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A test specimen of a two-channel polarimeter

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Abstract. A description of a two-channel polarimeter worked out and manufactured at SAO RAS is presented. We describe the way of polarization measurement, its theoretical justification, optical layout and electronic circuit, parameters of its principal components. The results of testing the polarimeter in observations of standard stars are also given.

Key words: telescopes — techniques: polarimetric

1. Introduction

At the present time polarization investigations of astrophysical objects arouse an extremely great interest. A knowledge of polarization complements significantly the available observational information, and in a number of cases it is decisive for understanding the processes occurring in the objects observed. That is why much importance has always been attached to polarimetric investigations and creation of present-day observing facilities at SAO RAS: a two-channel polarimeter has been developed and made, which measures quasisimultaneously the Stokes parameters in two spectral regions. The performance data of the device, its optical layout and electronic circuit and also the properties of the basic components are presented in the paper.

2. Polarization measurement procedure

The main principle used as the basis for polarization measurement with the given device implies that the light beam passes first through the phase shifting plate $\lambda/4$ with the azimuth of the fast axis equal to 0°, and then through an electrooptical modulator (EOM) oriented at 45° with respect to the azimuth of the fast axis. The modulator is fed with the voltage causing a phase shift of $+\lambda/4$, 0, $-\lambda/4$. This leads to a turn of the plane of polarized light transmission through 90°. Such an approach to measuring Q, U and V Stokes parameters was developed in the papers by Stepanov and Severny (1962); Kemp et al. (1972); Bukach et al. (1977); Kuvshinov and Levitan, (1983); Naidenov (1991, 1998). The procedure similar to that used by the above mentioned authors is implemented in our device. To describe it, we will make use of the apparatus of Müller matrices (Shurcliff, 1962) which describes the operation of any polarization measuring device by an actual matrix of 4×4 elements. The Stokes vector at the entrance and exit of the device can be described by simple multiplication of matrices. According to this, the input beam of light is described by the Stokes vector

$$M_1 = \begin{pmatrix} I \\ Q \\ U \\ V \end{pmatrix}. \qquad (1)$$

Let us denote the matrix of the entrance phase plate $\lambda/4$ with the fast axis oriented at 0° by M_2, the modulator matrix at a phase shift of +45° by M_3, 0° by M_4, −45° by M_5, the polaroid matrix by M_6, the entrance phase plate matrix with the fast axis oriented at 45° by M_7.

$$M_2 = \begin{pmatrix} 1 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & 0 & 1 \\ 0 & 0 & -1 & 0 \end{pmatrix}, \qquad (2)$$

$$M_3 = \begin{pmatrix} 1 & 0 & 0 & 0 \\ 0 & 0 & 0 & -1 \\ 0 & 0 & 1 & 0 \\ 0 & 1 & 0 & 0 \end{pmatrix}, \qquad (3)$$

$$M_4 = \begin{pmatrix} 1 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{pmatrix}, \qquad (4)$$

$$M_5 = \begin{pmatrix} 1 & 0 & 0 & 0 \\ 0 & 0 & 0 & 1 \\ 0 & 0 & 1 & 0 \\ 0 & -1 & 0 & 0 \end{pmatrix}, \qquad (5)$$

$$M_6 = \begin{pmatrix} 1 & 1 & 0 & 0 \\ 1 & 1 & 0 & 0 \\ 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 \end{pmatrix}, \qquad (6)$$

$$M_7 = \begin{pmatrix} 1 & 0 & 0 & 0 \\ 0 & 0 & 0 & -1 \\ 0 & 0 & 1 & 0 \\ 0 & 1 & 0 & 0 \end{pmatrix}. \quad (7)$$

When deriving I, Q, U parameters, multiply together the matrices for the phase shifts of the EOM+$\lambda/4$, 0, $-\lambda/4$ in the following manner:

$$I_1 = M_6 \times M_3 \times M_2 \times M_1, \quad (8)$$

$$I_2 = M_6 \times M_4 \times M_2 \times M_1, \quad (9)$$

$$I_3 = M_6 \times M_5 \times M_2 \times M_1, \text{obtain} \quad (10)$$

$$I_1 = 0.5 \cdot \begin{pmatrix} I-Q \\ I-Q \\ 0 \\ 0 \end{pmatrix}, \quad (11)$$

