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NORMALIZATION AND TEMPERATURE COMPENSATION FOR EXTRINSIC FIBER-OPTIC SENSORS

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This paper presents a novel measuring head for Faraday effect extrinsic fiber-optic sensor providing Δ/Σ normalization and independent optical temperature measurement. The temperature measurement is based on the optical activity temperature dependence of a $Bi_{12}GeO_{20}$ (BGO) crystal. Measurement accuracy is improved from 0.8% to 0.2%. A design modification is proposed for electric field measurement extrinsic fiber-optic sensor.

Keywords: optical fiber sensors, normalization, temperature compensation

Advantages of fiber-optic sensors (FOS) based on the Faraday effect in diagnostics of electric power systems have been widely recognized [1]. The main obstacle for large scale implementation of the Faraday effect FOS has been temperature dependent Verdet constant. A few solutions to this problem have been proposed [2—4]. Neither solution is considered to be optimal since all of them are either too complex and expensive or inadequate. For instance, the interferometric [2] solution measures the temperature over the exactly same optical path as used for the Faraday rotation but is expensive and impractical for a robust sensor.

We are proposing a new solution without additional optical crystals or other optical elements with temperature measurement in the immediate vicinity of the optical paths where the Faraday rotation is measured. This method senses the magnetic field and the temperature independently and is based on measuring of the optical activity which is temperature dependent. Temperature measured in this way is used to correct results for magnetic field or electrical current. BGO is appropriate choice for this purpose since this crystal possess substantial Verdet constant as well as temperature dependent optical activity [5].

In addition, this measuring head enables implementation of the Δ/Σ normalization method. Although the Δ/Σ normalization method is easily implemented in free space using Wollaston prism or birefrigent crystal [6], their use in extrinsic fiber-optic sensors is impractical. These optical components are to large comparing to sensing crystals and introduce problems with vibrations, light coupling and intrinsic temperature dependences. Therefore, to avoid using them we used polarizers and two slightly different optical paths for magnetic field sensing.

Faraday rotation for a uniform magnetic induction and a homogeneous crystal is

$$\theta = \int_0^l V\vec{B}d\vec{l} \ , \qquad (1)$$

where V is the Verdet constant, l is the crystal length and B is the magnetic induction.

The overall temperature dependence of the Faraday rotation is

$$\frac{1}{\theta}\frac{d\theta}{dT} = \frac{1}{V}\left(\frac{\partial V}{\partial \lambda}\frac{d\lambda}{dT} + \frac{\partial V}{\partial T}\right) + \frac{1}{l}\frac{\partial l}{\partial T} \ . \qquad (2)$$

It is essential to exclude the Verdet constant wavelength dependence since it can have major influence in equation (2). We used a LED with temperature regulation and stable 625 nm wavelength ($d\lambda/dT$=0), and reduced temperature dependence to $\frac{1}{V}\frac{\partial V}{\partial T} + \alpha\frac{1}{l}$, where α is the coefficient of thermal expansion of a BGO crystal with the value of $\alpha = 16.8\cdot10^{-6}K^{-1}$ [7]. Since measurement result now depends only on the crystal temperature, we simultaneously measure the optical activity, another temperature dependent optical property to compensate the Faraday rotation angle measurement θ. After finding θ it is straightforward to calculate magnetic induction or electric current that causes it. The following section describes the measuring head construction and next two sections present the experiment and the temperature compensation procedure and measurement results.

Measuring head

The measuring head depicted in Fig. 1 (left) was designed to provide two antiphase channels for θ measurement and normalization as well as a third channel for the optical activity measurement. The two channels designed for the Faraday rotation detection are constructed in reflection so that the optical activity as a reciprocal effect cancels. In addition, the optical path is doubled as well as the Faraday rotation. Since the refraction index of BGO crystal is 2.55 [7] there is sufficient light in the reflection without any kind of mirror.

Transmition axis of polarizers (shaded in picture) in front of receiving fibers are mutually perpendicular and at 45° with respect to the transmition axis of the polarizer in front of the source fiber to obtain maximum sensitivity. Thus voltages after paired transimpedance stages are:

$$U_1 = \frac{kI_0}{2}(1+\sin(2\theta)), \qquad U_1 = \frac{kI_0}{2}(1+\sin(2\theta)), \tag{3}$$

where I_0 is the intensity of the light source, and k is a constant that includes all optical losses, as well as the optoelectronic conversion efficiency. Angle θ is determined by the difference over the sum method and is therefore independent on the light source fluctuations (normalization):

$$\theta = 2VBl = \frac{1}{2}\sin^{-1}\left(\frac{U_1 - U_2}{U_1 + U_2}\right). \tag{4}$$

We used 10 mm long BGO crystal with 6 mm radius.

