Inherently temperature stable $Bi_{12}TiO_{20}$ -based fiber voltage sensor

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ABSTRACT

The inherent temperature stability of a fiber voltage sensor is far from industrial requirements. Usually, a special channel for a temperature control is needed. Temperature-dependent birefringence of optical elements, such as a quarter-wave plate and a sensitive crystal, is the main source of temperature-induced drift of sensor parameters. To solve this problem we used a special back reflecting prism as a phase-retarding element, BTO crystal as a sensitive element, and a double-pass scheme. The double-pass scheme enables to diminish the negative role of the optical activity in the crystal, to increase an interaction length and, thus, to enhance the sensitivity of the sensor. The special back reflecting prism demonstrates temperature stability more than 20 times better, than a zero-order quartz quarter wave plate. This permits to decrease the temperature-induced drift of sensitivity. The sensor demonstrates temperature stability of (1.5% from -20°C to 60°C) and sensitivity of 0.145% per 1V rms at 850 nm without using an additional temperature control channel.

Key words: Fiber optics sensors, Electro-optical devices.

1. INTRODUCTION

Fiber optical sensors of voltage and electric field attract a lot of interest in recent years as an alternative to traditional measurements in electric power systems. These sensors do not contain any conductive elements and, as result, do not introduce any perturbation in the measured electric field. The first fiber optic voltage sensor had been demonstrated quite a long time ago[1-6] . Meanwhile, there are two obstacles for application of these sensors in industry. First, the sensitivity of the sensors developed before, are rather low. The typical sensitivity of voltage sensors with a longitudinal modulation is between 0.039% per 1V rms[2] and 0.051% per 1V rms[1].

Second, the temperature stability of the entire sensor is far from indusrtial requirements. Usually, attention has been payed to the temperature stability of crystal parameters[1,2,6] . Meanwhile, there are other optical elements inside the sensor, such as quarter wave plates[7], which are sensitive to temperature changes. The changes of birefringence with temperature in this element causes the strong variation of the sensor's sensitivity.

We have proposed the new configuration of a fiber optic voltage sensor, based on the $Bi_{12}TiO_{20}$ crystal. Instead of a quarter wave plate we used a glass back-reflecting prism as a phase-retarding element. Using this prism, the good temperature stability of ±1.5% from -20°C to 60°C and excellent sensitivity have been demonstrated without using an additional temperature control channel.

2. BASIC PRINCIPLE OF THE SENSOR

The optical scheme of the sensor is shown in the Fig.1. The light from a 850nm-LED is launched into the sensor through a multimode fiber (300/320μm) and selfoc lens. The polarization state of the light after polarizing prizm is 45° to the axes of the electric field–induced birefringence in the crystal. The crystal with dimensions 5x5x2mm is aligned in such a way that the electric field and optical path is normal to the (100) crystal plane.

The polarized light returns back to the crystal after two reflections from both cathetuses of the back-reflecting prism. The vertical axes of the reflecting prism and the polarizing prism are misaligned at the angle of 45°±ϑ, where ϑ is the angle of polarization rotation due to the optical activity of the crystal. Sign «+» or «-» changes according to the crystal modification (left or right side rotation).

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After the second pass through the crystal the beam meets the polarizing prism where two orthogonal states of polarization are separated into two channels. The analyzer converts the polarization modulation into the modulation of an intensity in two channels. Both intensity-modulated beams are launched into the fibers, using selfoc lens (Fig.1).

The back-reflecting prism in this case accomplishes two functions. On one hand, it is a beam reflector in the double-pass scheme. The phase shift between «fast» and «slow» waves after the second pass through the crystal will be doubled, resulting in the increase of the sensor sensitivity.

