# Real-Time Polarimetry of the Solar Atmosphere Based on Dual DKDP Crystals (Postprint)

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## Abstract

Magnetic fields constitute the fundamental driving force of solar eruptive activities, and high-precision real-time polarimetric measurement represents a commonly employed approach for magnetic field diagnostics. However, conventional waveplate-based measurement methodologies necessitate multiple acquisitions and incorporate mechanical rotational structures, which are prone to inducing instrument jitter and degrading measurement precision; furthermore, waveplate rotation or mechanical switching substantially increases measurement duration. Presently, solar atmospheric polarimetry based on DKDP crystals and waveplates suffers from prolonged measurement cycles and inadequate real-time performance, rendering it unsuitable for magnetic field detection of rapidly evolving solar phenomena. Motivated by these limitations, this paper proposes a real-time solar atmospheric polarization detection technique founded on the dual-DKDP crystal principle, which utilizes two DKDP crystals with distinct fast-axis orientations to achieve rapid phase retardation variations through the application of different external voltages, thereby effecting polarization modulation of incident solar radiation and acquiring the Stokes vector of solar atmospheric polarization. Compared with conventional methodologies combining rotating waveplates and DKDP crystals, the proposed approach can enhance the single-shot polarization modulation rate from several seconds to the millisecond regime, substantially improving the real-time capability of solar magnetic field measurements. Simulation analysis results demonstrate that the proposed method achieves a measurement accuracy of $2 \times 10^{-3}$, improves the temporal resolution at individual wavelength points by over 20-fold, and enables real-time and accurate measurement of solar magnetic field polarization information.

# Full Text

## Preamble

### Real-Time Polarization Detection Technology for Solar Atmosphere Based on Double DKDP Crystals Principle

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## Abstract

Magnetic fields are the fundamental driving force behind solar eruptions, and high-precision real-time polarization measurement is a common method for magnetic field detection. However, conventional wave-plate-based measurement methods require multiple measurements and involve mechanical rotation structures that can cause instrument jitter and degrade measurement accuracy. The rotation or switching of wave plates also leads to long measurement times. Currently, solar atmospheric polarization measurement systems based on DKDP crystals and wave plates suffer from long measurement cycles and poor real-time performance, making them unsuitable for detecting rapidly changing magnetic fields in solar active regions. To address these limitations, this paper proposes a real-time polarization detection technology for the solar atmosphere based on the principle of double DKDP crystals. The method employs two DKDP crystals with different fast-axis orientations, using externally applied voltages to achieve rapid phase retardation changes for polarization modulation of incident sunlight, thereby obtaining the Stokes polarization vector of the solar atmosphere. Compared with traditional methods combining rotating wave plates and DKDP crystals, the proposed approach can increase the single polarization modulation rate from several seconds to the millisecond level, dramatically improving the real-time capability of solar magnetic field measurements. Simulation results demonstrate that the proposed method achieves a measurement accuracy of 2 $\times 10^{-3}$ and improves the temporal resolution of single-wavelength-point measurements by more than 20 times, enabling real-time accurate measurement of solar magnetic field polarization information.

**Keywords:** Solar magnetic field; Polarization measurement; DKDP; Real-time measurement

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# 1 Principle and Method

The polarization information of light can be represented by the electric vector, Jones vector, and Stokes vector. While the electric vector and Jones vector can only describe fully polarized light, the Stokes vector uses four intensity parameters to represent light of any polarization state. Therefore, this paper adopts the Stokes vector to represent the polarization state of the measured light. The specific expression of the Stokes vector S is:

$$S = [I, Q, U, V]^T$$

where: - $I = \langle E_{xE}x^* + E_{yE}y^* \rangle$ represents the total intensity of the light wave - $Q = \langle E_{xE}x^* - E_{yE}y^* \rangle$ represents the intensity difference between X and Y components after decomposing the light along the X and Y directions - $U = \langle E_{xE}y^* + E_{yE}x^* \rangle = 2E_{xE}y\cos\delta$ represents the intensity difference between 45° and 135° components after decomposition, where $\delta = \varphi_y - \varphi_x$ denotes the phase difference between X and Y components - $V = -i\langle E_{xE}y^* - E_{yE}x^* \rangle = 2E_{xE}y\sin\delta$ represents the intensity difference between right- and left-circular components, characterizing the circular polarization properties

Both Q and U describe the linear polarization characteristics of the light wave, while V represents its circular polarization characteristics.