$$I_2 = 0.5 \begin{pmatrix} I+Q \\ I+Q \\ 0 \\ 0 \end{pmatrix}, \quad (12)$$

$$I_3 = 0.5 \begin{pmatrix} I+U \\ I+U \\ 0 \\ 0 \end{pmatrix}, \quad (13)$$

where I_1 is the intensity of radiation recorded by the light detector, when under the action of the voltage applied to the crystal of the EOM, a phase shift of $+\lambda/4$ takes place. I_2 is the intensity of radiation at a phase shift of the EOM equal to 0, and I_3 is the radiation intensity at a phase shift of the EOM of $-\lambda/4$. The parameters describing the linear polarization can be found from the expressions

$$Q = \frac{I_2 - I_1}{I_1 + I_2}, \quad (14)$$

$$U = \frac{2I_3 - I_1 - I_2}{I_1 + I_2}, \quad (15)$$

$$\Theta = 0.5 \arctan(U/Q), \quad (16)$$

$$P = \sqrt{U^2 + Q^2}. \quad (17)$$

For measuring Stokes parameters I, Q, V multiply together the matrices in the following way

$$I_1' = M_6 \times M_3 \times M_7 \times M_1, \quad (18)$$

$$I_2' = M_6 \times M_4 \times M_7 \times M_1, \quad (19)$$

$$I_3' = M_6 \times M_5 \times M_7 \times M_1. \quad (20)$$

Stokes parameters Q and V are derived from expressions (14) and (15) with the plate $\lambda/4$ withdrawn from the light beam, having substituted I_1', I_2', I_3' for I_1, I_2, I_3.

3. The design of the polarimeter

3.1. The optical layout

The optical arrangement of the instrument displayed in Fig. 1 is in many respects typical of polarimeters, however, some innovations are incorporated. The chief difference consists in the application of a new method of modulation. The novelty is that a quarter-wave $\lambda/4$ achromatic phase shifting plate is inserted in the beam of light in front of the electrooptical modulator. Thus, to obtain the whole set of phase shifts, the EOM must provide sequentially the phase shifts $+\lambda/4$, 0, $-\lambda/4$. To obtain such shifts is much more simple than the phase shifts $\lambda/2$.

A second distinguishing feature is the location of the light filters. These are placed in front of the photoelectric multiplier (PEM) in a parallel beam of light behind the Fabry lens, which enables synchronous measurements in two spectral ranges extracted by the appropriate light filters. Such variants of observations may be of interest in performing some astrophysical tasks.

A third distinguishing characteristic of the device is that the Wollaston prism used in the polarimeter has been made thin. Its total thickness is only 5 mm, and the refraction angle is 9.5°. The advantages of such a prism are evident; these are the small light losses, the absence of chromatic effects in beams of different polarization. The demerit of such a prism is that the angle of beam divergency is as small as 3.3°. For technical reasons (sizes of the PEM sockets) the spatial divergence of the beams need to be increased at the shortest distance from the Wollaston prism. A mirror wedge decreases considerably this distance through decreasing of the beam divergence angle and therefore diminishes the size of the instrument. This approach reduces the light losses at the same time.

The polarimeter was built to be used at the Cassegrain foci of the 1 m and 0.6 m telescopes with an aperture of 1:12.5 or close to it. All optical units are mounted on a panel inside the casing of the apparatus. A set of circular diaphragms is located in the focus. The aperture diameters are 0.13, 0.27, 0.4 and 0.67 mm which corresponds to 2, 4, 6, 10 arcseconds for the 1 m telescope, and 3.6, 7.5, 11.0, 18.5 for the 0.6 m telescope. During the pointing to an object and also for checking the position of the object in observations, viewing of the field is introduced. A collimating lens that transforms the diverging beam of light into a parallel one is placed behind the diaphragms. The collimating lens is followed by a quarter-wave achromatic phase-shifting plate $\lambda/4$. A mechanical unit, which inserts the phase-shifting plate $\lambda/4$ into the beam of light and withdraws it from the latter, is shown in Fig. 1. Lenear polarization measurements according to expressions (8–17) are made with the

