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Polarimetric Imaging of Coffee

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Abstract: Polari metric imaging technique for characterizing the coffee sample depends on the reflection, scattering and transmission of the polarized light when it is incident on the anisotropic sample. In a typical experiment a highly collimated monochromatic polarized beam with predefined state of polarization from a source is incident on surface of the sample under consideration. From the reflected and transmitted states of polarization the variation of polarization in the sample is understood. The methodology and experimental setup for obtaining intensity images is specified. The image processing algorithms for obtaining 16 elemental Mueller Matrix images is established for the first time on Coffee sample and is verified theoretically to meet the conditions of a complete polarimeter. The obtained images are processed by a self developed program to determine the normalized elemental Mueller Matrix which is further used to understand the depolarization, diattenuation and retardance coefficients in the sample under consideration.

Key Words:-Polarization states, Coffee sample, Mueller Matrix and Degree of polarization.

1. INTRODUCTION

Mueller Polarimetry is a widely used technique of polarization measurement in which a linear variation between the polarization state of incident and excited beams from a sample are obtained, it describes the polarization properties of the sample by using a Polarization State Generator (PSG) and Polarization State Analyzer (PSA) with rotating wave plates, polarizer and analyzer.

The polarization effects that take place in the sample of interest are understood in terms of the images obtained with predefined polarization states that are further processed to understand the characteristic change in the image and are attributed to the variation in sample.

Mueller matrix measurement system was described in the works of some researchers [1-6]. The optical polarization effects simultaneously occurring in the sample are studied with respect to the 49 captured images and then reduced to 16 element Mueller matrix images. These elements obtained are processed by MatLab codes for processing images pixel by pixel and are then normalized to first element to get a signature matrix. The polarization change in the sample is understood in terms of the values and images obtained from the signature matrix.

The basic constraint for a Mueller matrix [10] to be physically realizable is that the incident Stokes vector is physically realizable from the resultant Stokes vector through the Mueller matrix.

2. THEORY

The polarization state of light is characterized by stokes parameters represented [9] as

$$S = \begin{pmatrix} S_0 \\ S_1 \\ S_2 \\ S_3 \end{pmatrix} \quad \text{---------- (1)}$$

A light beam represented by this Stokes vector when incident on an optical element (here the coffee sample), undergoes a transformation, represented by a 4 X 4 matrix called the Mueller or Polarization matrix and the transformed Stokes vector is written [9] as

$$S' = M \times S \quad \text{---------- (2)}$$

$$\begin{pmatrix} S_0' \\ S_1' \\ S_2' \\ S_3' \end{pmatrix} = \begin{pmatrix} m_{11} & m_{12} & m_{13} & m_{14} \\ m_{21} & m_{22} & m_{23} & m_{24} \\ m_{31} & m_{32} & m_{33} & m_{34} \\ m_{41} & m_{42} & m_{43} & m_{44} \end{pmatrix} \begin{pmatrix} S_0 \\ S_1 \\ S_2 \\ S_3 \end{pmatrix} \quad \text{--------- (3)}$$

Where $\begin{pmatrix} S_0' \\ S_1' \\ S_2' \\ S_3' \end{pmatrix}$ is the stoke vector of transmitted/reflected/scattered light.

$\begin{pmatrix} m_{11} & m_{12} & m_{13} & m_{14} \\ m_{21} & m_{22} & m_{23} & m_{24} \\ m_{31} & m_{32} & m_{33} & m_{34} \\ m_{41} & m_{42} & m_{43} & m_{44} \end{pmatrix}$ is the Mueller matrix and

$\begin{pmatrix} S_0 \\ S_1 \\ S_2 \\ S_3 \end{pmatrix}$ is the stoke vector of incident light.

This S' matrix gives measurable polarization information of the output light beam.

The Mueller matrix M can be also written as

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$$M = m_{11}\begin{pmatrix} 1 & \bar{D}^T \\ \bar{P} & m \end{pmatrix} \quad \text{---------- (4)}$$

Where $\bar{D} = \frac{1}{m_{11}}\begin{pmatrix} m_{12} & m_{13} & m_{14} \end{pmatrix}^T$ &

$$\bar{P} = \frac{1}{m_{11}}\begin{pmatrix} m_{21} & m_{31} & m_{41} \end{pmatrix}$$

are called as Diattenuation and Polarizance vector respectively and 'm' is a 3 X 3 matrix [4].

