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Electro-optic modulators for solar magnetic field observations at ISTP

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ABSTRACT

The paper describes the main stages in developing electro-optic modulators (EOMs) based on the KDP group crystals for solar magnetographs at ISTP SB RAS. The optical-physical characteristics of modulators are studied. The reasons for EOM failure are analyzed, and ways to eliminate them are proposed. The EOM designs have been developed for different types of control voltages.

Key words: solar magnetograph, polarization, Pockels effect, KDP crystal

1 Introduction

The general method underlying the operation of a solar magnetograph is the measurement of radiation polarization parameters. Improvement of measurement methodology proceeds through the creation of new polarized light analyzers and methods for controlling them. Polarized light analyzers are developed at ISTP based on modulators using the Pockels effect in electro-optical crystals. By changing the polarization of light passing through the crystal under the influence of applied voltage, one can measure all Stokes parameters, which fully describe the polarization state of the radiation field. Polarization parameters on a spectral line section provide information about the magnitude and direction of the magnetic field vector on the Sun. Requirements for EOMs for observing magnetic fields concern the following parameters:

- transmission,
- clear aperture,
- provision of light beam modulation depth when controlled by a sinusoidal voltage source or by constant and alternating pulse voltage,
- uniformity of phase shift from control voltage across the modulator's field of view,
- birefringence due to mechanical stresses in the modulator,
- optical radiation wavefront distortions across the field of view,
- angular aperture,
- ability to operate in conditions of high humidity and temperature changes,
- stability of operational parameters.

The national optical-mechanical industry does not produce the necessary EOMs with parameters satisfying observation conditions. With the aim of creating modulators operating in a wide frequency range, preserving optical radiation wavefront quality and uniformity of the phase shift across the aperture, capable of measuring polarization degree with accuracy of 1×10^{-4} and higher, various EOM designs have been developed and tested at ISTP since 1965 to improve their optical and operational characteristics. This work analyzes the main design features of modulators developed at ISTP and causes of their failure. It also proposes technical solutions ensuring stable operation of EOMs and aimed at minimizing magnetographic measurement errors.

2 Electro-optic modulators of magnetographs for operation with analog signal

The need for EOMs arose with putting into operation the first solar magnetographs (Nikulin et al., 1958; Kuznetsov et al., 1966). The first modulator at ISTP (then SibIZMIR) was manufactured by V.E. Stepanov in 1965. This classical modulator consisted of a plane-parallel plate of the ADP (ammonium hydrogen phosphate) electro-optical crystal, cut perpendicular to the optical axis and glued between two protective glasses with transparent conductive coatings, adjacent to the plate. At the institute's laboratory, transparent conductive tin oxide SnO_2 electrodes (Fig. 1a) were applied by pyrolysis method at a high temperature of 430°C to the surface and chamfer of the protective glass, conductive paste was fired into the glass chamfer, and high-voltage outputs were soldered to the paste. The structure was placed in a housing made of plexiglass or fluoroplastic and filled with Canadian balsam or wax compound (Fig. 1b). The clear aperture of modulators is 10–20 mm.

ADP crystals (and later appearing KDP and DKDP crystals with lower control voltage) are technologically very delicate: soft ones are easily scratched; water-soluble crystals

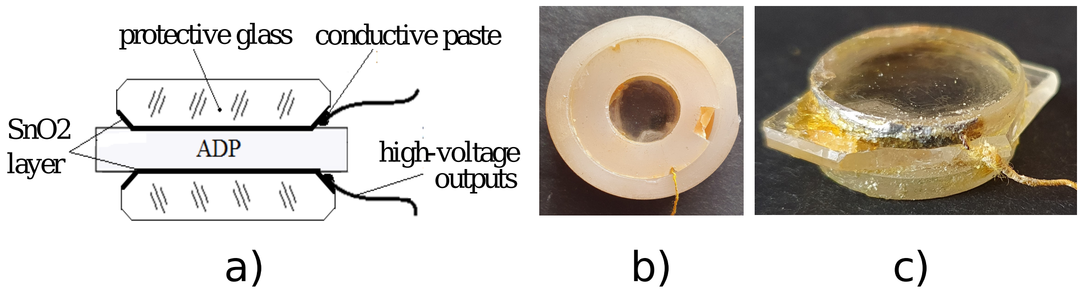

Fig. 1. EOM design on the ADP crystal: a) scheme, b) external view, c) destroyed modulator.