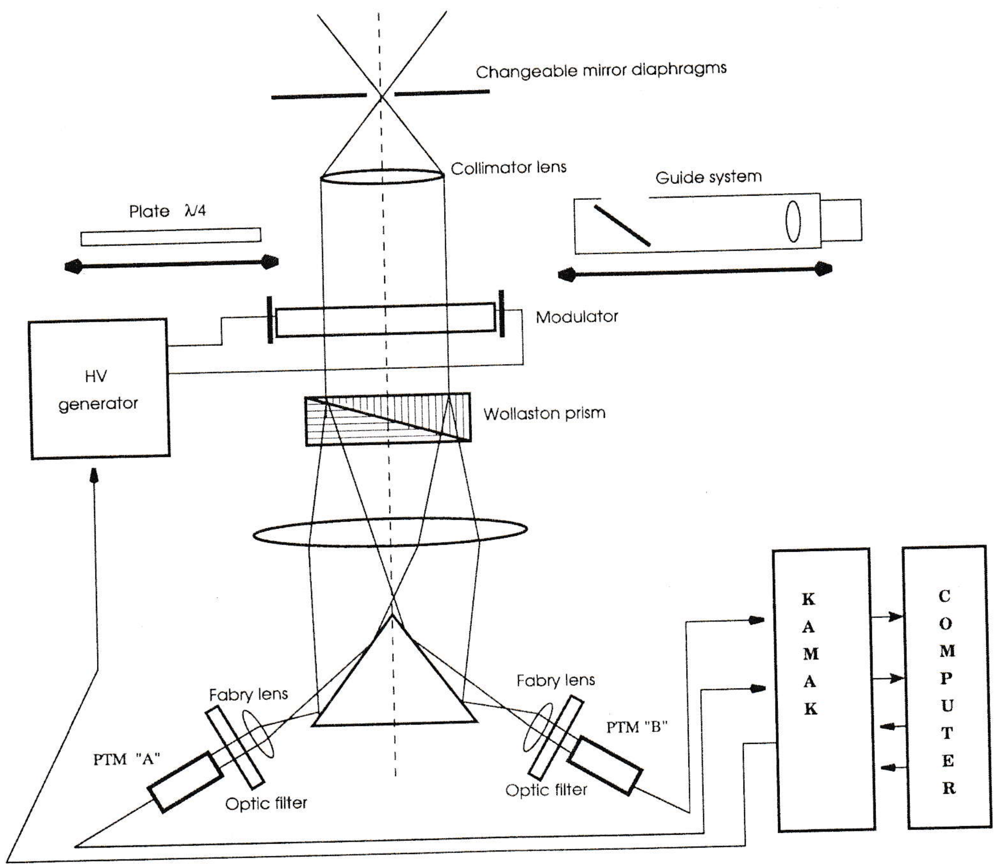

Figure 1: *A Block-diagram of the two-channel polarimeter.*

plate $\lambda/4$ inserted into the beam. Circular polarization measurements in accordance with expressions (18–20) are made when the plate $\lambda/4$ is withdrawn from the beam of light. Next is the active optical unit — the modulator which represents a flat parallel crystal DKDP and a Wollaston prism intended for spatial divergence of the orthogonally polarized light beams. The exit lens serves for conversion of the parallel beams of light to converging ones. The mirror prism (the wedge) is meant to increase the spatial separation of the beams of light. Behind the Fabry lenses, which form the telescope entrance pupil image on the PEM photocathodes, the light filters are placed in the parallel light beam (Fig. 1).

3.2. Electronic equipment

The electronic equipment of the polarimeter consists of the following units:

- Pulse-forming amplifiers of the PEM channels are incorporated in one unit which is mounted on the polarimeter casing. They are designed to amplify and transmit electric pulses arriving from the PEM via a long cable to the acquisition system which is situated in the control room together with the control computer.
- A high voltage pulse power source for EOM is attached to the polarimeter housing near EOM. The pulse source produces special shape pulses for the EOM under control of electric signals arriving from the data acquisition system.
- The data acquisition system is located in the operating room near the control computer which is intended to control the data acquisition process and the polarimeter operation.

The block diagram of the electronic equipment mounted on the polarimeter is shown in Fig. 2. It includes two units which are mounted on the polarimeter casing, i.e. near the light detectors: amplifiers that form pulses arriving from the PEM and a high-voltage electronic-and-optical voltage modulator.