## 1.1 Traditional Wave Plate and DKDP Crystal Modulation Method

Traditional polarization measurement schemes employ a $\lambda/4$ wave plate and DKDP crystal as polarization modulation devices, requiring six modulations to obtain six intensity values for a complete Stokes vector measurement. In this scheme, the DKDP crystal fast axis is oriented at 45°, and the polarizer transmission axis is at 0°.

[Figure 1: see original paper] Schematic diagram of traditional $\lambda/4$ wave plate + DKDP polarization analyzer

For longitudinal magnetic field measurements, the quarter-wave plate is removed from the optical path, and rectangular high voltages of opposite polarity are applied to the DKDP crystal to modulate the phase retardation between $\pm\lambda/4$. This allows left- and right-circularly polarized light to alternately pass through the analyzer, enabling extraction of the Stokes V signal from their difference. For transverse magnetic field measurements, the quarter-wave plate is inserted into the optical path with its optical axis oriented at 0°, and rectangular high voltages are applied to the DKDP crystal. This causes linearly polarized light with azimuth angles of 0° and 90° to alternately pass through the analyzer, yielding the Stokes U signal from their difference. By adjusting the quarter-wave plate axis to 45° and applying rectangular high voltages, linearly polarized light at 45° and 135° alternately passes through, and the Q signal is obtained from their difference.

The modulation parameters of the polarization analyzer are summarized below:

$\lambda/4$ wave plate + DKDP polarization modulation parameters

| $\lambda/4$ wave plate | DKDP crystal | Polarizer | Measurement result |
|---|---|---|---|
| Out of path | $\pm\lambda/4$ | 0° | $I_1 = I + Q$ |
| | | | $I_2 = I - Q$ |
| 0° | $\pm\lambda/4$ | 0° | $I_3 = I + U$ |
| | | | $I_4 = I - U$ |
| 45° | $\pm\lambda/4$ | 0° | $I_5 = I + V$ |
| | | | $I_6 = I - V$ |

In this scheme, the quarter-wave plate switching time is on the order of seconds, and measuring a single wavelength point requires acquiring six intensity images with three quarter-wave plate switches. In solar magnetic field measurements, multi-wavelength-point measurements are generally preferred over single-wavelength-point measurements to avoid effects from saturation-induced nonlinearity, Doppler shifts, and Faraday rotation. Typically, six wavelength points across the spectral line profile are selected, making a complete spectral measurement require at least 36 image acquisitions.

### 1.2 Double DKDP Crystal Modulation Method

When the polarization state of light is represented by the Stokes vector S, the effect of a transmission medium on the light's polarization state can be described by a Mueller matrix M. After passing through n transmission media sequentially, the Stokes vector becomes:

$$S' = M_{nM_{n-1}} \cdots M_{2M_{1S}} \tag{2}$$

The principle of polarization measurement is illustrated below:

[Figure 2: see original paper] Polarization measurement principle diagram

A polarimeter typically consists of a polarization modulator and an intensity detector. For an incident polarized light with unknown Stokes vector S, after passing through modulation state a, its Stokes vector becomes $S_a = [I_a, Q_a, U_a, V_a]^T$, with the corresponding Mueller matrix $M_a$:

$$M_a = \begin{bmatrix} a_{11} & a_{12} & a_{13} & a_{14} \\ a_{21} & a_{22} & a_{23} & a_{24} \\ a_{31} & a_{32} & a_{33} & a_{34} \\ a_{41} & a_{42} & a_{43} & a_{44} \end{bmatrix} \tag{3}$$