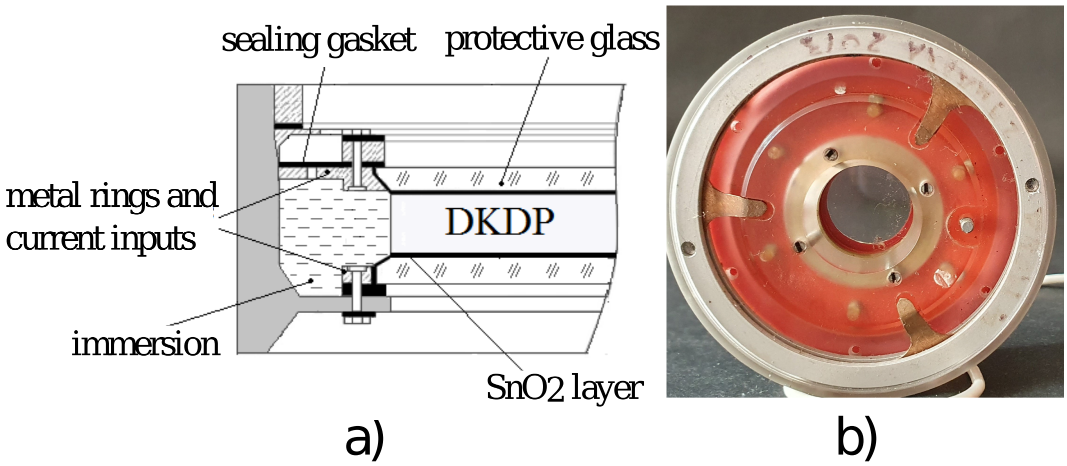

Fig. 2. Immersion EOM: a) scheme, b) external view.

become blurred in humid atmosphere; those having large expansion coefficient crack at small temperature variations; and there are those that decompose at temperatures ~150–200°C. The latter prevented applying conductive coatings and electrodes directly to the crystal.

The disadvantage of this design is the peeling of the conductive coating under the influence of vibrations from the piezoelectric effect, destruction of the compound, depressurization of the block and, as a consequence, electrical breakdown and crystal destruction (Fig. 1c; Markov et al., 1988).

In 1980, the modulator design was changed; namely, there was transition from rigid to elastic construction. The electro-optical crystal is placed in immersion between two protective glass plates with transparent conductive coatings (Fig. 2). Coatings, as before, were applied both to the inner surfaces of the plates and to the chamfers, to which metal conductive rings were mechanically pressed. To prevent immersion leakage, the rings were attached to the housing bearing elements through elastic gaskets. One ring with glass was fixed immovably in the housing, and rotation of the second ring changed the gap between the optical elements of the stack. The entire stack was sealed in the housing by the second ring gasket by using a pressure bushing. Using this technology, modulators with clear aperture of 20–40 mm were manufactured, as well as EOM with clear aperture of 100 mm, which consists of four DKDP plates with common conductive glasses. This modulator (Fig. 3) was intended for installation of a polarization-free refractor telescope before the objective (Grigoriev, Kobanov, 1980).

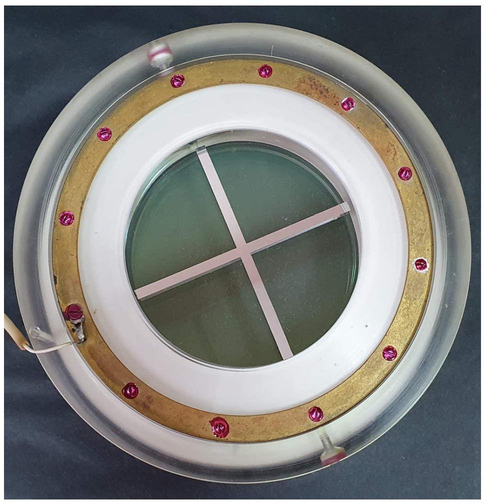

Fig. 3. Composite four-component EOM.

