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Filled liquid crystal depolarizers

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The construction and properties of scattering type liquid crystal depolarizers are discussed. The Mueller matrices that describe these devices are measured and compared to ideal depolarizers and ideal linear materials. The present depolarizers do not perform as well as crystal pseudodepolarizers. Nevertheless, when polarized light is incident on one of these devices the polarization of the transmitted light can be uniform to within 5%. These devices have the advantage that they can be made to areas as large as 30–30 cm or larger, are inexpensive, and can be electrically switched off and on. [DOI: 10.1063/1.1401799]

INTRODUCTION

In certain instances, the polarization exhibited by normal light beams can be highly undesirable. For example, the many reflections and beam shapings that occur in a typical spectrophotometer introduce polarizations into the incident beam. Thus, reflectance measurements at non-normal incident angle can be misinterpreted unless the light polarization is considered and controlled. In other cases, such as in the study of liquid crystals and other intrinsically optically anisotropic materials, control of polarization and the effects of the sample on the polarization of the incident light are critical.

It is difficult to eliminate polarization of a light beam. Shurcliff[1] pointed out nearly 4 decades ago that ''some success can be achieved by scattering light from a cloud of randomly arranged particles of appropriate size and shape or by employing an integrating sphere.'' At the same time, he observed that these schemes dramatically reduce the direction and angular width of the beam and tend to be very wasteful of the incident light. He states that a better approach is to use depolarizers, or more correctly ''pseudodepolarizers,'' ''polarization scramblers,'' or ''randomizers.'' These devices do not achieve truly unpolarized light but rather divide the incident beam into a large range of varying and intermixed polarization angles. Thus, for practical purposes, the light that has passed through a ''pseudodepolarizer'' acts as if it were totally unpolarized. There are two commonly available types of pseudodepolarizers: the wedge type and the Lyot.[2] The wedge depolarizer consists of a quartz wedge and often a silica compensation wedge to correct for angular deviation of the light that passes through the quartz wedge. Devices of this type operate over a wide band of wavelengths, roughly 200–2500 nm. Some types have an even wider bandwidth. The Lyot depolarizer is achromatic and consists of two quartz plates assembled with their optic axes at 45° to one another. One plate is twice as thick as the other. Typically both types of depolarizers are small (area <10 cm^2) and expensive. They also are more effective when used with large beam sizes. These types of depolarizers and others are discussed in the book on polarizers edited by Billings.[3]

In this article, we discuss filled liquid crystal depolarizers that, in some ways, are not as effective as the depolarizers discussed above, but have the advantage of low cost and large size. These are scattering type depolarizers. Unlike many scattering depolarizers, these devices do not greatly attenuate the beam because of scattering (70% of incident white light is transmitted) nor cause a large increase in the angular width of the incident beam. A HeNe laser beam increases its angular width by approximately 1°C passing through the depolarizer. In fact, one may read a printed page through these depolarizers at relatively close spacing between a printed page and the depolarizer. While it is not critical in the current application, the depolarizer can be electrically switched ON and OFF. In this article, we will first discuss some of the simpler optics of depolarizers. The construction of the filled depolarizers will then be discussed, and finally, the experimental results will be presented.

II. THEORETICAL BACKGROUND

The Stokes vector **S** consists of Stokes parameters, four quantities that describe the intensity, and polarization of a beam of light. Together, these parameters form a concise mathematical description of all types of incoherent beams of light. These vectors can be used to describe beams from sources as well as beams scattered from particles in a medium. The four parameters all have dimensions of intensity and correspond to time-averaged intensities. The notation for these four components varies from author to author. We will use the same notation as Shurcliff[4] and write the Stokes (column) vector in the following form:

$$\begin{bmatrix} I \\ M \\ C \\ S \end{bmatrix} = I * \begin{bmatrix} 1 \\ M/I \\ C/I \\ S/I \end{bmatrix}.$$

Often this vector is normalized by the intensity so that the maximum absolute values of M, C, and S are one. This normalization is also shown in the above equation. The four

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parameters have the following meanings. I is the time-averaged intensity. The parameter M describes the horizontal preference of the polarization. The normalized $M(=M/I)$ obtains the value $+1$ for horizontally polarized light, -1 for vertically polarized light, and 0 for light polarized at $\pm 45°$ from the horizontal. C describes the $+45°$ "polarization preference" of the beam. In this notation, $+45°$ corresponds to lines that run 45° from the horizontal and from lower left to upper right. For a normalized vector, a beam polarized at $+45°$ obtains $C/I=1$, while a beam polarized at $-45°$ obtains $C/I=-1$. $C=0$ for vertically or horizontally polarized light. The final parameter S describes the right circular polarization "preference" of the beam.