Since intensity detectors can only measure light intensity (the I value), we have:

$$I_a = a_{11}I + a_{12}Q + a_{13}U + a_{14}V \tag{4}$$

After four different modulation states (a, b, c, d), four intensity values are obtained:

$$\begin{bmatrix} I_a \\ I_b \\ I_c \\ I_d \end{bmatrix} = \begin{bmatrix} a_{11} & a_{12} & a_{13} & a_{14} \\ b_{11} & b_{12} & b_{13} & b_{14} \\ c_{11} & c_{12} & c_{13} & c_{14} \\ d_{11} & d_{12} & d_{13} & d_{14} \end{bmatrix} \begin{bmatrix} I \\ Q \\ U \\ V \end{bmatrix} \tag{5}$$

Denoting this as $I_m = XS$, when the modulation matrix X is invertible, the equation has a unique solution, and the Stokes vector of the unknown light is:

$$S = X^{-1}I \tag{6}$$

We propose a polarization measurement method based on double DKDP crystals, as shown in Figure 3. The polarization modulator of this analyzer consists of two DKDP crystals with different fast-axis orientations and a polarizer, with a light intensity acquisition camera serving as the detector.

[Figure 3: see original paper] Schematic diagram of the structure of the polarization analyzer based on DKDP

Assuming the incident light has Stokes vector $S_{in}$:

$$S_{in} = [I, Q, U, V]^T \tag{7}$$

After passing through the polarization modulator, the Stokes vector becomes $S_{out}$:

$$S_{out} = M_p \cdot M_2 \cdot M_1 \cdot S_{in} \tag{8}$$

where $M_1$, $M_2$, and $M_p$ are the Mueller matrices of the first DKDP crystal, second DKDP crystal, and analyzer (polarizer), respectively.

Let DKDP1 have a fast-axis angle of 0° and phase retardation $\delta$, DKDP2 have a fast-axis angle of 45° and phase retardation  , and the polarizer transmission axis be at 0°. The polarizer's orientation angle is related to the Cartesian coordinate system selection; for convenience, we set the polarizer's transmission direction as the X-axis of the coordinate system. The Mueller matrices are:

$$M_1 = \begin{bmatrix} 1 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & \cos\delta & -\sin\delta \\ 0 & 0 & \sin\delta & \cos\delta \end{bmatrix} \tag{9}$$

$$M_2 = \begin{bmatrix} 1 & 0 & 0 & 0 \\ 0 & \cos\varepsilon & 0 & \sin\varepsilon \\ 0 & 0 & 1 & 0 \\ 0 & -\sin\varepsilon & 0 & \cos\varepsilon \end{bmatrix} \tag{10}$$

$$M_p = 0.5 \begin{bmatrix} 1 & 1 & 0 & 0 \\ 1 & 1 & 0 & 0 \\ 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 \end{bmatrix} \tag{11}$$

The resulting Stokes vector after the polarization analyzer is:

$$S_{out} = [I_{out}, Q_{out}, U_{out}, V_{out}]^T = M_p \cdot M_2 \cdot M_1 \cdot S_{in} \tag{12}$$

The intensity detected by the light detector is:

$$I = 0.5(I + Q\cos\varepsilon + U\sin\varepsilon\sin\delta - V\sin\varepsilon\cos\delta) \tag{13}$$

By changing the applied voltages to the two DKDP crystals, four different polarization modulation states are obtained, and the intensity detector measures four different intensity values $I_{out} = [I_1, I_2, I_3, I_4]^T$. Since only relative Stokes vector values are typically needed, the 0.5 factor can be omitted, yielding the polarization modulation matrix:

$$X = \begin{bmatrix} 1 & \cos\varepsilon_1 & \sin\varepsilon_1\sin\delta_1 & -\sin\varepsilon_1\cos\delta_1 \\ 1 & \cos\varepsilon_2 & \sin\varepsilon_2\sin\delta_2 & -\sin\varepsilon_2\cos\delta_2 \\ 1 & \cos\varepsilon_3 & \sin\varepsilon_3\sin\delta_3 & -\sin\varepsilon_3\cos\delta_3 \\ 1 & \cos\varepsilon_4 & \sin\varepsilon_4\sin\delta_4 & -\sin\varepsilon_4\cos\delta_4 \end{bmatrix} \tag{14}$$