On the other hand, this prism introduces $\pi/2$-phase shift between «fast» and «slow» waves in the crystal. That permits to work in the regime of the best sensitivity of the sensor[8]. To calculate the refractive index of the back reflecting prism we used the following consideration. The phase shift Δ between **S** and **P** polarizations on the glass/air interface of the back-reflecting prism under conditions of the total internal reflection is determined by equation[9] :

$$\tan(\Delta/2) = \frac{(n_1/n_0)\times\sqrt{(n_0/n_1)^2\times\sin^2\varphi - 1}}{\sin\varphi\times\tan\varphi} \qquad (1)$$

where φ is the angle of incidence, n_1 and n_o are the refractive indices of the air and glass prism, respectively. Using eq. (1) and $\varphi=\pi/4$, $n_1=1$ the refractive index of the back–reflecting prism can be calculated as

$$n_0 = \sqrt{\frac{2}{1-\tan^2(\Delta/2)}} \qquad (2)$$

The phase shift Δ should be equal to $\pi/4$ to obtain the circular polarization of the beam after two consecutive reflections from cathetuses of the prism. From this condition the refraction index of the prism n_o is calculated to be 1.553773974. We used the glass[10] БК-10 (Russia) with n_o=1.56023 at λ=863nm in our experiments .

Using Jones matrix formulation, the transfer function of the sensor (Fig.1) can be presented as :

$$I=|P\times R(-45°)\times C_{ref}\times R(45°)\times R(-45°-\vartheta)\times PHASE\times R(45°+\vartheta)\times R(-45°)\times C_{dir}\times R(45°)\times E|^2 \qquad (3)$$

where E – the Jones vector of light at the input of the crystal; R(…..) – the rotation matrix; C_{dir} – the Jones matrix of the BTO crystal for incident light; PHASE – the Jones matrix of the back reflecting prism; C_{ref} – the Jones matrix of the BTO crystal for back reflected light; P – the Jones matrix of the analyzer.

With this equation we have compared the sensitivity of the proposed two-pass sensor with that of the single-pass sensors, described before [1,2,4,5]. The dependence of the transfer function on the phase shift between "fast" and "slow" waves in the BTO crystal for the two-pass sensor is shown in Fig.2 (curve#1). The curve#2 (Fig.2.) presents the transfer function of the single-pass BTO sensor. As is seen from the figure, the first minimum is achived by the curve #1 when the phase difference between "fast" and "slow" waves is equal to 0.817 radians; while the first minimum of the curve #2 corresponds to the phase difference of 1.571 radians. Thus, the sensitivity of the two-pass sensor is approximately two times more, than that one of the single-pass sensor.

We have also compared the sensor sensitivity for two crystals: BSO ($Bi_{12}SiO_{20}$) and BTO. The BSO crystal has the high value of the electro-optical constant $\mathbf{r_{41}}$ and this crystal is well available. The feature of the BSO is a high intrinsic optical activity (11.5°/mm). The BTO crystal has the same value of the electro-optical constant $\mathbf{r_{41}}$, but it's optical activity is much less (1.5°/mm). The transfer functions of the BSO-based single-pass (curve #3) and double-pass (curve #4) sensors are shown in Fig.2. The thickness of the crystal is supposed to be 2mm. As follows from calculations, the sensitivity of the single-pass sensor (Fig.2, #2 and #3) changes slightly in the presence of the optical activity for both types of the crystals. However, for double-pass configuration the sensitivity of the BSO-based sensor decreases significantly compared to the BTO-based sensor. Thus, the low optical activity of the BTO crystal makes it more preferable in the double-pass configuration.

We have compared the temperature sensitivity of the proposed sensor with that of the sensors with quarter-wave plates [1-5]. The temperature sensitivity of phase plates is well known [7,11]. We consider the quartz-made quarter-wave plate of the zero order. The thikness (L) of this plate is 24 μm at 850 nm wavelength. The optical phase shift in the phase plate, caused by temperature changes is given by :

$$\Delta\varphi_{plate}=2\pi\times\Delta n\times L\times\gamma\times\Delta T/\lambda \qquad (4)$$

where $\Delta n=0.00885$ is the quartz birefringence at $\lambda=850$ nm, $\gamma=1.4\times10^{-4}$, $°C^{-1}$ is the constant which determines the changes of birefringence with temperature [7], $\Delta T=100°$ is the temperature range. It should be noted that thermal expansion is neglected in (4).