The Mueller calculus is a matrix method of predicting the effects of various devices, including free space, on an incident beam described by a Stokes vector. A Mueller matrix $\mathbf{M}$ is a 4×4 matrix that can be used to describe the effects of an optical device, propagation, or a collection of scattering centers on a beam of light describes by the Stokes vector $\mathbf{S}$. This is done by applying the rules of the matrix algebra to the system. Thus, the Stokes vector of a light beam after passing through an optical device is given by: $\mathbf{S_{out}}=\mathbf{MS_{in}}$. In this expression, $\mathbf{S_{out}}$ is the Stokes vector describing the beam after passing through the media described by the Mueller matrix $\mathbf{M}$ and the Stokes vector of the incident beam is $\mathbf{S_{in}}$. Mueller matrices for both real and ideal devices are discussed in Shurcliff.[1] Bohren and Hoffman[4] as well as van de Hulst[5] discuss the corresponding matrix for scattering media, where it is called the scattering matrix.

In the present context, the source beam is expected to have little circular polarization because simple to use, broadband circular polarizers are not available. We will ignore the Stokes parameter S. Furthermore, one of our goals is to characterize the scattering depolarizer via its Mueller matrix. To facilitate this development will we present, without proof, the Mueller matrix of an ***ideal*** depolarizer, the Mueller matrix of a uniform, loss-less media, and the Stokes vector of an unpolarized beam of light. First, an unpolarized beam of light is described by the following normalized Stokes vector: $I\{1,0,0,0\}$. In this expression, the column vector has been written as a row vector and the curly brackets are to remind the reader that this vector is actually a column vector. Furthermore, note that this is standard notation for writing the column vector as a row vector. The Mueller matrix of uniform lossless media is the 4×4-identity matrix. This leads to the Stokes vector after propagation through the device being identical to that incident on the device. Except for reflection losses, this should approximate the voltage ON state of one of these switchable depolarizers. The Mueller matrix for an ideal depolarizer is given by the following expression:

$$\begin{bmatrix} 1 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 \end{bmatrix}.$$

Observe that by applying this matrix to an arbitrary Stokes vector given by $\{I,M,C,S\}$, the result is $\mathbf{S_{out}}=\{I,0,0,0\}$. This corresponds to a completely depolarized beam of light. Later the Mueller matrix for the scattering depolarizers developed in this laboratory will be presented.

EXPERIMENTAL DETAILS

Construction of cells

The construction of prototypes of these depolarizers is straightforward. Indium–tin–oxide (ITO) coated glass with a resistance of approximately 30 Ω/sq. is cleaned with organic solvents and dried. Glass spacers of various diameters (6, 16, and 47 μm) are then spin (or spray) coated onto the glass plates. Parallel plate cells are formed from a spacer coated glass plate and a similarly cleaned nonspacer covered glass plate. These plates are clamped together and glued along two of the outside edges. There are no surface coatings or passivating layers applied to the glass plates in the present study. The cells were filled with a liquid crystal–particle dispersion using capillary action in the isotropic phase. This temperature depended on the liquid crystal used and corresponds to approximately 65 °C for E7, 100 °C for E44, and 36 °C for K15.

The filled liquid crystal particle dispersion was made by adding a measured amount of Nissan colloidal particles (in methanol) into Merck E7 or K15 liquid crystal and evaporating the solvent carrier of the colloidal particles. Several colloidal materials were investigated. These included both small (8–10 nm diam) and large (70–100 nm diam) silica particles, and higher refractive index Antimony Pentoxide particles. The concentration of particles was generally in the range of 0.5%–7% (by weight) and was chosen to achieve a good compromise between transmitted light quality and depolarization efficiency. The evaporation of the methanol was performed at atmospheric pressure at a temperature roughly 10 °C above the nematic to isotropic phase transition temperature. During this slow evaporation of the methanol, the sample was vortex mixed. From time to time large aggregates of particles formed. These were broken into small particles by gently breaking them up with a spatula. Typically, a sample was heated and mixed for several hours and then left to age overnight before being used. Some settling of the particles occurred. For this reason, the liquid crystal–particle dispersion was vortex mixed for a few seconds just before a cell was filled. Depolarizers of a given thickness constructed from the same mixture at different times yielded essentially identical depolarization curves. These cells appeared to be stable for several months. Unlike some recent studies of particles in nematics, the particles do not appear to be excluded from the nematic phase.[6]

Because of the refractive index mismatch between the particles and the liquid crystal, and/or the distortion in the liquid crystal caused by the particles and the untreated surface, these cells scatter light. By applying an ac electric field (60 or 1000 Hz) of roughly 1 V/μm the scattering of light transmitted through the cell can be largely eliminated. Thus, these depolarizers can be turned ON and OFF at will. When no voltage is applied across the device (the voltage OFF state) the device is a depolarizer, while when a sufficiently large voltage is applied (voltage ON state) the device is optically a homogeneous material.