Thus, $I_{out} = 0.5X \cdot S_{in}$. When the polarization modulation matrix X is invertible, we obtain:

$$S_{in} = 2X^{-1}I_{out} \tag{15}$$

where $S_{in}$ is the Stokes vector of the light to be measured.

## 2 Parameter Optimization Design

During polarization measurement, accuracy is affected by errors in the polarization modulator's modulation matrix and the intensity detector's measurement errors. Different selections of polarization modulation matrix parameters influence error propagation differently. While ensuring the invertibility of the polarization modulation matrix, appropriate parameter selection can significantly reduce the impact of noise disturbances and systematic errors on measurement results. Here, we consider only intensity detector errors as an example.

Let $I'$ be the measured intensity value, $I$ the true intensity value, $S'$ the calculated Stokes vector, and $S$ the true value. The intensity error is $\Delta I = I' - I$, and the Stokes vector error is:

$$\Delta S = S' - S = X^{-1}I' - S = X^{-1}(I + \Delta I) - S = X^{-1}\Delta I$$

From $I = XS$, we have:

$$\|I\| = \|XS\| \le \|X\|\|S\|$$

$$\|\Delta S\| = \|X^{-1}\Delta I\| \le \|X^{-1}\|\|\Delta I\|$$

This gives the upper bound of relative error $\|\Delta S\|/\|S\|$, showing that intensity detector errors may be amplified by $\|X^{-1}\|\|X\|$ times during solution. Polarization modulation matrix errors follow the same principle, though the derivation is omitted here. The quantity $\mathrm{cond}(X) = \|X^{-1}\|\|X\|$ is typically called the condition number (CN) of matrix X. A smaller condition number results in less error amplification during matrix equation solving. According to research and simulation verification, the minimum condition number for full Stokes vector measurement is $\sqrt{3}$. Therefore, when the modulation matrix condition number equals $\sqrt{3}$, the polarization modulation parameters are optimal.

The polarization modulation matrix is given by equation (14). Using the faster quasi-Newton algorithm, the optimization is achieved by minimizing the CN of matrix X. The quasi-Newton algorithm is an effective and mature method for solving unconstrained optimization problems. Compared with the Newton algorithm, it only requires the objective function to be continuously differentiable once, making it easy to implement with low computational cost. Typically, there are infinite solutions achieving the same optimal CN, all providing identical performance for polarization measurement. Here, we select one representative parameter set:

Parameters of polarization modulation scheme

| DKDP1 delay (rad) | DKDP2 delay (rad) | Polarizer angle |
| --- | --- | --- |
| 0 | $2\pi/3$ | 0° |
| $\pi/2$ | $2\pi/3$ | 0° |
| 0 | $4\pi/3$ | 0° |
| $\pi/2$ | $4\pi/3$ | 0° |

The resulting polarization modulation matrix is:

$$X_{CN} = \begin{bmatrix} 1 & -0.5773 & -0.5774 & -0.5774 \\ 1 & -0.5773 & 0.5773 & 0.5773 \\ 1 & -0.5774 & -0.5774 & 0.5774 \\ 1 & -0.5774 & 0.5774 & -0.5774 \end{bmatrix}$$

With this matrix, error amplification during solution is minimized.

Additionally, the equally weighted variance (EWV) of the polarization modulation matrix is another standard for evaluating error propagation, though EWV values are primarily influenced by data redundancy. The new measurement scheme proposed here is applicable only to extremely narrow bandwidth ($\Delta\lambda \leq 0.1$Å) scenarios, typically used in conjunction with filters where spectral dispersion issues can be neglected, so polarization measurement efficiency is not considered. The DKDP crystals used in this work have a transmission range of 200–2150 nm, with transmittance reaching 97% at the target wavelength of 532.4 nm.