Modulators of this type worked well with sinusoidal voltage control, but when switching to code-pulse control (Stepanov et al., 1975; Grigoriev, Kobanov, 1980) and low modulation frequencies, the signal shape was distorted (Fig. 4). This disadvantage is associated with the polarizabil-

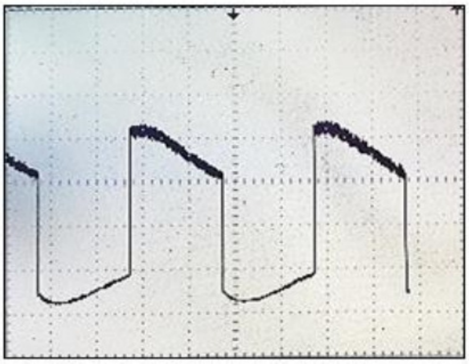

Fig. 4. Oscillogram of a modulator signal.

ity of the immersion layer separating the crystal surface and the conductive coating; there appears a discrepancy between the applied voltage and the acting field inside the crystal (Markov et al., 1988). With decreasing gap between the crystal and protective glasses with applied conductive coatings, this effect decreases but does not disappear.

3 Electro-optic modulators for magnetographs with code-pulse control

Since 2003, a transparent conductive layer of indium and tin oxides (ITO), instead of SnO_2, has started to be applied directly to the crystal surface in a vacuum chamber at room temperature by magnetron sputtering method (Borodin et al., 2003). High-voltage outputs were attached with conductive adhesive at one location of the transparent coating of the crystalline plate (Fig. 5).

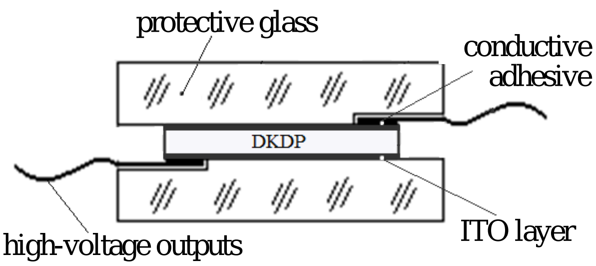

Fig. 5. Scheme of EOM with conductive coating on crystal.

Experiments confirmed that when electrodes are applied directly to the crystal surface, the immersion polarization effect is completely absent at all modulation frequencies, allowing operation in a wide frequency range. Figure 6 shows the oscillogram of a modulator signal with rectangular control voltage shape; there are no signal front distortions.

Despite the fact that in optic modulators the load is purely capacitive, the magnitude of supplied currents can become significant due to the steepness of the fronts, which are made as high as possible. Therefore, connecting current inputs at one point is undesirable, as this causes coating destruction due to significant current density at the point of contact

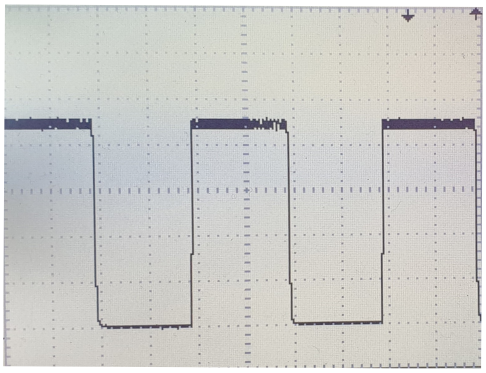

Fig. 6. Oscillogram of a modulator signal.

