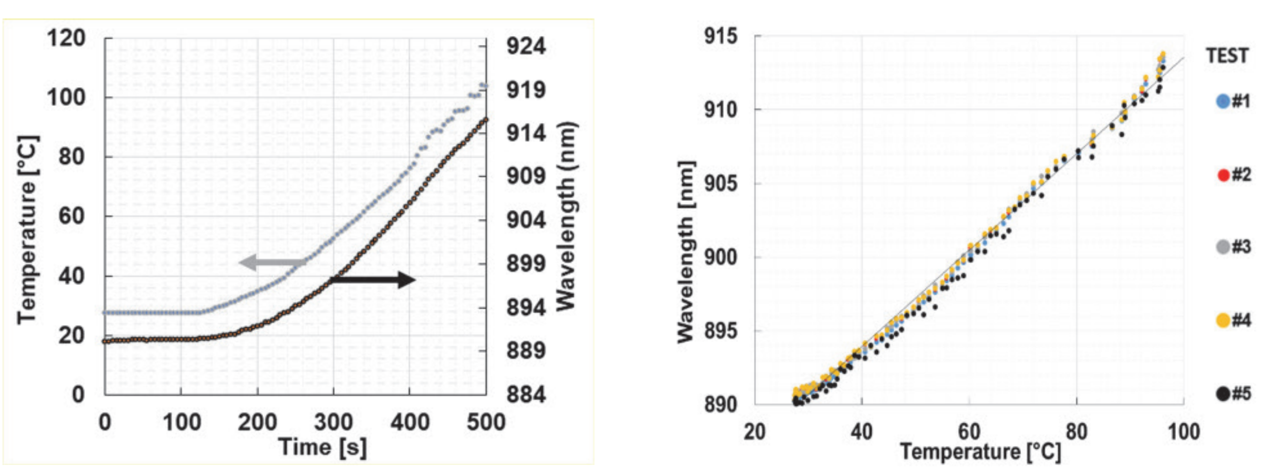

Fig. 9. (a) Temperature and wavelength shift in time, (b) wavelength shifts in five tests for the optical fiber sensor after macrobending
Rys. 9. (a) Zmiana temperatury i długości fali w czasie, (b) zmiana długości fali podczas pięciu testów z wprowadzonymi makrozgięciami na światłowodzie

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Ocena wprowadzanych makrozgięć na światłowodzie na działanie czujnika temperatury dedykowanego do monitorowania transformatorów

Streszczenie: Sensory światłowodowe doskonale sprawdzają się w diagnostyce i monitorowaniu stanu transformatorów. Norma IEC 60076-2:2011 wskazuje na możliwość użycia czujników światłowodowych do pomiaru temperatury uzwojenia transformatora. W niniejszym artykule badany jest wpływ makrozgięć na działanie światłowodowego czujnika temperatury. Uzyskane dane potwierdzają, że czujnik nadal działa prawidłowo, pomimo wprowadzonego makrozgięcia w postaci sześciokrotnego zawinięcia światłowodu wokół cylindra o średnicy 14 mm.

Słowa kluczowe: sensor GaAs, temperatura, transformator, światłowód, monitorowanie

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