Amplifier-formers

The intensity of the light flux that has passed the polarimeter optics is recorded with two PEMs in two light ranges cut out by light filters. The recorded photons are accumulated in four counters sequentially during the exposure, depending on the voltage sup-

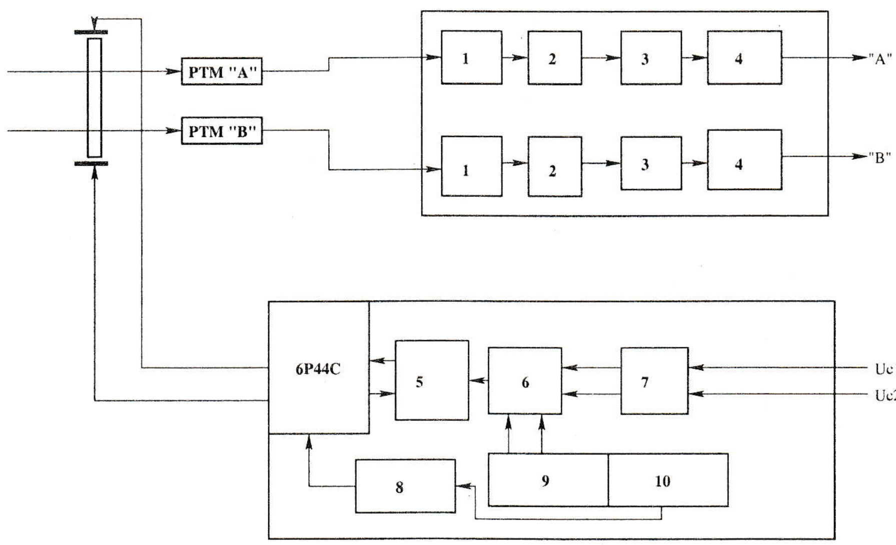

Figure 2: *Electronic circuit of the two-channel polarimeter. 1 – 4 are components of the two-channel preamplifier. 5 – 10 are components of the high-voltage modulator.*

Table 1:

	Parameter
Sensitivity	$2 \cdot 10^{-3} v$
Halfwidth of the output pulse	40 ns
Amplitude of the output pulse	5 v
Feed voltage	6 v

plied to the EOM. In accordance with expressions (14–20), this allows the Stokes parameters to be determined. The pulse-forming amplifiers of the "red" and "blue" channels (respectively "A" and "B" (1) in Fig. 2) have the same circuit, are made on basis of modern integral microcircuits, have high stability, sensitivity, protection against interferences, and are very identical in parameters. This is a circuit with stable feedbacks, it provides amplification coefficient stability and minor intrinsic input noises, which do not exceed $0.3\mu v$. The fundamental parameters of the amplifiers are presented in Table 1.

Signals amplified in (1) (Fig. 2) come to the two-stage commutator (2) and next to the output signal former (4) through the delay line (3). The lower threshold of the discriminator is set to be higher than the amplification circuit noise amplitude and can be adjusted in the process of preparation and balancing of the equipment. The upper threshold of the discriminator is fixed. The signals arriving from the PEM, the amplitude of which is higher than the upper threshold of the discriminator, are rejected. The output signal former standardizes the pulses in length and contains a powerful stage to operate for a long coaxial line.

The high-voltage electronic-and-optical modulator

The phase shift in the beam of light depends on the voltage applied to the crystal DKDP. The voltage is generated and supplied from a controlled high-voltage source. The requirements placed upon this source are rather discrepant and stringent: on the one hand, it has to produce rapid voltage variation by values of about 2–4 kilovolts, on the other hand, it is to maintain a specified voltage with a precision no worse than 1% during data acquisition. The quests for the solution of this problem led to a development of highly efficient and compact device incorporating a powerful electronic valve 6P44C instead of the bulky transformer devices. Fig. 3 shows oscillograms formed with the high-voltage modulator and also their consistency with the phase shift of the radiation that passed through the modulator. High-voltage pulses are formed depending on the control voltage which is generated by way of superposition of two gating series of pulses, Uc1 and Uc2, that arrive from the polarimetric data acquisition system. The pulse duration of one series is $1\mu s$, that of the other series is $0.5\mu s$. The formed high voltage supplied to the EOM depends on the sum of logic levels of the two pulses of the gating series Uc1 and Uc2 at every time moment in accordance with the data of Table 2.