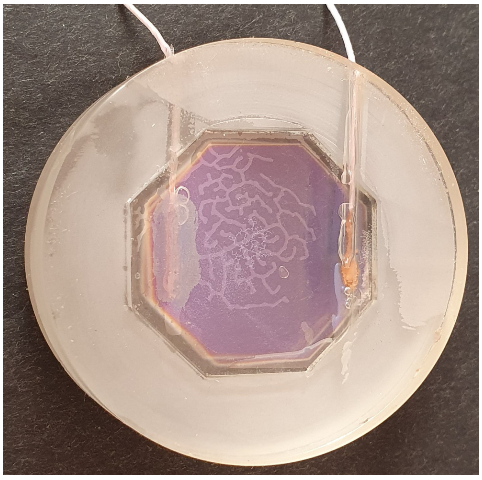

Fig. 7. Coating destruction in EOM.

(Fig. 7). To prevent this, since 2008, voltage has been supplied to the conductive layer of a round crystalline plate along the entire perimeter by metal rings, which are diffusely connected under pressure to the ITO layer by a thin indium ring (Fig. 8; Proshin et al., 2013).

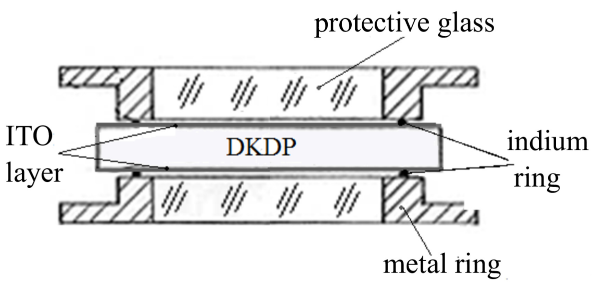

Fig. 8. Scheme of EOM with voltage supply through an indium ring.

Modulators operate in a wide frequency range based on rectangular pulses without wavefront distortion and birefringence across their entire aperture (Fig. 9). For the SOLSIT solar telescope (Demidov et al., 2018), such modulators were manufactured with clear aperture of 65 mm and thickness of

2 mm (Fig. 10). Crystal thickness determines the modulator's angular field, which increases with decreasing crystal thickness. Accordingly, the crystalline plate thickness is made minimal, about 2 mm, at which electrical breakdown of the plate does not yet occur from applied control voltage. During modulator manufacturing, the processing technology of water-soluble crystals was improved to increase surface cleanliness and reduce scattered light.

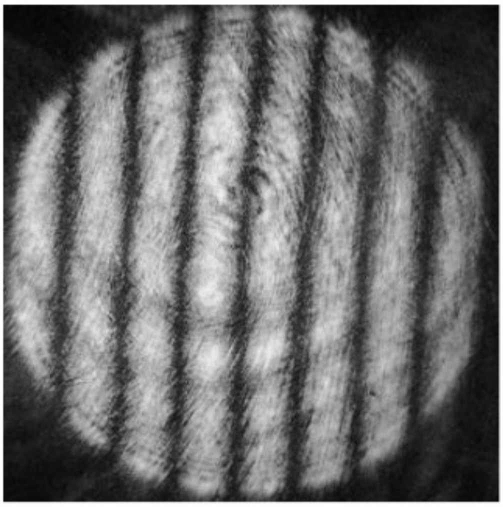

Fig. 9. Interferogram of the ∅50 mm modulator wavefront with applied voltage.

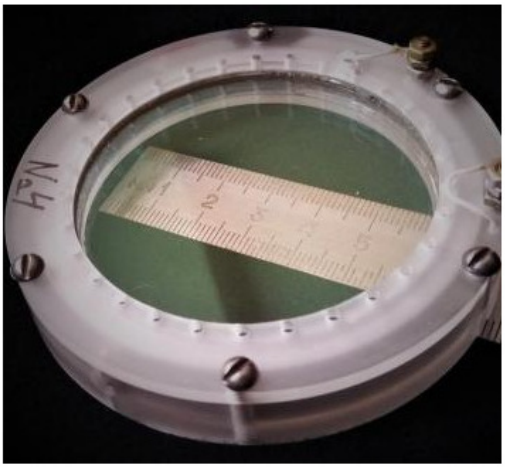

Fig. 10. Modulator for SOLSIT.

During long-term operation, defects began to appear in EOMs (Fig. 11), which cause light scattering and, consequently, reduction of useful signal. Destruction was found to occur not in the crystal itself but in the ITO conductive film. Defects can be divided into two types: destruction repeating crystal growth layers (Fig. 11a) and destruction in the form of islands of various shapes (Fig. 11b).