## 3 Simulation Analysis and Verification

Traditional wave-plate-plus-DKDP polarization analyzers typically employ a six-modulation measurement scheme. Due to the presence of redundant terms, their accuracy is slightly better than a four-modulation scheme under equivalent conditions (CN = $\sqrt{3}$). Here, we compare the accuracy difference between the two schemes and verify whether the proposed DKDP polarization analyzer meets measurement requirements. The required solar polarization measurement accuracy is $2 \times 10^{-3}$. Since the extinction ratio error of commonly available polarizers is approximately $10^{-6} - 10^{-4}$, the resulting measurement error is negligible. Therefore, we compare the effects of intensity detector errors, DKDP phase retardation errors, and angular errors of DKDP crystals and polarizers on measurement results for both schemes.

### 3.1 Intensity Detector Errors

During measurement, intensity values obtained by the detector contain errors due to environmental stray light and inherent detector noise. These errors directly affect the measured polarization accuracy, making it necessary to verify that the proposed scheme meets precision requirements.

Typically, intensity detector nonlinearity is 1–2%, which is insufficient for polarization measurements and requires calibration of the response function. Assuming a detector nonlinearity error of $\delta = 0.02$ and considering only intensity detector errors, the polarization error caused by intensity errors is calculated as:

$$\Delta S = S' - S = X^{-1}I' - X^{-1}I \tag{17}$$

To evaluate scheme performance, we analyzed measurement accuracy for 1000 different incident polarization states (with varying polarization components) under intensity noise levels of 0.02 and 0.001 (standard deviation). Generally, fully polarized states can be represented by points on the Poincaré sphere surface. We selected 1000 uniformly sampled points on the Poincaré sphere, including 20 circles with different ellipticities from south to north pole, with 50 azimuthal points on each circle serving as incident polarization states. In simulations, 100 intensity values were generated for each state by adding signal-independent Gaussian noise, and the standard deviation of 100 measurement errors was calculated as the measurement error for that polarization state.

[Figure 4: see original paper] Poincaré sphere
[Figure 5: see original paper] Polarization sampling points

In Figure 6, Q1-V1 show results from our proposed DKDP polarization measurement scheme, while Q2-V2 show results from the traditional scheme. Evidently, both schemes produce Stokes vector errors of the same order of magnitude. However, with 2% detector nonlinearity, both schemes exhibit errors at the $10^{-2}$ level, failing to meet measurement requirements. When detector nonlinearity is reduced to 1‰, the results in Figure 7 show that for Stokes Q, U, and V components, the traditional scheme's error is approximately $1.4 \times 10^{-3}$, while the new polarization measurement scheme's error is about $1.7 \times 10^{-3}$. Both are below $2 \times 10^{-3}$, satisfying polarization measurement requirements.

[Figure 6: see original paper] Stokes vector error comparison ($\delta = 2\%$)
[Figure 7: see original paper] Stokes vector error comparison ($\delta = 1$‰)

### 3.2 DKDP Crystal Phase Retardation Error

During measurement, when switching DKDP crystal phase retardation via applied voltage, errors in the voltage-phase retardation curve can lead to polarization measurement errors. After calibration of the voltage-phase retardation curve at the target wavelength (532.4 nm in this work), DKDP crystal retardation errors are generally less than 0.001 radians. We must verify that polarization measurement errors caused by phase retardation errors remain within acceptable limits. The polarization state sampling method is identical to that described above. In simulation, independent Gaussian noise with 0.001 radian standard deviation is added, yielding measurement errors for 1000 polarization states.

[Figure 8: see original paper] Comparison of measurement errors caused by DKDP phase delay error

In Figure 8, Q1-V1 represent results from our double-DKDP polarization measurement scheme, while Q2-V2 represent traditional scheme results. Clearly, polarization measurement errors caused by DKDP phase retardation errors are below $10^{-3}$ for both methods. The Q component measurement is superior to the traditional method, while U and V component errors are nearly equal, meeting measurement requirements.

