Computer simulation of the fiber optic electric field sensor

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Abstract. The article describes an approach for simulating the fiber optic electric field sensor with a sensitive element operating on the Pockels effect arising in an optical waveguide recorded in a lithium niobate crystal. The sensor simulating was implemented in the NI LabVIEW programming environment and built using a mathematical apparatus based on the formalism of Jones matrices, which allowed to describe the polarization state of the light beam at the output of the sensor and to calculate the intensity of the interference signal at the photodetector input. Besides, additional modulation with a sawtooth signal and digital phase detection were used in the simulation. The sensor model described in the article can be easily modified and complicated, which makes it possible to use it for research and analysis of both parasitic effects and different optical sensor configurations.

1. Introduction

The development of modern energetics requires the measurement of high voltages and currents with great accuracy. Traditionally, for these purposes electromagnetic current and voltage transformers are used. However, they have a number of disadvantages due to their physical nature (the phenomenon of resonance, hysteresis, residual magnetization, and saturation), design features and difficulty in operation. In addition, the fleet of used devices is obsolete and requires replacement, which is quite expensive [1]. In this regard, great interest is shown in the creation of contactless optical current and voltage measuring transformers, a part of which are the fiber optic electric and magnetic fields sensors [2, 3].

The use of fiber optic sensors in optical transformers provides the following advantages compared with traditional meters:

- immunity to electromagnetic noise from all of the meter parts, except for the sensing element;
- the possibility of use in the conditions of explosion and fire hazardous environments;
- low probability of electrical breakdown and remote measurement;
- high sensitivity and stability to environmental influences;
- small size and weight.

Despite advances in improving fiber optic sensors, this technology still faces a number of difficulties. First of all, specialists are struggling to improve the accuracy and reduce the cost of ready-made solutions, which requires scientific research in both the revision of the optical scheme and digital processing algorithms. It is known that in order to eliminate the influence of external parasitic effects on the inlet fiber to the sensitive element and the outgoing fiber from it, the fast and slow polarization modes after the sensor were reversed [4]. In addition, the influence of polarization mismatches in the
elements of the optical scheme was analytically and experimentally investigated and it was shown that splicing of the PM fibers with the polarization axes mismatch of 1.5 degrees resulted in 1.5 times decrease of the sensor error [5]. In this connection, the task of modeling the sensor operation is actual because it will allow to investigate the processes occurring in it, predict the response of the system to various external influences (for example, noise, optical mismatches, incorrectness of the initial parameters, inaccuracy of the optical circuit, etc.), eliminate the noise effect, analyze various processing algorithms, improve measurement accuracy by applying the best sensor configuration.

This article presents the simulation in NI LabVIEW of the fiber optic electric field sensor with a sensitive element operating on the Pockels effect arising in an optical waveguide recorded in a lithium niobate crystal. One of the advantages of the sensor modeling approach described in the article is visibility and the ability to add, exclude or replace various elements of the optical scheme without completely rewriting the program code. It is not always possible to carry out an analytical analysis of the influence of parasitic factors on the sensor measurement error and often the analysis is significantly complicated by the presence of all factors at the same time. In this regard, the proposed sensor simulating will significantly simplify the analysis. It does not require the derivation of analytical formulas, it is only necessary to set the parameters of external influences.

2. Mathematical description of the fiber optic electric field sensor circuit operating "on the pass"

The electric field sensor is made on the basis of a polarization fiber-optic interferometer, the circuit of which is shown in figure 1.

**Figure 1.** Optical scheme of the electric field sensor. The numbers 1-6 indicate the junction of optical elements or fiber splicing.

If, in a conventional interferometer, the interference of rays that have passed through different geometrical paths occurs at the output, then at the output of such a sensor, interference of rays propagating in orthogonal linear polarization modes is formed. The difference in the course of the fiber-optic interferometer is given by the difference in the optical lengths of the crystal for the “fast” and “slow” polarization modes. The methods of phase detection of interference oscillations carried out using phase modulation of the signal are widespread. For this purpose, an electro-optical modulator (EOM) is used in the circuit, which operates according to the same principle as the sensitive element.