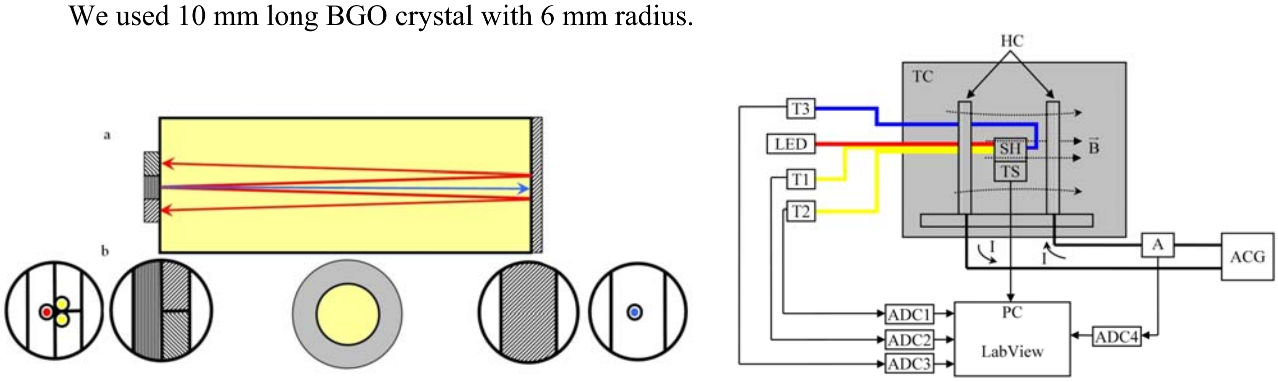

Fig.1. Cross sections of the measuring head:
a — longitudinal; *b* — transversal (left) and setup (right)

Transmition axis of the polarizer in front of the third channel fiber is at 45° with respect to the output state of linear polarization in the absence of a magnetic field and at minimal temperature. Therefore the third channel at the minimal temperature is given by

$$U_3 = \frac{k_3 I_0}{2}(1-\sin(\Delta\varphi(\Delta T)+\theta)), \tag{5}$$

where $\Delta\varphi(\Delta T)$ is the optical activity shift due to the temperature rise ΔT. If excitation current is periodic, the Faraday rotation θ can be eliminated by averaging several periods since the temperature is always changing slowly.

Experimental setup and measurements

The setup is depicted in Fig. 1 (right). The Sensing head (SH) is placed in the centre of the Helmholtz coils (HC) that sourced the magnetic field (B). Bearing in mind dimensions of the coils and the Faraday crystal, magnetic field inside Faraday crystal can, for all practical purposes, be considered homogeneous.

Temperature of the sensing head was measured by a LM74 integrated temperature sensor (TS) placed directly beneath the sensing head. AC current supply for the coils was provided by an autotransformer (ACG). The relation between the current through the coils (I) and the magnetic induction was established using a Hall sensor and found to be linear.

$$B[T] = 0.001282 \times I[A]. \tag{6}$$

The coil current was measured by sampling the analog output of the FLUKE i3000s current probe (A) with an AD converter (ADC4).

The light source was provided by the temperature stabilized red LED module from Omicron at 625 nm wavelength (LED). Light was converted to a voltage with transimpedance stages (T1, T2 and T3) and sampled with AD converters (ADC1, ADC2 and ADC3).

Helmholtz coils were placed in a temperature chamber (TC). The Chamber was cooled down to the minimal temperature of –5°C and heated up to 30°C at 4°C/h rate during which the sampling took place.

The described setup was used to calibrate the FEFOS and the temperature sensing method. Having in mind the linear nature of the FEFOS response one relates the FEFOS sensed magnetic field (and hence the coil current I_F) as $I_F=C_F\theta$.

Therefore the calibration of the FEFOS transfer function is a matter of determining the scaling factor used to scale the result for θ obtained from equation (4). This was experimentally determined to be C_F=2.81 A/rad at the chamber temperature of 15°C.

The procedure starts by cooling the temperature chamber to a temperature little below the $T_{\min}$= –5°C. Once this was accomplished, the cooling was disengaged and the current flow started in the coils. This current produces the magnetic field and heats the chamber since the coils dissipate around 20 W of heat. All four signal channels are sampled together with the temperature sensor and collected data is used to calculate the reference coil current *I*, the reference chamber temperature *T* and the FEFOS sensed current I_F.

FEFOS senses the temperature T_F as a function of C_3 which represents normalized value of U_3. This polynomial is determined by fitting $T(C_3)$ and will be quantified in the next section. Temperature compensated FEFOS result I_C is determined by using the FEFOS relative error at FEFOS sensed temperature T_F using $I_C=I_F/(1-P_C(T_F))$. FEFOS relative error is determined by calibration procedure and fitted with a polynomial $P_C(T)$ used for temperature compensation and will also be quantified in the next section.

The chamber was again cooled to required temperature and the measurement procedure repeated, this time using the temperature compensated FEFOS sensing results stored for processing. Once the data have been sampled the reference current and temperature levels are calculated. Then, FEFOS is used to obtain the chamber temperature T_F using third channel output and polynomial P_T. Uncompensated current magnitude I_F is determined by the FEFOS primary and secondary channels and using equation (4). This current is then compensated for temperature variation by applying the polynomial P_C to obtain the compensated FEFOS result I_C. The procedure is repeated until the final temperature point $T_{\max}$ is reached.