Evaluation and discussion

The depolarizers were characterized using three different, although related techniques. The simplest characterization technique placed the depolarizer between two Polaroids, and measured the transmitted light as a function of angle between the two Polaroids. The second characterization configured the same optical apparatus as the previous measurements to measure the Mueller matrix (scattering matrix) of the sample. The third characterization technique studied images of small printed letters when viewed through a depolarizer. A detailed microscopic examination of such images was also studied. Each of these characterizations will now be discussed in detail.

The polarization dependent characterization of the depolarizers was performed using a white light source (Oriel Model 77501 fiber optic illuminator) connected to a large diameter fiber. The output of the fiber was supported in a standard holder. A sheet polarizer in a rotation stage followed next in the optical train. This polarizer was generally oriented so that the light passing through it was (essentially) polarized either vertically, horizontally, or at 45° from the horizontal. The filled nematic cell followed next in the optical train. Another sheet polarizer on a rotation stage followed. Two detectors were used. Most often, a Tektronics J6523 1° narrow band luminance probe was the detector. However, a silicon diode detector was also utilized. The second polarizer ("the analyzer") was characterized with both detectors and the appropriate characterizations used in subsequent analysis. This apparatus is part of an Electro-Optics Measurement system developed at the Liquid Crystal Institute at Kent State University.

Cells of 6, 16, and 47 μm plate spacing were constructed and tested. The 6 μm thick cells showed very little scattering and were not further studied. The 16 and 47 μm thick cells both depolarized light effectively when the liquid crystal was either K15, or the wide-temperature range nematic mixture E7. However, effective depolarization could not be obtained with another wide-temperature range nematic mixture E44. The birefringence of all three liquid crystals is similar, so this is not the cause of the variation in depolarization. However, the relative hydrophobicity, and hydrogen bonding strengths of these materials varies and may be the cause of this variation. We also note that K15 is a pure compound, not a mixture like E7 and E44. The amount of depolarization depended on the cell thickness, and both the type and amount of colloid dispersed in the liquid crystal. In light of the range of variables, several generic observations may be made. First, even the best depolarizer was in no way perfect. When such depolarizers were illuminated by polarized light, the residual variation in the transmitted light intensity with polarizer–analyzer angle was never less than about 5% and ranged as high as 30%. The amount of variation depended on both the cell spacing and the amount of colloid in the liquid crystal. Too much colloid lead to cells that did not depolarize very effectively at the spacings studied. Moreover, higher concentrations of colloid in thinner cells were as effective as lower concentrations of colloid in wider spaced cells. A 10% or less variation in intensity was obtained when the product of the concentration of colloid and the cell thickness was approximately 40%–50% microns. For example, 10% colloid dispersion and a 4 μm thick device, or a 1% colloid dispersion and a 40 μm thick device both obtain a product of (40% microns).

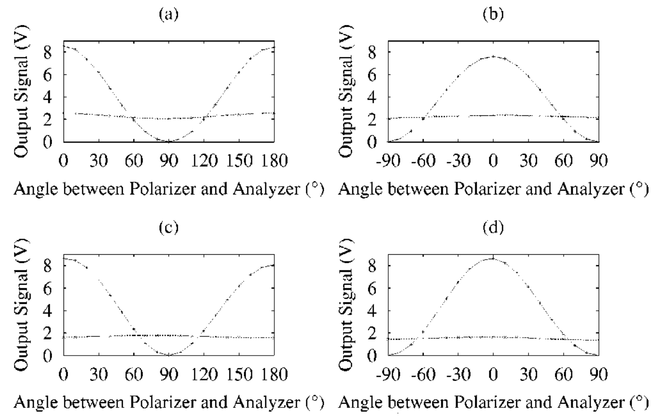

FIG. 1. The transmitted voltage vs angle between the polarizer and analyzer for no depolarizers and two types of depolarizers and incident polarization vertical [(a) and (c)] and horizontal [(b) and (d)]. In all four panels the larger voltage corresponds to no depolarizer present. Panels (a) and (b): K15 and 2.6% Antimony depolarizer (47 μm spacing). Panels (c) and (d): E7 and 2.4% large silica colloid depolarizer (16 μm spacing).

Graphs of typical results of the variation in light transmitted through two of these depolarizers for polarized incident light (both vertically and horizontally) as a function of angle between the polarizer and analyzer are shown in Fig. 1. Note that there is some variation in the transmitted light intensity, and the two cells shown have different variations about their mean values.