We apply the formalism of Jones matrices to describe the change in the state of polarization of light as it propagates in an electric field sensor built according to this scheme [6, 7]. In this case, the connecting fibers, the EOM and the sensing element have the same effect on the state of polarization as the phase plates. So it can be described by matrices of phase plates.

In the modulator, the phase shift consists of two terms as in equation (1). The first random slowly varying is a quasi-static phase difference of two polarization modes, and the second is variable and is determined by the modulating signal $U(t)$.

$$\varphi_M = \varphi_0^0 + k_U U(t).$$

(1)
In the electro-optical sensitive element, the phase shift is determined by identical two terms, only the second is determined by the induced external field $E(t)$ as in equation (2).

$$\varphi_S = \varphi_S^0 + k_E E(t).$$

(2)

In the connecting fiber, the phase shift between the orthogonal polarization modes is associated with the difference of the refractive indices for the “fast” and “slow” modes and is determined by the beat length $L_b$ and fiber length $l$ according to equation (3).

$$\varphi_{\text{fiber}} = 2\pi l / L_b.$$  

(3)

To take into account the rotation of the axes of coordinates of any element of the scheme relative to another element or the selected system basis, and also to take into account the effect of mismatches at the splicing points of two fibers or at the points of connection of elements with fiber leads to the accuracy of recording the measured value, rotation matrices are introduced.

Thus, the common matrix of the system has the form as represented in equation (4).

$$T = P R_E F_{6-5} R_5 S R_4 F_{4-3} R_3 M R_2 F_{2-1} R_1.$$  

(4)

In equation (4) $[R_{1,2,3,4,5,6}]$ is the rotation matrix, $[F_{5,5,4,3,2,1}]$ is the connecting fiber matrix, $[M]$ is the modulator matrix, $[S]$ is the sensor matrix, $[P]$ is the polarizer matrix. The numbers 1-6 indicate the junction of optical elements or fiber splicing in accordance with figure 1. These matrices are presented in detail in equation (5), where $2\varphi_{6-5,4-3,2-1} = \varphi_{\text{fiber}}$ for the corresponding fiber.

$$[T] = \begin{bmatrix} 1 & 0 & \cos \alpha_6 & \sin \alpha_6 \\ 0 & 1 & -\sin \alpha_6 & \cos \alpha_6 \\ -\sin \alpha_4 & \cos \alpha_4 & 0 & 0 \\ \cos \alpha_4 & -\sin \alpha_4 & 0 & 0 \end{bmatrix} \begin{bmatrix} e^{-j\varphi_6} & 0 & 0 & 0 \\ 0 & e^{j\varphi_5} & 0 & 0 \\ 0 & 0 & e^{j\varphi_3} & 0 \\ 0 & 0 & 0 & e^{j\varphi_2} \end{bmatrix} \begin{bmatrix} \cos \alpha_5 & \sin \alpha_5 \\ -\sin \alpha_5 & \cos \alpha_5 \\ \cos \alpha_3 & \sin \alpha_3 \\ -\sin \alpha_3 & \cos \alpha_3 \end{bmatrix} \begin{bmatrix} e^{-j\varphi_M} & 0 \\ 0 & e^{j\varphi_M} \end{bmatrix}.$$  

(5)

Using the Jones matrix method, it is possible to associate the components of the electric field vector of the beam passing through the sensor $[D_{\text{out}}]$ with the components of the electric field vector of the original beam $[D_{\text{in}}]$ using the common matrix of the element system as shown in equation (6).

$$[D_{\text{out}}] = [T] \cdot [D_{\text{in}}].$$  

(6)

The intensity of the light beam is calculated according to equation (7).

$$I = [D_{\text{out}}] \cdot [D_{\text{out}}^*]^T.$$  

(7)

3. Implementation of the fiber optic electric field sensor model

The simulation of the fiber optic electric field sensor was performed in the NI LabVIEW programming environment. Such features of the NI LabVIEW as the use of virtual instruments in the process of writing program code make modeling in this environment more visual and flexible. Each matrix in equation (4) was modeled as a separate virtual instrument. This makes it easy to analyze various fiber optic sensor circuits by simply adding or replacing matrix in a common system (a common program). Thus, it will not be necessary to rewrite the program code for various fiber optic sensor circuits.