Experimental results and discussion

Fig. 2 (left) presents normalized channel 3 output as a function of the reference temperature.

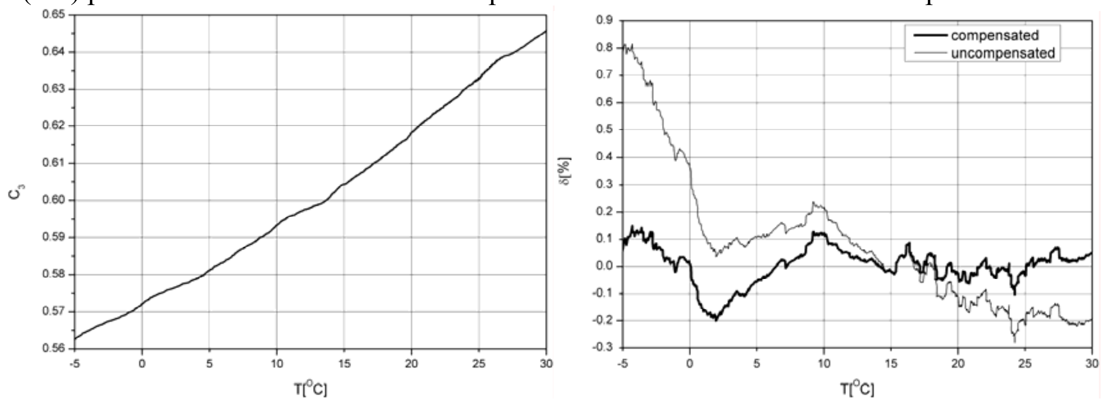

Fig. 2. Normalized channel 3 output as a function of the reference temperature (left), and comparison of relative errors of uncompensated and compensated FEFOS sensed currents (right)

Results presented in the figure have been used to determine the coefficients of the temperature polynomial by means of polynomial regression:

$$T_F = P_T(C_3) = -631.10965 + 1724.11278C_3 - 1084.98768C_3^2 . \quad (7)$$

Compensation polynomyal P_C was determined by fitting a second order polynomial to the FEFOS relative error as a function of the reference temperature:

$$P_C(T) = 0.48269 - 0.03591T + 4.30513E0 - 4T^2 . \quad (8)$$

To verify the temperature compensation method we have performed the test procedure as previously described and the obtained results are presented in Fig. 2 (right).

Pockels measuing head

BGO crystal is often used for sensing purposes. Since it also posseses Pockels effect it can be used for electric field and voltage measurements. If the proposed method of normalization and temperature compensation could be extended to electric field measurements, it would be an economic benefit.

For Faraday effect measurement with maximum sensitivity linear polarization of light is needed while for Pockels effect measurement circularly polarized light is required. To overcome this problem and keep measuring head robust and simple we propose introducing two wavelenghts (λ_1 and λ_2) to input fiber using 2×1coupler. Single waveplate is added after the input polarizer. This waveplate is designed to introduce 2π phase shift for wavelenght λ_1 and $5/4{\cdot}2\pi$ phase shift for wavelenght λ_2, creating circularly polarized light for wavelenght λ_2 and leaving wavelenght λ_1 at linearly polarized state. Chanel 3 for temperature measurement is unchanged and chanels 1 and 2 for electric field measurement are still anti phasewith transmition axes of analizers set for maximum sensitivity.

Having experimentally demonstrated the need for accurate temperature compensation of FEFOS sensed current, a novel, simple and robust sensor construction modification has been described in this paper. Sensing head that allows simultaneous measurement of the optical activity and current measurement by delta sigma normalization means has been constructed. Temperature dependence of the crystals optical activity has been used to measure the temperature of the volume enclosed by two optical paths used to sense current. There are no additional optical elements or crystals involved. Mathematical model for calibration and compensation of the FEFOS has been presented and experimentally tested. Experimental results clearly demonstrate that the proposed method is capable of compensating temperature effect thus limiting the deviation with respect to calibration instrument to 0.2%. Extension of the method to Pockels effect measurement is proposed with similar measuring head and same BGO crystal.

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Нормализация и температурная компенсация внешних волоконно-оптических датчиков.

Представлена новая измерительная головка для внешних волоконно-оптических датчиков на основе эффекта Фарадея, которые позволяют производить Δ/Σ нормирование и независимое измерение оптической температуры. Измерения температуры основаны на зависимости температуры оптической активности $Bi_{12}GeO_{20}$ (BGO) кристалла. Точность измерения повышается с 0,8 до 0,2%. Предложена модификация конструкции для измерения электрического поля внешних волоконно-оптических датчиков.

Ключевые слова: *волоконно-оптические датчики, нормирование, температурная компенсация.*