As follows from equation (4), the temperature changes over 100°C causes the additional phase retardance in the zero-order phase plate of about 1.26°. Usually, the low -order phase plates are not in use because of difficulties in fabrication. The high-order phase plates are much less stable compared with low-order phase retarders. For example, the phase shift between «fast» and «slow» waves in the quartz quarter-wave plate[11] of the order N=28.25 (thikness 1.973mm, $\lambda=633$nm) changes 1.03° with the temperature increase of 1°C. Temperature changes over 100°C would lead to the phase retardance of 103°.

Let consider now the temperature stability of a glass back-reflecting prism. As is seen from equation (2), the phase shift between **S** and **P** polarization after two reflections is given by:

$$\Delta\varphi_{prism} = 4\times a\tan\sqrt{1-2/n_0^{\,2}} \qquad (5)$$

The temperature stability of the prism depends on temperature properties of the glass refractive index. The temperature constant of БК-10 glass is $2*10^{-6}$ $°C^{-1}$ [10]. The dependence of the phase shift between **S** and **P** polarization after two reflections in the prism as a function of temperature is shown in the Fig. 3. As is seen from Fig.3, the phase shift caused by temperature changes over 100°C is only 0.05°. Thus, a back-reflecting prism as a phase-retarder is at least 20 times more stable than a zero-order quartz quarter-wave plate.

3. EXPERIMENT

In the experiment we investigated the sensitivity and temperature stability of the sensor. Figure 4 shows the output signal of the sensor processing unit as a function of the applied voltage (60 Hz). As follows from Fig.4, the dependence of the sensor output signal on the applied voltage becomes nonlinear for amplitudes about 1000 V. It is directly related to the nonlinear behavior of the sensor transfer function (see Fig.2, curve #1) and to the high sensitivity of the sensor (0.145 % on 1V RMS). The minimal detected voltage (SNR=3dB, frequency band 1.5-25000Hz) was 0.35V.

Fig.5 shows the temperature dependence of the modulation depth for different channels of the sensor. As is seen from the Fig.5, the depth of modulation for different channels of the sensor varies in opposite directions with temperature. Such a behavior can be explained by the complex mechanical structure of the sensor. All elements of the sensor (BTO crystal, the glass prisms, selfoc lens) are glued together and the sensor represents a single unit. The significant change of temperature (from -20°C to 60° C) causes the appearance of mechanical stresses in the sensor head. The intrinsic mechanical stresses, in turn, result in an additional linear birefringence in the crystal due to the photoelastic effect. The temperature-induced drift of the additional linear birefringence leads to the changes of the optical power in each channel, resulting in changes of the sensor sensitivity.

To improve the temperature stability and signal-to-noise ratio the output signals from both channels were processed in the electronic block with specially chosen weights. As a result, the combined signal demonstrated better stability. The temperature dependence of the combined signal from two channels is shown in Fig.6. The temperature stability of the sensor output signal was measured to be about ±1.5 % in the range from -20°C to + 60°C.

4. CONCLUSION

We have demonstrated a fiber-optic electric voltage sensor based on the BTO crystal with an inherently high temperature stability. A special back-reflecting prism was used as a phase-retarding element to substitute temperature-sensitive birefringent elements in the optical scheme. The sensor demonstrates temperature stability of ±1.5% from -20°C to 60°C and sensitivity of 0.145% per 1V RMS at 850 nm without using a temperature control channel.