Uc1 and Uc2 pulses come to the input of the trigger (7) in Fig. 2. The trigger controls operation of the unit forming stepwise pulses with microsecond fronts (6). These pulses are intensified by the amplifier (5) and come to the grid of the 6P44C valve in the anode circuit of which high-voltage pulses with desired parameters do form. Apart from the trigger, the oper-

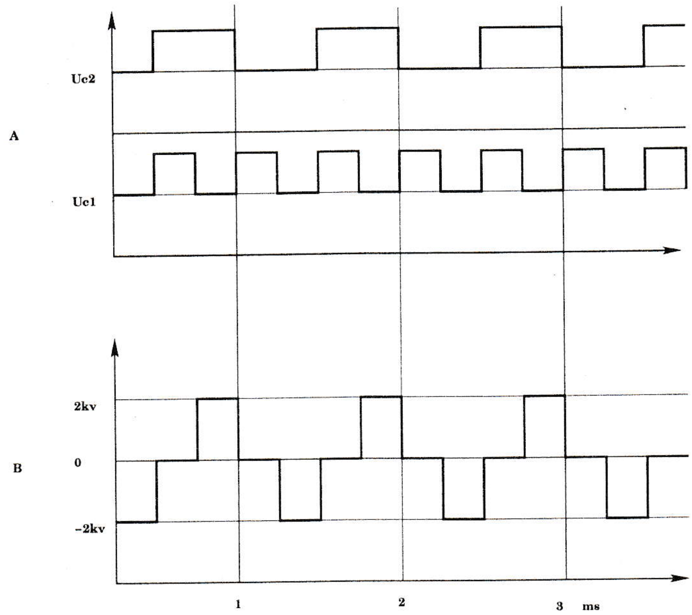

Figure 3: *Oscillograms of control voltages of the EOM (I) and of high voltage coming to the EOM (II).*

Table 2:

Uc1	Uc2	$U(kV)$
0	0	- 2
1	1	0
1	0	+ 2
0	1	0

ation of the unit (6) is provided by the current generator (9) connected to the power supply unit (10). This unit maintains in operation the high-voltage power source of the valve (8). It should be noted that the application of pulses of so high voltage with very steep fronts required additional measures to be taken to insulate the crystal DKDP from the housing of the device to exclude electric break-through, otherwise the high-voltage modulator would fail and the crystal be ruined; either constitutes a serious hazard to the observer.

The data acquisition system is exibited in Fig. 4 and incorporates a number of electronic units made to comply with the KAMAK standard. This equipment consists of both the standard units and a device designed and placed in service especially for operating with this apparatus.

Pulses arriving from the PEM "A" and "B" are transmitted by amplifier-formers to the buffer (1) over a long coaxial cable of the data acquisition system. The buffer is designed for protection against interferences and electric "induction" arising in the long cable transmitting the signal. Next, the "cleaned" and standardized signals are received by the input register of the demultiplexer (2). The demultiplexer switches to the flux of pulses, coming from the PEM, one of the four registers of the 16-digit counters. The counters are installed in the KAMAK crate and are labled (3) — (6) in Fig. 4, depending on the voltage supplied to the EOM, which corresponds to different phase shifts in the beam of light. The operation of this unit, as well as the operation of the EOM is controlled by a clock generating two series of synchropulses Uc1 and Uc2 (see Fig. 3) with TTL parameters and a frequency of 100 (or 200) Hz. Accumulation of photocounts occurs only at the time when the voltage of the EOM settles at a specified value and ends before the voltage starts to change, that is the influence of transition processes is completely excluded. The capacity of the counters was found from the value of a maximum permissible flux of 100000 pulses/s. The photocounts accumulated in these counters correspond thus to the light fluxes that have passed through the EOM at different phase shifts of the modulator. Analysis of the ratios of the values of these fluxes according to formulae (14–20) makes it possible to compute both the 4 Stokes parameters and the angle corresponding to the position of the plane of oscillations of the electric vector of radiation with respect to the meridian (position angle). All electronic units, the pulse flux counters of the channels "A" and "B", high-voltage feed sources of the PEM, etc are made to conform to the KAMAK standard, including the crate controller