### 3.3 DKDP Crystal Fast Axis and Polarizer Angle Errors

Since DKDP crystals and polarizers are fixed in the polarization analyzer, their angular errors after calibration are much smaller than 0.001 radians. Here, we assume both DKDP crystal fast axis and polarizer angle errors are 0.001 radians to verify whether measurement precision requirements are satisfied. Using the same sampling method, we add independent Gaussian noise with 0.001 radian standard deviation to the DKDP2 crystal fast axis angle parameter to obtain polarization measurement errors affected by fast axis angle error. Similarly, we obtain errors caused by polarizer angle error.

[Figure 9: see original paper] DKDP2 fast axis angle error results
[Figure 10: see original paper] Polarizer angle error results

Figures 9 and 10 show that under both angle error influences, only the Q component of the measured Stokes vector is affected by DKDP2 crystal fast axis angle error and polarizer angle error, with measurement errors below $2\times10^{-3}$, meeting polarization measurement requirements. Since DKDP crystals are fixed, their fast axis angle error impact is far smaller than in traditional rotating wave-plate structures.

Finally, we compare measurement times between the two schemes. The millisecond-level response time of DKDP crystals is negligible. Assuming a camera acquisition rate of 10 frames per second and acquiring two frames per modulation position for improved accuracy:

Scheme comparison (single wavelength point)

| Scheme | Modulation steps | Camera frames | Measuring time |
|---|---|---|---|
| Traditional | 3 (wave plate) | 10 frames / 12 frames | >16.2 s |
| Double DKDP | millisecond | 10 frames / 8 frames | 0.8 s |

Scheme comparison (6 wavelength points)

| Scheme | Modulation steps | Wavelength points | Switching time | Camera frames | Measuring time |
|---|---|---|---|---|---|
| Traditional | 3 (wave plate) | 6 | >5 s | 72 frames | >111.2 s |
| Double DKDP | millisecond | 6 | 1 s | 48 frames | 18.8 s |

The comparison shows that for single-wavelength-point polarization measurement, the traditional scheme's measurement time (>16.2 s) is more than 20 times longer than the double-DKDP scheme ( 0.8 s). For six-wavelength-point measurements, the traditional scheme requires >111.2 s, while the double-DKDP scheme needs only 18.8 s. Due to lower wavelength-point switching frequency, the traditional scheme's measurement time is about 6 times longer than the double-DKDP scheme. Therefore, the proposed real-time polarization measurement scheme based on double DKDP crystals can improve temporal resolution by 20 times and 6 times for single- and multi-wavelength-point measurements, respectively.

## 4 Conclusion

Solar atmospheric detection plays a crucial role in space weather forecasting and solar physics research. Solar magnetic fields are the fundamental driving force behind solar activity eruptions, and polarization measurement is an essential process for solar magnetic field detection. Current polarization measurement methods mainly include rotating wave-plate modulation and wave-plate-plus-DKDP crystal modulation. While the wave-plate-plus-DKDP method reduces wave-plate rotations and shortens measurement time compared with pure rotating wave-plate methods, the presence of wave-plate structures still requires substantial time, resulting in poor real-time performance and susceptibility to instrument jitter. Leveraging the millisecond-level electro-optic response speed of DKDP crystals, this paper proposes a real-time polarization measurement method based on the double DKDP crystal principle, using two DKDP crystals as polarization modulation devices. This advances modulation time from seconds to milliseconds, significantly improving measurement real-time performance. Simulation verification demonstrates the method's feasibility, achieving accuracy better than $2 \times 10^{-3}$ and improving temporal resolution by 20 times and 6 times for single- and multi-wavelength-point measurements compared with traditional schemes, representing significant progress for real-time solar atmospheric polarization detection.

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*Note: Figure translations are in progress. See original paper for figures.*