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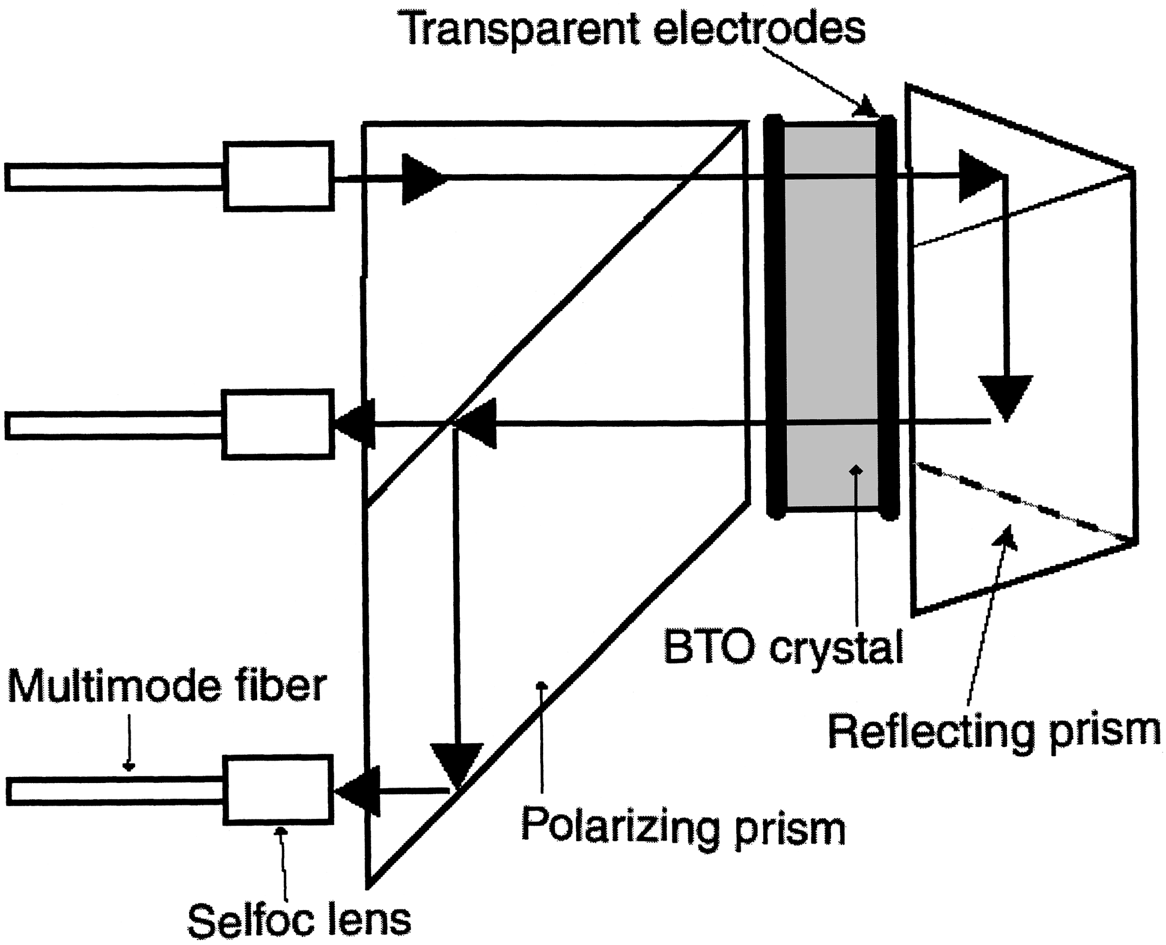