Diattenuation characterizes the intensity transmittances of the incident polarization states. The diattenuation takes values from 0 to 1 and is defined as,

$$D = \frac{T_{\max} - T_{\min}}{T_{\max} + T_{\min}} \quad \text{---------- (5)}$$

All Mueller matrices may not be physically realizable. The basic constraint for a Mueller matrix[10] to be physically realizable is that,

$$\left(MM^T\right)^T = \sum_{i,j=0}^{3} {m_{ij}}^2 \le 4{m_{00}}^2 \quad \text{---------- (6)}$$

This imposes a condition that the Degree of Polarization is less than or equal to one, i.e.,

$$P = \frac{\sqrt{\left(S1^2 + S2^2 + S3^2\right)}}{S0} \le 1 \quad \text{------ (7)}$$

The equal sign applies for non-depolarizing systems and the inequality otherwise. In our earlier communications [14] we have proved that we get a recognizable Mueller matrix for these coffee samples.

Retardance is a property that indicates the phase change and has constant intensity transmittance for any incident polarization state and is described by [12]

$$\vec{R} \equiv R\hat{R} = \begin{pmatrix} Ra_1 \\ Ra_2 \\ Ra_3 \end{pmatrix} \equiv \begin{pmatrix} R_H \\ R_{45} \\ R_C \end{pmatrix} \quad \text{---------- (8)}$$

Where, the components indicate, horizontal, 45^0 and circular retardance respectively. The net linear retardance is

$$R_L = \sqrt{R_H^2 + R_{45}^2} \quad \text{---------- (9)}$$

and the total retardance is

$$R = \sqrt{R_H^2 + R_{45}^2 + R_C^2} = \sqrt{R_L^2 + R_C^2} = \left|\vec{R}\right| \quad \text{---- (10)}$$

3. EXPERIMENTAL PROCEDURE

The Coffee sample is illuminated with He-Ne laser of 20mW power and 632.8 nm wavelength with predefined polarization state [7,8]. The collection optics is kept at 45^0 from the input beam direction throughout the experiment. As shown in Figure 1.

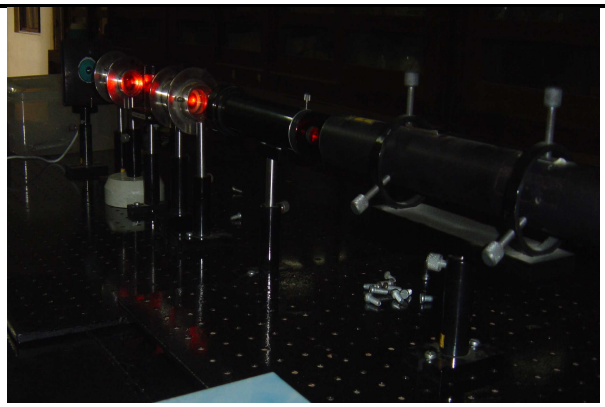

Fig.1. Experimental setup

The samples considered here is Coffee obtained from Gadeo region of Ethiopia and is shown in Figure2.

Fig.2. Coffee Sample

Grown on the rolling hills of southwestern Ethiopia, the Arabica type Yirgacheffe gourmet coffee is hand-sorted and harvested. Each batch is wet processed to improve the acidity and enhance its clean floral notes. Full bodied with mild earthly flavor, the coffee is roasted medium-light, it produces

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a unique fragrance and a lingering intensified finish. It boasts a sweet, rich and smooth flavor.

The sample is then powdered and further sewed to obtain a uniform granular size and is ready experimentation as shown in Figure3.

Fig.3. Roasted and powdered coffee

A beam of photons from the source through a PSG was made to fall on the sample material and reflected beam was made to pass through PSA and fall on the CCD detector connected to a computer that records the intensity information. By varying the optical elements in the PSG and PSA, 49 different intensity images were recorded.

