by Dr. Baoliang (Bob) Wang and Dr. Theodore C. Oakberg

When the photoelastic modulator (PEM) is used as a polarization analyzer, it is generally useful to use a dual PEM system. A dual PEM system can obtain all four Stokes vectors simultaneously. By using a dual PEM system, the unparalleled high sensitivity, spectral range, and stability of Hinds photoelastic modulators (PEM) can be applied to study polarization.

One of the first uses for a dual PEM system was astronomical polarimetry. Applications can also be found in Stokes Polarimetry and Optical Rotation. Other polarization analysis PEM applications include laser light characterization and magnetic field diagnostics in tokamaks throughout the world.

The modulator axes of the two modulators are at 45 degrees, with the polarizer passing axis at 22.5 degrees with each modulator. The angular designations for each modulator are determined by the angular direction of polarized light to which each modulator subsystem is sensitive. The electronic block diagram corresponds to the one given in Figure 1.

The relationships between the electronic output voltages and the appropriate polarization parameters are given in Table 1. Hinds Instruments has five standard dual PEM systems for applications that require different useful apertures and measurements in different spectral regions. The dual PEM models are:

- I/FS50-60
- I/FS47-50
- II/FS20-23
- II/FS42-47
- II/ZS37-50

The I/FS50-60 and the I/FS47-50 systems are made with fused silica and use the Series I PEM. The Series I PEMs have a rectangular shaped optic with a typical useful aperture of 16 mm. These small systems are useful when the light source has a small beam.


Condition: when the peak-to-peak retardation of both PEMs is set at

\[ J_0 (\delta_1) = J_0 (\delta_2) = 0 \]

Normalized Stokes parameters:

\[ Q = \frac{Q}{\sqrt{V_D}^2 + U_D^2 + \sqrt{V_C}^2} \]
\[ U = \frac{U}{\sqrt{V_D}^2 + U_D^2} \]
\[ V = \frac{V}{\sqrt{V_D}^2 + U_D^2} \]

Other polarizations parameters:

- Degree of Polarization: \( DOP = \frac{\sqrt{Q^2 + U^2 + V^2}}{I} \)
- Degree of Linear Polarization: \( DOLP = \frac{\sqrt{Q^2 + U^2}}{I} \)
- Degree of Circular Polarization: \( DOCP = \frac{|V|}{I} \)

**TABLE 1. RELATIONSHIPS BETWEEN THE ELECTRONIC OUTPUT VOLTAGES AND THE APPROPRIATE POLARIZATION PARAMETERS**

APPLICATIONS FOR DUAL PEM SYSTEMS

Polarization Analysis and Stokes Polarimetry

The most common use for a dual PEM system is to analyze the state of polarization of a light source. There are different ways to represent light polarization. One of these is to use Stokes vectors or parameters \( (I, Q, U, \text{ and } V) \). Using the 1f and 2f signal from each of the modulators, a dual PEM system is able to provide all four of the Stokes parameters simultaneously. In this representation, \( I = (I_45 + I_{-45}) \) is the total light intensity. \( Q \) is known as the linear preference and is represented \( Q = (I_{45} - I_{-45}) \). The 45° linear preference is known as \( U \) and is shown by \( U = I_{45} - I_{-45} \). The last component of the vector is \( V = I_{cpl} \).

**TABLE 2: DUAL HEAD SPECIFICATIONS**

<table>
<thead>
<tr>
<th>MODEL</th>
<th>OPTICAL MATERIAL</th>
<th>NOMINAL 1F FREQUENCY</th>
<th>SPECTRAL RANGE</th>
<th>RANGE OF ( \lambda/4 ) RETARDATION*</th>
<th>USEFUL APERTURE²</th>
</tr>
</thead>
<tbody>
<tr>
<td>II/ZS37-50</td>
<td>ZINC SELENIDE</td>
<td>37 &amp; 50 kHz</td>
<td>550nm - 18( \mu )m</td>
<td>2( \mu )m - 18( \mu )m</td>
<td>14mm</td>
</tr>
<tr>
<td>II/FS20-23</td>
<td>FUSED SILICA</td>
<td>20 &amp; 23 kHz</td>
<td>170nm - 2.6( \mu )m</td>
<td>170nm - 2( \mu )m</td>
<td>45mm</td>
</tr>
<tr>
<td>II/FS42-47</td>
<td>FUSED SILICA</td>
<td>42 &amp; 47 kHz</td>
<td>170nm - 2.6( \mu )m</td>
<td>1.6( \mu )m - 2.6( \mu )m</td>
<td>23mm</td>
</tr>
<tr>
<td>I/FS50-60</td>
<td>FUSED SILICA</td>
<td>50 &amp; 60 kHz</td>
<td>170nm - 2.6( \mu )m</td>
<td>170nm - 2( \mu )m</td>
<td>16mm</td>
</tr>
<tr>
<td>I/FS47-50</td>
<td>FUSED SILICA</td>
<td>47 &amp; 50 kHz</td>
<td>170nm - 2.6( \mu )m</td>
<td>170nm - 2( \mu )m</td>
<td>16mm</td>
</tr>
</tbody>
</table>

* \( J_0 = 0 \)

² Aperture with ≥90% average efficiency (diameter), as per B. Wang "Useful Aperture" Hinds Instruments
Astronomical Polarimetry

One of the first uses of the photoelastic modulator (PEM) was astronomical polarimetry. Dr. James Kemp, late Professor of Physics at the University of Oregon, used PEMs to study the polarization of light from nearby stars and features on the sun, such as sunspots. The four Stokes parameters (I, Q, U, V) give a complete description of the polarization state of an astronomical object. Dr. Kemp was able to measure degree of polarization down to 10^-6.

PEM-based polarimeters typically use a II/FS42-47 PEM system. Detection of the two linear components is made at 2f1 and 2f2 while the circular component is detected at 1f1 or 1f2.

Tokamak

Hinds Instruments manufactures a dual PEM system specifically designed for Motional Stark Effect (MSE) diagnostic polarimeters associated with tokamaks. Two octagonal optical element/transducer assemblies, one operating at 20 kHz and the other at 23 kHz, are mounted in a single optical head enclosure. The retardation axes of the two assemblies are at 45 degrees with respect to each other, as required for a PEM-based Stokes polarimeter.

Optical head enclosures are made either from aluminum or from a non-conductive plastic material (e.g. Delrin). This material eliminates eddy currents and strong forces occurring in conductive materials in rapidly changing strong magnetic fields. The head enclosure is made like a clam-shell, with one optical assembly mounted in each half. The two optical elements are separated by only 10 mm. This and the large aperture (100 mm) allow use of a wide range of sighting angles through the PEM optical head.

Dual PEM systems are in use in these tokamaks: TFTR in Princeton, NJ, DIII-D in San Diego, CA, JT-60 in Naka, Japan, JET Joint Undertaking in Abingdon, UK, the Institute for Plasma Research in Gandhinagar, India, and ASDEX Upgrade in Garching, Germany. For more information on this application, please see Hinds Instruments PEM Newsletter #11. A picture of this PEM system can be seen in Figure 3.

Dual PEM systems provide the capability to make real time polarization analysis measurements. These systems are available in a wide variety of materials and configurations to support many diverse applications. A Hinds sales engineer or application scientist will be glad to explain in more detail any of these options. Please contact us with any questions or comments that you may have.

REFERENCES