Figure 2 shows a part of the common program for the model of a fiber-optic electric field sensor, which shows the matrices of circuit elements as virtual instruments and their connection in a general program. The matrices of each element were in a separate frame, which can be easily added not only.
along the edges of the common system, but also the middle, and can also be easily removed from the system without breaking the general program.

Figure 2. Block diagram of a part of the fiber optic electric field sensor model in LabVIEW.

The sensor model used additional phase modulation with a 20 kHz sawtooth signal and digital phase detection. A harmonic signal with a frequency of 50 Hz was set as a signal simulating the electric field and acting on the sensitive element. Digital processing of the interference signal generated at the output of the electric field sensor was carried out on the basis of the four-step cross algorithm [5].

The front panel of the general program for the sensor model shown in figure 3 provides for setting various parameters for each element of the optical circuit.

Figure 3. Front panel of a part of the fiber optic electric field sensor model in LabVIEW.
For example, for a modulator, you can set the frequency and amplitude of the modulating signal, set the operating point of the interferometer, take into account the rotation angle between the axes of the input fiber and the modulator, and the output fiber and the modulator. For the connecting fiber, it was provided to specify the beat length and the fiber length, as well as the angles of polarization mismatches at the entrance and exit of the fiber.

As a result of the simulation, an interference signal generated at the output of a fiber-optic current sensor and a demodulated signal representing the harmonic effect on the sensitive element were obtained (figure 4).

![Interference signal and demodulation signal of the fiber optic electric field sensor model.](image)

**Figure 4.** Interference signal (left) and demodulation signal (right) of the fiber optic electric field sensor model.

4. Conclusion
In the NI LabVIEW programming environment, we simulated the operation of the fiber optic electric field sensor. The simulation result is identical to the operation of a real sensor, so this model can be expanded and complicated to analysis of the introduced errors in the measurements caused by various external influences on the sensor, the mismatch of optical elements, noise, temperature drift, etc. In the future, this model can be easily modified, which will allow to explore various options of circuits for fiber optic current and voltage sensors.

References
[1] Toney J E, Tarditi A, Pollick A, Pontius P, Sriram S and Kingsley S A 2014 IEEE Sensors J. 14 1364-9
[2] Celso Gutierrez-Martinez 2009 Electric Field Sensing Schemes Using Low-Coherence Light and LiNbO3 Electrooptical Retarders Optical Fiber New Developments ed C Lethien (Croatia: InTech) chapter 6 pp 101–124
[3] Bohnert K, Frank A, Müller G M, Yang L, Lenner M, Gabus P, Gu X, Marchese S V 2018 Fiber optic current and voltage sensors for electric power transmission systems Proc. of SPIE vol 10654 (Orlando: SPIE) 1065402
[4] Petrov V, Medvedev A, Liokumovich L and Miazin A 2016 Int. J. of Modern Physics A 31 (2-3) 1641032
[5] Temkina V S, Medvedev A V, Petrov V M, Miazin A S 2016 Humanities & Science University J. Physics, Mathematics, Engineering and Biology 24 34–40
[6] Yariv A and Yex P 1984 Optical waves in crystals (New York: Wiley)
[7] Collett E 2003 Polarized Light in Fiber Optics (Lincroft: The PolaWave Group)
[8] Malacara D, Servin M and Malacara Z 2005 Interferogram Analysis for Optical Testing 2nd Edition (Boca Raton: Taylor & Francis Group)