49 intensity images with various orientations of Polarizer and Analyzer are necessary to obtain the 16 elements of Mueller matrix images [13]. The 49 intensity images obtained are named as follows

I_{OO} I_{OH} I_{OV} I_{OP} I_{OM} I_{OR} I_{OL}
I_{HO} I_{HH} I_{HV} I_{HP} I_{HM} I_{HR} I_{HL}
I_{VO} I_{VH} I_{VV} I_{VP} I_{VM} I_{VR} I_{VL}
I_{PO} I_{PH} I_{PV} I_{PP} I_{PM} I_{PR} I_{PL}
I_{MO} I_{MH} I_{MV} I_{MP} I_{MM} I_{MR} I_{ML}
I_{RO} I_{RH} I_{RV} I_{RP} I_{RM} I_{RR} I_{RL}
I_{LO} I_{LH} I_{LV} I_{LP} I_{LM} I_{LR} I_{LL}

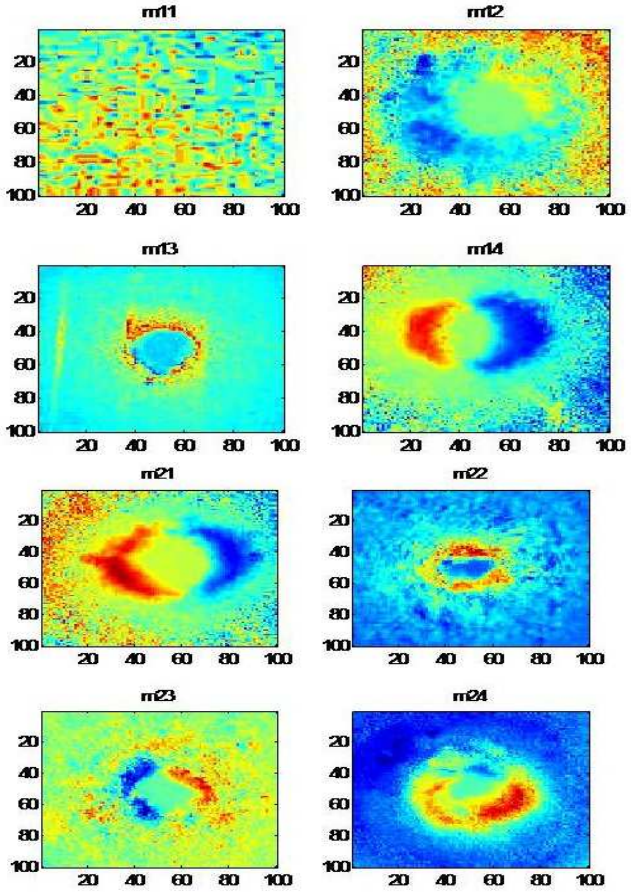
where, the first subscript indicates input state, and the second subscript the output state.

After acquiring 49 intensity images the 16 elemental Muller Matrix is obtained from the following relations

$\mathbf{m_{11}} = I_{OO}$; $\mathbf{m_{12}} = I_{HO} - I_{VO}$
$\mathbf{m_{13}} = I_{PO} - I_{MO}$; $\mathbf{m_{14}} = I_{LO} - I_{RO}$
$\mathbf{m_{21}} = I_{OH} - I_{OV}$; $\mathbf{m_{22}} = (I_{HH} + I_{VV}) - (I_{HV} + I_{VH})$
$\mathbf{m_{23}} = (I_{PH} + I_{MV})) - (I_{PV} + I_{MH})$; $\mathbf{m_{24}} = (I_{RV} + I_{LH}) - (I_{RH} + I_{LV})$
$\mathbf{m_{31}} = I_{OP} - I_{OM}$
$\mathbf{m_{32}} = (I_{HP} + I_{VM}) - (I_{HM} + I_{VP})$; $\mathbf{m_{33}} = (I_{PP} + I_{MM}) - (I_{PM} + I_{MP})$
$\mathbf{m_{34}} = (I_{RM} + I_{LP}) - (I_{RP} + I_{LM})$; $\mathbf{m_{41}} = I_{OL} - I_{OR}$
$\mathbf{m_{42}} = (I_{HL} + I_{VR}) - (I_{HR} + I_{VL})$; $\mathbf{m_{43}} = (I_{PL} + I_{MR}) - (I_{PR} + I_{ML})$
$\mathbf{m_{44}} = (I_{RR} + I_{LL}) - (I_{RL} + I_{LR})$

4. RESULTS

The 49 intensity images with various orientations of polarizer, Analyzer and waveplates are obtained and from them the 16 element Muller Matrix image are obtained and are shown in Figure 4



