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Variation of linear and circular polarization persistence for changing field of view and collection area in a forward scattering environment

John D. van der Laan*[a], Jeremy B. Wright[a], David A. Scrymgeour[a], Shanalyn A. Kemme[a], and Eustace L. Dereniak[b]

[a]Sandia National Laboratories, 1515 Eubank Blvd. SE, Albuquerque, NM, 87123;

[b]College of Optical Sciences, University of Arizona, 1630 E. University Blvd., Tucson, AZ 85721

ABSTRACT

We present experimental and simulation results for a laboratory-based forward-scattering environment, where 1 μm diameter polystyrene spheres are suspended in water to model the optical scattering properties of fog. Circular polarization maintains its degree of polarization better than linear polarization as the optical thickness of the scattering environment increases. Both simulation and experiment quantify circular polarization's superior persistence, compared to that of linear polarization, and show that it is much less affected by variations in the field of view and collection area of the optical system. Our experimental environment's lateral extent was physically finite, causing a significant difference between measured and simulated degree of polarization values for incident linearly polarized light, but not for circularly polarized light. Through simulation we demonstrate that circular polarization is less susceptible to the finite environmental extent as well as the collection optic's limiting configuration.

Keywords: Polarization, scattering, circular polarization, linear polarization, forward scattering

1. INTRODUCTION

Recently we have shown circular polarization persists through forward scattering environments better than linear polarization via simulation [1–6]. Specifically, we investigated the variation in circular polarization persistence for fog and dust environments with varying wavelength in the infrared and the evolution of both circular and linear polarization states as light scatters throughout scattering environments. In this conference paper we present experimental and simulation results for a laboratory-based scattering environment of 1 μm diameter polystyrene spheres suspended in water. The results presented here experimentally confirm circular polarization's superior persistence, shown in our previous work, for forward scattering environments and increasing optical thicknesses. Additionally, circular polarization is much more tolerant than linear polarization to variations in the field of view and collection area of the measuring optical system.

2. BACKGROUND

The polarization of light is defined mathematically by the Stokes parameters and Stokes vector,

$$\vec{\boldsymbol{S}} = \begin{bmatrix} S_0 \\ S_1 \\ S_2 \\ S_3 \end{bmatrix} = \begin{bmatrix} \langle E_\parallel E_\parallel^* + E_\perp E_\perp^* \rangle \\ \langle E_\parallel E_\parallel^* - E_\perp E_\perp^* \rangle \\ \langle E_\parallel E_\perp^* + E_\perp E_\parallel^* \rangle \\ i\,\langle E_\parallel E_\perp^* - E_\perp E_\parallel^* \rangle \end{bmatrix} \propto \begin{bmatrix} I_H + I_V \\ I_H - I_V \\ I_{45} - I_{135} \\ I_R - I_L \end{bmatrix}, \quad (1)$$

where ∥ corresponds to the parallel component, ⊥ corresponds to the perpendicular component, and * corresponds to the complex conjugate. S_0 is the total intensity of the light, S_1 is the preference for horizontal or vertical linear polarization, S_2 is the preference for 45 or 135 degree linear polarization, and S_3 is the preference for right or left circular polarization. The sum of the squares of the S_1 through S_3 Stokes parameters must always be less than or equal to the square of the S_0 Stokes parameter. Light can vary from purely polarized to completely unpolarized. The Degree of Polarization (DoP) defines the percentage of light that is purely polarized,

*johvand@sandia.gov

$$DoP = \frac{\sqrt{{S_1}^2 + {S_2}^2 + {S_3}^2}}{S_0}. \tag{2}$$

The DoP can vary from 0 for completely unpolarized light, to 1 for purely polarized light.

3. EXPERIMENTAL SETUP AND SCATTERING ENVIRONMENT

The experimental setup used to investigate linear and circular polarization's persistence for the forward scattering environment is shown in Figure 1. The same setup was used for both polarization states. A HeNe laser with a wavelength of 543.5 nm and a power of 5 mW acted as the illumination source. Due to investigations of large optical thicknesses, and thus small collected scattered light signals, the laser was optically chopped at a frequency of 200 Hz and a lock-in amplifier was used. The initial polarization state of the laser light was set using a polarizing beam cube. The beam was vertically linearly polarized. Desired incident polarization states were generated using polarization generating optics consisting of the polarizing beam cube and a quarter-wave retarder (labeled λ/4). The quarter-wave retarder was rotated to two different angular positions in order to generate incident vertical linear polarization or left circular polarization.

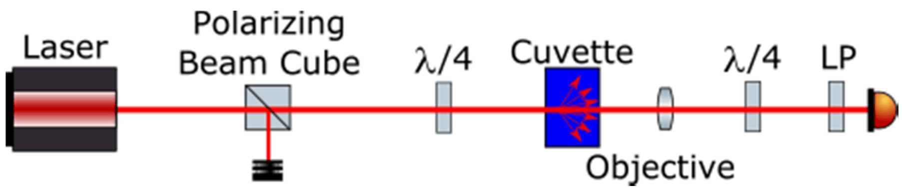

Figure 1 – Experimental Setup

Once the desired incident polarization was generated, the light was incident normal to the front face of a cuvette. The cuvette had a front and back optical face with dimensions 1x4 cm. The overall length and height of the cuvette were 3 and 4 cm, respectively. The glass cuvette confined the experimental scattering environment's dimensions. The experimental scattering environment consisted of a solution of nearly monodisperse 1 µm diameter polystyrene microspheres suspended in water. Polystyrene microspheres are convenient and well-calibrated in size and refractive index. The experimental scattering solution consisted of polystyrene microspheres with a mean particle diameter of 0.99 µm and a standard deviation of 0.03 µm acquired from PolySciences, Inc. Polystyrene's refractive index at the experimental wavelength of 543.5 nm is 1.597 [7]. The particle diameter and incident light's wavelength determine the size parameter of the scattering environment. The size parameter is defined as,

$$x = \frac{2\pi a n}{\lambda}, \tag{3}$$

where a is the radius of the scattering particle, n is the refractive index of the external medium, and λ is the vacuum wavelength of the light [8]. For the polystyrene microspheres in water scattering environment, the size parameter, x = 7.628. For comparison, this size parameter corresponds to marine fog particle sizes at infrared wavelengths. This scattering environment is considered a forward scattering environment [8].

