The study of response of electro-optic phase modulator based on LiNbO$_3$ with the aim of improving the accuracy of fiber-optic gyroscope

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Abstract. The work offers the method for a study of parasitic refractive index drift (RID) of electro-optical modulator (EOM) based on the lithium niobate (NL) crystal under the action of applied electric voltage. As a result there is proposed a method of compensation EOM’s inertial behavior. Described method can be used for improving the accuracy of fiber-optic interferometric sensors and of fiber-optic gyroscope in particular.

1. Introduction
EOMs based on NL crystal (LiNbO$_3$) are widely used in electro-optical devices due to unique properties of NL, such as a large electro-optical coefficient, wide transparency range, mechanical and chemical stability, as well as the possibility of formation of channel waveguides in NL crystal [1, 2].

Despite many advantages of modulators based on NL, they have several disadvantages. Because of the dielectric nature of the NL crystal parasitic refractive index drift (RID) is observed under action of the applied electrical voltage [3, 4, 5]. This effect has an unwanted influence on the optical wave propagating through the modulator and thus it makes an additional phase shift, which leads to increased measurement error [6]. That is why the investigation of this parasitic effect in EOMs based on NL crystal is currently an urgent task to improve the accuracy of fiber-optic interferometric sensors in general and of fiber-optic gyroscope in particular.

2. The study of parasitic RID of phase EOM based on NL crystal
In this work we have proposed and have implemented the method of study of parasitic RID of phase EOM based on NL crystal. Parasitic RID can be measured only in case of using the phase EOM as a part of the interferometer, where parasitic RID leads to the interferometer’s phase shift and to the according to its intensity change. In order to measure RID time and applied voltage dependences transient processes were investigated. The experimental setup (figure 1) represents the Mach-Zehnder fiber interferometer with a phase EOM in one of its arm. We used the phase EOM from multifunctional integrated optical scheme (MIOS), fabricated on X-cut NL. MIOS includes a polarizer, X-type coupler and two phase EOMs. Optical waveguides axes are oriented along Y axis of NL. An external electrical field was applied along Z axis of NL, so EO coefficient $r_{33}$ was used.
Figure 1. The experimental setup for studying of the parasitic RID of the phase EOM based on NL crystal.

Since a process of parasitic RID is most clearly observed in case of a jump of the applied voltage, in other words, in case of a sharp change in the magnitude and/or direction of the external electric field, the shape of the modulating signal for measuring transient processes of the modulator should be a step function of the applied voltage.

The amplitude of the step was chosen to be according to the phase shift equal $\pi/2$, and there were analyzed only those interferometer’s responses which were received in quadrature operating point. Such a principle was applied in order to measure transient process in the linear part of the interferometric response, where normalized intensity changes are equal to the phase changes. Figure 2 shows the EOM’s step response which was recalculated from interferometer’s response in operating point $-\pi/2$ in case of applying a jump of voltage to electrodes of the phase EOM. The jump of voltage was counted in such a way to shift interferometer’s operating point from $-\pi$ to $-\pi/2$.

Figure 2. EOM’s step response in case of applying a jump of voltage to its electrodes.

Revealed parasitic RID of phase EOM in case of changing the modulating voltage may be caused by mobile charges formed as a result of penetration of the metal electrodes in the thickness of the substrate and by defects in the surface layers of the crystal [6]. They move under the influence of an electric field generated by electrodes, and also create its own field which can increase or, conversely, weaken external field. Such charges have limited mobility, so they exhibit inertia in relation to changes in the external field. Thus, the process of relaxation of charges caused by the field generated by electrodes creates a drift of the magnitude of the total electric field and, as a result, it creates
parasitic RID of phase EOM, which makes an additional phase difference, which leads to increased measurement error.

3. The method of compensation of parasitic RID of phase EOM based on NL crystal

Transient response of the EOM in time domain pictured at figure 2 can be performed in frequency domain. The calculated transfer function in z-domain is expressed as:

$$Y(z) = \frac{0.9821 z^{-1} - 0.9815 z^{-2}}{1 - 1.006 z^{-1} + 0.004902 z^{-2} + 0.002045 z^{-3}}.$$  

The knowledge of the transfer function gives us an opportunity to calculate the inverse filter which can be used for pre-emphasis of the modulating voltage signal. Frequency responses of the EOM and of the inverse filter are shown at figure 3.

Figure 3. Frequency response of the EOM and of the inverse filter.

Pre-emphasis of the modulating voltage allows to compensate EOM’s parasitic phase drift. Comparing of transient response of the EOM and of the system consisting of EOM and inverse filter is shown at figure 4.

Figure 4. EOM’s step response and compensated by inverse filter step response.
Figure 4 shows that application of inverse filter for pre-emphasis of the modulating voltage signal for compensation the parasitic phase shift. Such compensation method can improve the accuracy of fiber-optic interferometric sensors in general and especially of fiber-optic gyroscope.

4. Conclusion
Revealed parasitic RID of phase EOM in case of changing the modulating voltage may be caused by mobile charges in the surface layers of the NL crystal. They move under the influence of an electric field generated by electrodes, and also create its own field which can increase or, conversely, weaken external field. Such charges have limited mobility, so they exhibit inertia in relation to changes in the external electric field. In order to compensate the parasitic phase shift caused by the process of relaxation of charges there is proposed to describe the inertia process of EOM by filter and to pre-emphasize the modulating voltage signal by the inverse filter. Described method can be used for improving the accuracy of fiber-optic interferometric sensors.

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