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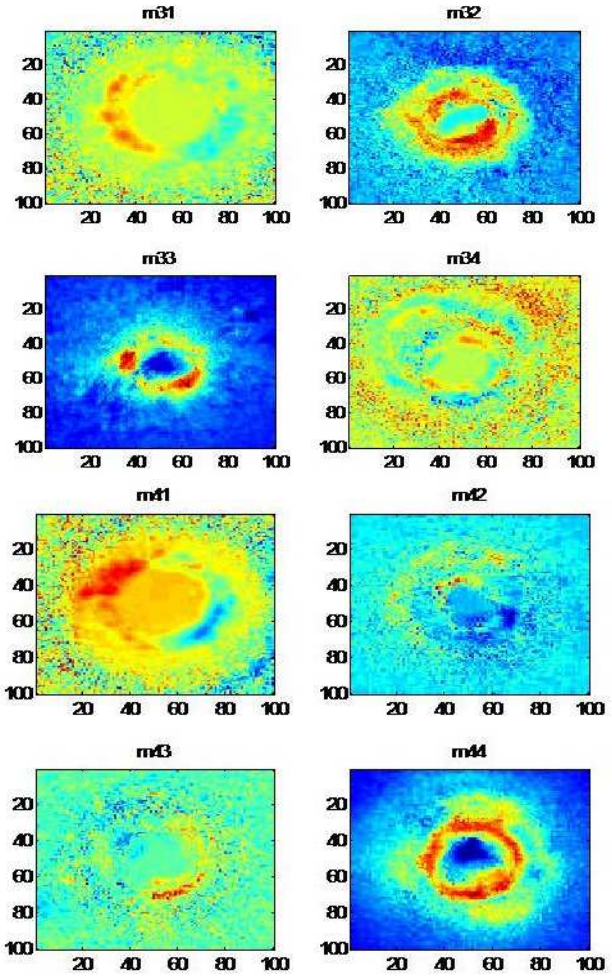

Fig.4. The 16 element Mueller matrix images of Yirgacheffe Coffee

After acquiring 16 images, the images are processed in MATLAB platform to acquire intensity component of each and every pixel of image [13]. This Mueller Matrix obtained is normalized to the first element of the matrix to isolate the intensity dependent effects in the image and also simplifies the analysis [11]. The measured Mueller Matrix is shown in Table 1.

Table1. Mueller Matrix values of Coffee.

(M_{11}) 1	(M_{12}) -0.0698	(M_{13}) 0.0001	(M_{14}) -1.4419
(M_{21}) -1.1163	(M_{22}) 0.0698	(M_{23}) 0.2558	(M_{24}) -0.4651
(M_{31}) -0.3488	(M_{32}) -0.4186	(M_{33}) 0.0930	(M_{34}) 0.9535
(M_{41}) -0.7674	(M_{42}) -0.0930	(M_{43}) -0.1395	(M_{44}) 0.0465

From the measured Mueller matrix the necessary condition for Complete Mueller Polarimeter is calculated and is in accordance with equation (6).

From the measured Mueller Matrix the Diattenuation, Retardance and Depolarization images are acquired and the mean values of Diattenuation and Depolarization for the sample are as shown in Table3.

Table 3: Mean values of Diattenuation, Depolarization and Retardance.

Coffee sample	Mean values
Diattenuation	1.3803
Depolarization	0.0030
Retardance	2.0932

5. DISCUSSION

The polarization response of coffee sample was observed and it is observed to compile with equation (6). The diattenuation, depolarization, Retardance values are observed. The depolarization value is attributed to the different scatterings of incident light by sample, if the sample surface is lambertian it is exhibiting high depolarization of light and thus showing sharp back scattered intensity distribution with high polarization of light. A high specular reflectance nature was observed for the diattenuation the reason being different surface texture content on the surface though same granular size is used for investigation. Retardance value is due to discontinuity present on the sample surface this value is also compositional and moisture or water content present in the coffee sample.

6. CONCLUSIONS

Optical signature of the Coffee sample in the form of a Mueller matrix was obtained and as expected it exhibited polarization anisotropic character which is evident from the results tabulated. The experiment results of this study indicated that pixel by pixel processing of the images obtained effectively identified various optical polarization changes and scattered intensity distributions present in the coffee sample.

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