These cells were also characterized via their Mueller matrices. The K15-2.6% Antimony Pentoxide cell shown in Fig. 1 was studied in the depolarizing (scattering) state. The Mueller matrix deduced from this data is

$$\begin{bmatrix} 0.690 & -0.0003 & -0.0013 & - \\ -0.010 & 0.0497 & -0.0021 & - \\ -0.0053 & -0.032 & 0.0233 & — \\ — & — & — & — \end{bmatrix}.$$

The dashes indicate that the matrix element was not determined, and no symmetry was imposed upon the various elements of the matrix. Predictions of measured intensities based on this matrix agree with the experimental measurements to better than 5%. Moreover, these data have not been corrected for reflection losses at the air–glass interfaces. The similar matrix for an E7-2.4% large silica colloid sample was determined to have the following forms in the voltage OFF (depolarizing) and voltage ON (26 V peak square wave at a frequency of 992 Hz) (nondepolarizing) states:

$$\begin{bmatrix} 0.683 & -0.006 & -0.0021 & - \\ -0.033 & 0.0224 & -0.0026 & - \\ 0.0131 & -0.034 & 0.0241 & - \\ - & - & - & - \end{bmatrix}$$

$$\begin{bmatrix} 0.877 & -0.0036 & -0.0041 & - \\ -0.0036 & 0.847 & 0.03 & - \\ -0.0145 & -0.033 & 0.868 & - \\ - & - & - & - \end{bmatrix}.$$

Observe that for both depolarizers the dominant term is the 11 component. It is not exactly 1.00 because of the scattering of the light out of the incident beam. Also, observe that all of the other terms are close to zero at most 7% of the maximal, 11 component. Note that when voltage is applied to the depolarizer it is switched to an essentially homogeneous media. The predominant terms are on the main diagonal, these three terms are all very close to equal, and the off diagonal terms are all very close to zero, roughly 4% or less of the diagonal terms. The diagonal terms in this case are not one as predicted for propagation through homogeneous media because of the reflection losses, absorption by the ITO electrodes, and residual scattering losses of the sample. Nevertheless, these Mueller matrices verify that in the voltage ON state, these devices act very similar to homogeneous media, and in the voltage OFF state, these devices are good depolarizers. In both cases, the Mueller matrices approach those of the ideal cases.

These depolarizers are of the scattering type. They necessarily cause some loss of resolution of patterns that occur in the light that passes through them. In practical applications, this loss of resolution, as well as the related angular spreading that accompanies this scattering, may be a problem. The loss of resolution depends on the positions of the source, the depolarizer, and the detector. However, it is commonly observed that when the source and the depolarizer are adjacent this loss in resolution may **not** prevent the source from readily being determined.[7,8] We anticipate that these depolarizers will be useful in applications where they are near the source. To test the resolution in such circumstances a test page of various font sizes was printed onto standard printer paper. This sheet was then sandwiched between two microscope slides to form a test plate. The depolarizer was placed on top of this test plate and the test plate studied. Under normal room lighting, one could easily read three-point font. To further quantify the observation the depolarizer and test plate were placed under a microscope and the images studied. Figure 2 is an example of typical results of such a study. The left panel of this figure shows a three-point ‘‘c’’ on the test plate viewed through a depolarizer. The right panel shows the same ‘‘c’’ when a voltage of 25 V rms, 60 Hz is applied to the depolarizer. While some fine details are lost, the appearance of ‘‘noise’’ in the printed dots is visible in both panels. This loss in resolution is not very extensive and, in fact, is much smaller than that resulting from putting a piece of ‘‘invisible’’ tape on the test plate.

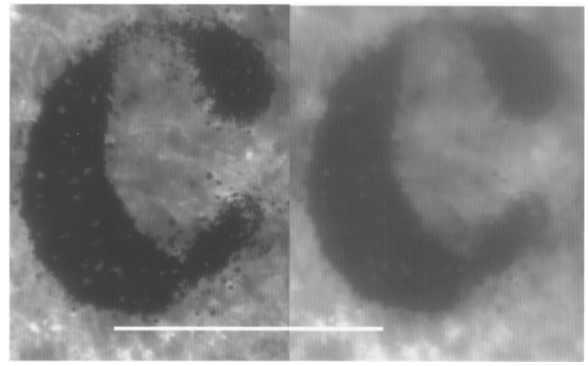

FIG. 2. A ‘‘c’’ viewed through a depolarizer: (right panel) depolarizing state, (left panel) voltage ON, nondepolarizing state. The small dots are individual dots from the printer, and the white bar is 500 μm long.

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