The cause of defect appearance may probably be crystallization of the amorphous ITO film on the crystalline substrate and destruction of the ITO film under the action of the piezoelectric effect, which is a feature of the electro-optical crystal. To prevent these defects, it is proposed to apply a transparent coating that is capable of protecting the DKDP crystal from moisture, while the subsequent ITO coating from crystallization and heteroepitaxial orientation of atoms of formed crystals and decomposition of the ITO coating into separate islands on the DKDP crystal surface.

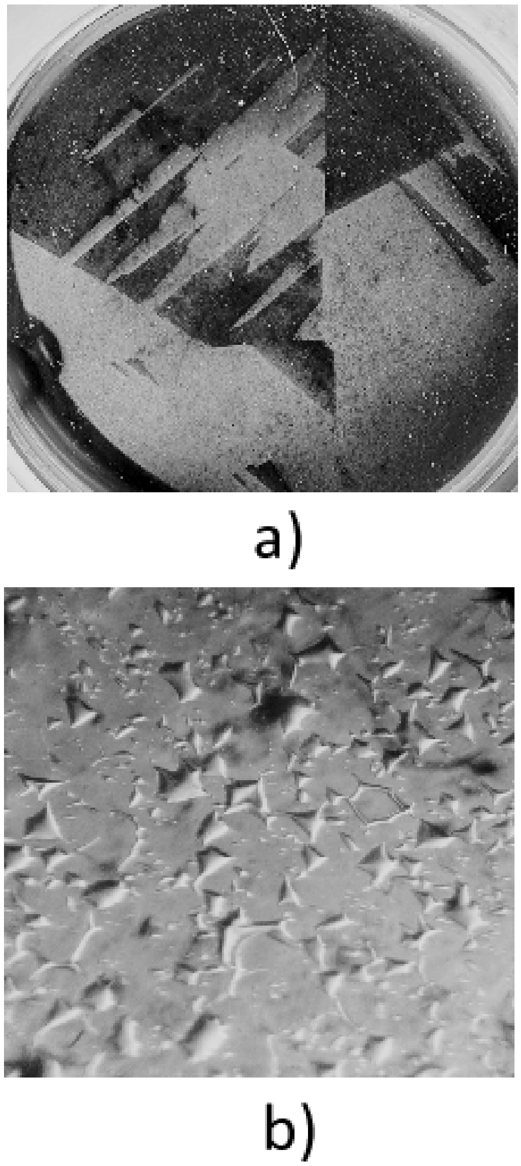

Fig. 11. Defects of the ITO film: a) destruction in the form of crystal growth layers, ∅50 mm modulator, without magnification; (b) destruction in the form of islands of various shapes, section of the ∅30 mm modulator, seven-fold magnification.

4 Conclusions

After creating the first full magnetic field vector magnetograph and starting regular observations, production of a small series of magnetographs was organized at the experimental plant of SB RAS. During 1965–1970, magnetographs were manufactured and delivered to foreign observatories

(Czechoslovakia and GDR), to USSR observatories (Abastumani Observatory, Astronomical Institute in Alma-Ata, Ussuri Astrophysical Observatory, Shemakha Astrophysical Observatory). These and all subsequent magnetographs for telescopes AST (Sayan Solar Observatory), STOP (Sayan Solar Observatory, Baikal Astrophysical Observatory, Ussuri Astrophysical Observatory, Kislovodsk Mountain Astronomical Station), SOLSIT (Baikal Astrophysical Observatory) were equipped with electro-optic modulators manufactured at ISTP. Modulator parameters allow conducting magnetographic observations at ambient temperatures from −25 to +30°C with thermal "shock" from heating in the solar beam and rapid cooling when the beam is removed from the modulator, as well as in high humidity conditions using high control voltage.

The experience accumulated at ISTP has allowed solving a number of technological issues aimed at improving EOM operational characteristics and creates a basis for developing EOMs for large solar telescopes.

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