Fig.1. Electric field sensor

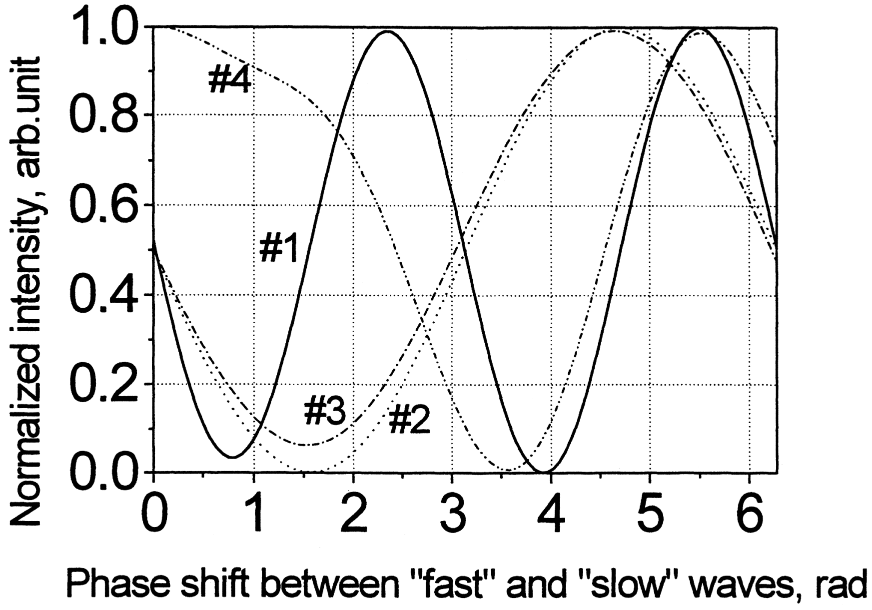

Fig.2. Transfer functions of the sensors

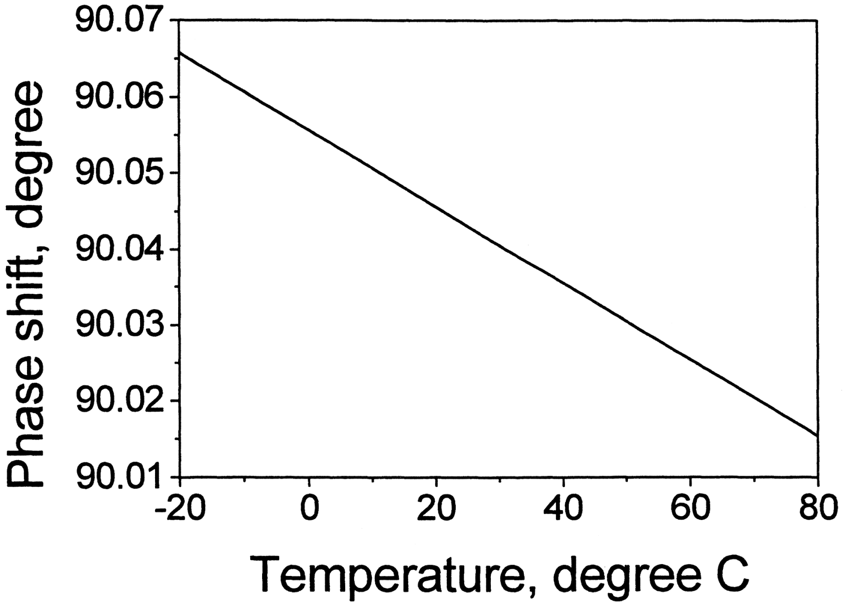

Fig.3. Phase shift between S and P polarisation in prizm as a function of temperature