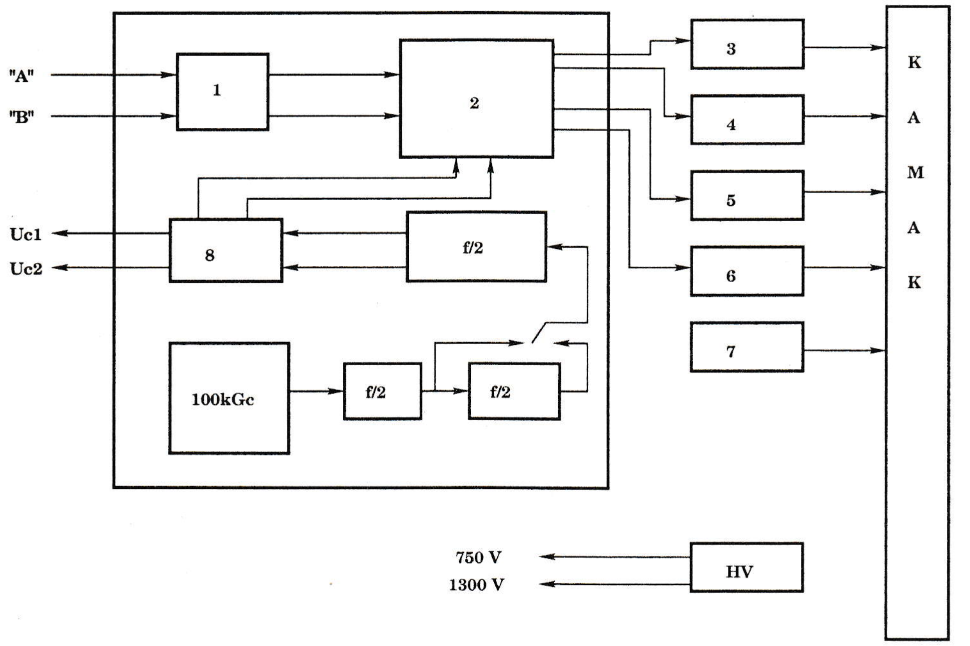

Figure 4: *Data acquisition system diagram. 1 — buffer, 2 — demultiplexer, 3–6 — 16-digit counters, 7 — KAMAK controller, 8 — amplifier.*

that connects KAMAK to the control computer IBM PC/AT.

PEMs of types FW-130 (channel A) and EMI-9789 A (channel B) are used in the polarimeter as light detectors. The actual quantum efficiency of both PEMs was estimated by way of comparing their counts with those of the template detector PEM-106 E395 from the photometric installation of SAO RAS (Debur, 1998) calibrated at the State Standard. The quantum efficiency of the employed PEMs determined by Debur (1999) is presented in Fig. 5. The "A" channel PEM, FW-130, has a comparatively higher sensitivity in the region from 600 to 700 nm; for this reason it operates in the red spectrum region. It has also a higher quantum efficiency as compared to EMI-9789 A which is used in the blue region (see Fig. 5). Determination of the optimum supply voltage of the PEMs was carried out by Debur (1998). The optimum voltage for the PEM EMI 9789 A is about 750 v. With this voltage the "dark" current is 80 pulses/s at a temperature of 24° C and for the PEM of type FW-130, the optimum voltage is 1300–1400 v, and the "dark" current is 280 pulses/s, respectively. The dependence of the S/N ratio on voltage for this type of PEM is slighter than for the EMI-9789 A PEM.

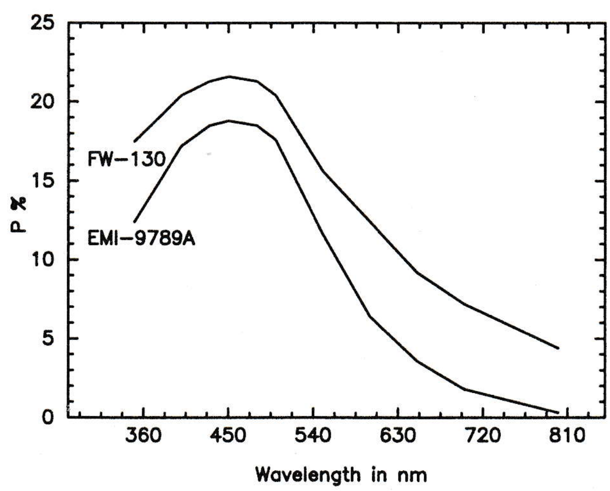

Figure 5: *Quantum efficiency of the PEM vrs wavelength.*

4. Test results

Trial observations with the two-channel polarimeter were made in 2000 August using standards of zero and nonzero polarization. Stars of the 3rd to 7th stellar magnitudes were selected. The main aim of the trial observations was to show the capability of the proposed polarimeter circuit in the investigation of radiation polarization. The measurements were made of linear polarization only, because they were obvious to suffice for testing the apparatus. The results of observations are collected in Table 3. It should be noted that the linear polarization was defined by a standard method, i.e. as a result of vector subtraction of the background polarization value from the observed object. Together with the value of the measured polarization, the values of errors and of the S/N