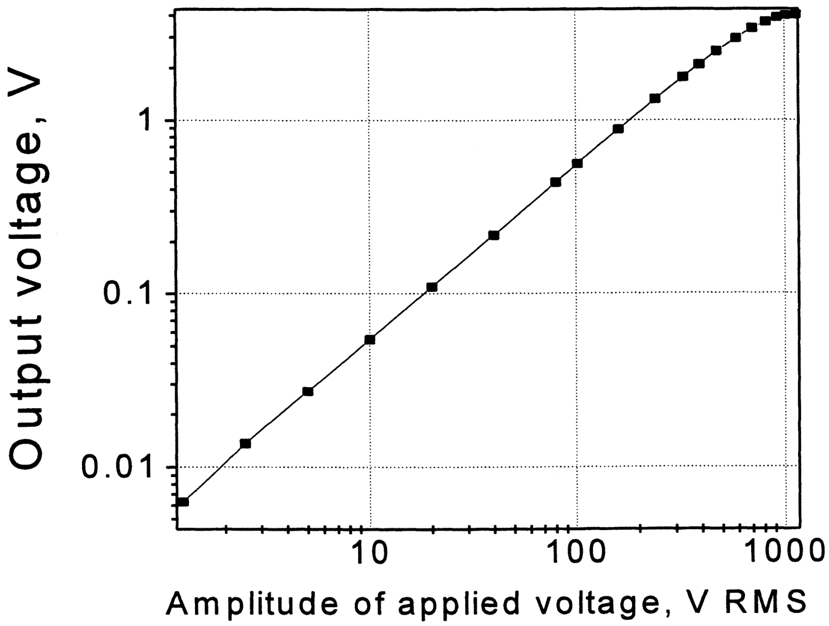

Fig.4. Output signal of the sensor as a function of applied voltage

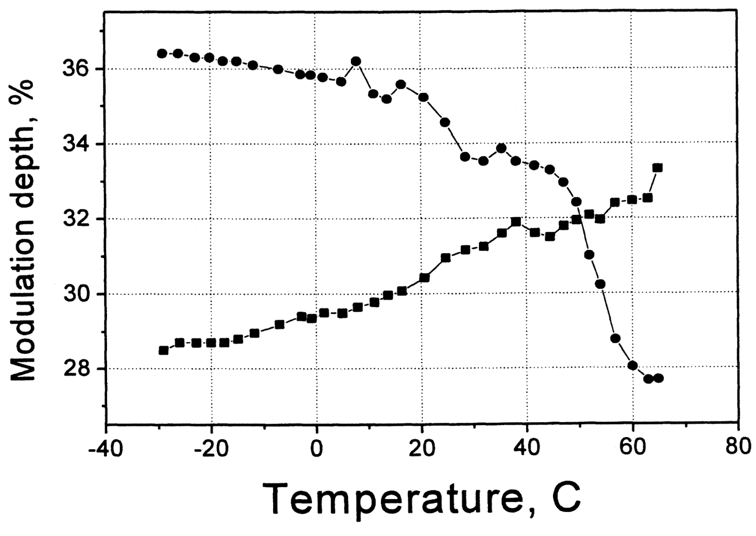

Fig.5. Temperature drift of modulation depth in the both channels of the BTO sensor

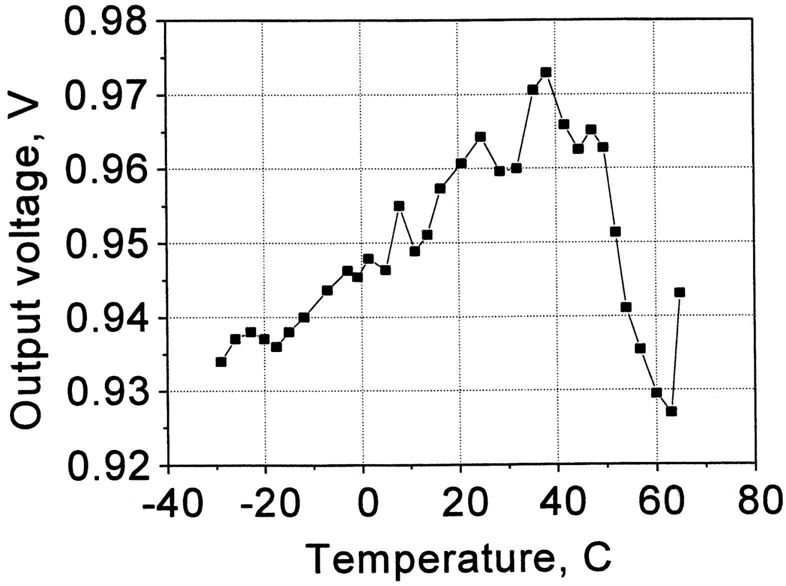

Fig.6. Temperature drift of the sensor's signal