Table 3:

Object	m_v	P(A)%	ΔP(A)%	Θ(A)	P(B)%	ΔP(B)%	Θ(B)	P%tabl.	Θtabl.	Object/background
β Cas	2.27	0.014	0.015		0.025	0.019		0.015±0.027		51
ξ Peg	3.4	0.035	0.019		0.025	0.18		0.028±0.019		49
HD187929	3.8	1.511	0.18	87.61	2.1	0.195	89.51	1.8±0.001	98	45
HD198478	4.9	2.547	0.275	2.85	3.224	0.29	7.68	2.8±0.001	3	42
ϕ Cas	5	4.99	0.32	83.48	4.07	0.34	89.39	3.4±0.001	94	33
HD154445	5.61	4.123	0.35	86.9	2.49	0.39	87.74	3.8±0.075	88	21
HD183143	6.9	5.5	0.55	0.52	0.53	0.54	0.56	6.1±0.001	0	9.1

The results of testing of the two-channel polarimeter by standard stars of zero and nonzero polarization P(A) and P(B) — polarizations found via expression 17 from the measured Stokes parameters Q and U. ΔP(A), ΔP(B) — are the measurement errors, Θ is the position angle.

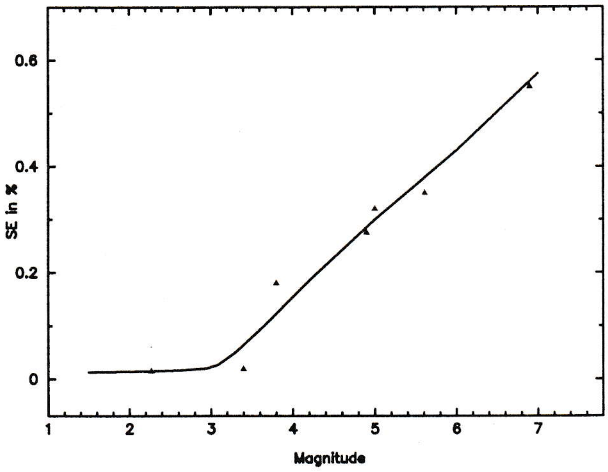

Figure 6: *Measurement accuracy (standard error SE) against stellar magnitude.*

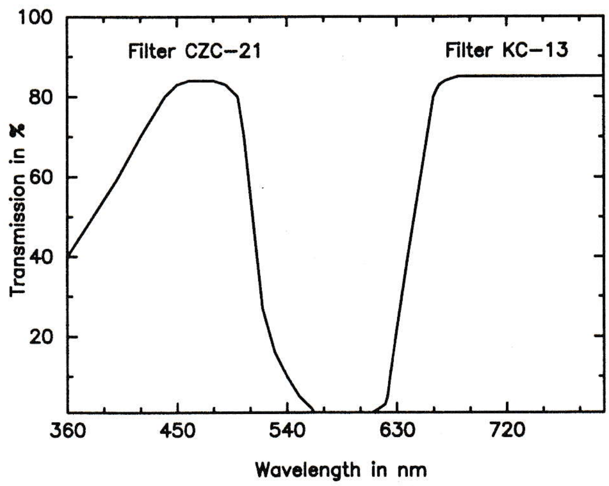

Figure 7: *Light filter transmission curves.*

ratio are presented. Fig. 6 shows the relation between measurement accuracy (standard errors) and stellar magnitude.

The discrepancy between the measured polarization values and the values borrowed from Turnsnek et al. (1990) is most likely to be due to the fact that the measurements were made in noncoincident regions. The characteristics of the filters used in the device are shown in Fig. 7. It might also be well to point out that all the data were obtained at exposures of 10 minutes and were mostly of test character.

5. Conclusions

The two-channel polarimeter created at SAO RAS can measure reliably polarization of stellar objects. It is shown that the novel units incorporated in the polarimeter are quite serviceable and their approach can be employed in working out other devices of this kind. When further upgraded, it can be made portable, convenient for use at other telescopes and in expeditions. A small-size data acquisition system, which will rule out the employment of the heavy KAMAK facilities, is being worked out at present.

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