For all the experiments, a volume of 6 mL of water and polystyrene microspheres filled the cuvette. Various densities of polystyrene microspheres were used to create different optical thicknesses of the scattering environment. Measurements started with small optical thicknesses and increased for subsequent measurements.

A Mitutoyo infinity-corrected objective lens with a numerical aperature of 0.42 was used to collect the scattered light that exited the back face of the cuvette. The objective collected light in a 100 µm radius circular spot size with a half angle field of view (HFOV) of 24.83 degrees. Collected light is collimated after passing through the objective. The collimated light is passed through polarization analyzing optics to determine the collected scattered light's polarization state. The polarization analyzing optics includes a rotating quarter-wave retarder and a fixed linear polarizer. The linear polarizer is fixed at an angular position of 0 degrees. After the polarization analyzing optics, a 1 cm square silicon PIN diode detector measures the intensity of the collected light. The polarization analyzing optics and detector make up a rotating quarter-wave retarder fixed-polarizer polarimeter. This polarimeter is a full Stokes polarimeter, and thus can fully measure all four Stokes parameters.

4. EXPERIMENTAL PROCESS

The rotating quarter-wave retarder fixed-polarizer polarimeter measures the four Stokes parameters by modulating the collected signal intensity [9]. The quarter-wave retarder was rotated to 37 different angular positions, corresponding to 5 degree increments from 0 to 180 degrees. At each angular position the collected light is sampled 100 times at a sampling rate of 512 Hz. The voltage signal from the detector is measured via the lock-in amplifier. The 100 sampled voltage values are averaged. This process is completed three times for each incident polarization state. The polarimeter was calibrated with a known incident polarization state and only water in the cuvette. The ideal intensity modulation is given by the following equation,

$$I(\theta) = \frac{1}{2}(S_0 + S_1\, cos^2(2\theta) + S_2 \sin(2\theta)\cos(2\theta) - S_3 \sin(2\theta)), \tag{4}$$

where the angle θ is the angular position of the quarter-wave retarder [9]. The calibration and measurement of the Stokes parameters used the data reduction (least-squares fit) method. For an individual measurement, the measured intensity is given by,

$$I_q = A_q S, \tag{5}$$

where I_q is the measured intensity, A_q is the analyzer vector determined by the polarization analyzing optics, and S is the collected light's Stokes vector. The angular positions of the rotating quarter-wave retarder create an array of intensity measurements, $\boldsymbol{I}$, which are dependent of the $\boldsymbol{W}$ measurement matrix which is defined by the polarimeter and the A_q vectors.

$$\boldsymbol{I} = \boldsymbol{WS} \tag{6}$$

The Stokes vector of the collected scattered light is then determined by using the inverse of the measurement matrix.

$$\boldsymbol{S_{measured}} = \boldsymbol{W^{-1}I} \tag{7}$$

The data reduction method utilizes the pseudoinverse matrix as the ideal inverse matrix since the system is overdetermined. The pseudoinverse matrix is also called the data reduction matrix. This technique was used for all the measurement results. The scattered light's DoP was calculated from the measured Stokes parameters.

5. SIMULATION PROCESS

A polarization tracking Monte Carlo simulation was performed in order to compare simulation and experimental results [10]. The simulation tracks the Stokes parameters and location of simulated photons throughout the scattering environment and when the photon exits the scattering environments back face. The simulation assumes a scattering environment that is a slab of defined length and infinite lateral width. The length of the simulated slab was defined to be the same as the length of the experimental cuvette. The optical collection system utilized in the simulations was also defined to be the same as the experimental configuration (100 µm radius circular collection area and 24.43 degree HFOV). For subsequent analysis and investigation the collection area and HFOV of the simulation were varied.

6. EXPERIMENTAL AND SIMULATION RESULTS

The collected DoP for the scattering environment of 1 µm polystyrene microspheres in water with varying optical thickness is shown in Figure 2. This figure also shows the simulation results for the same scattering environment and collection optics but with an infinite lateral extent of the scattering environment. Circular polarization maintains its DoP better than linear polarization. Circular polarization persists through larger optical thicknesses better than linear polarization for this forward scattering environment both in simulation and experimental results. Linear polarization measurements maintain higher DoP than that predicted in simulations. This departure of the DoP measured and simulated for linear polarization is hypothesized to be due to the limited lateral extent of the cuvette used in the experiment. Freund and Kaveh commented on this same issue in response to MacKintosh, et al.'s polarization memory work [11,12]. The walls of the cuvette can cause internal reflections from the glass surface that is not taken into account in the simulation results. These reflections from the cuvette walls are polarization dependent. We observed in measurement that circular polarization is less affected by the internal reflections compared to linear polarization. Circular polarization is more tolerant of the scattering environment and optical collection system configuration (shown in the next section) than linear polarization. Overall, circular polarization outperforms linear polarization in maintaining its DoP through increasing optical thickness in both simulation and experiment for the 1 µm particle forward scattering environment.

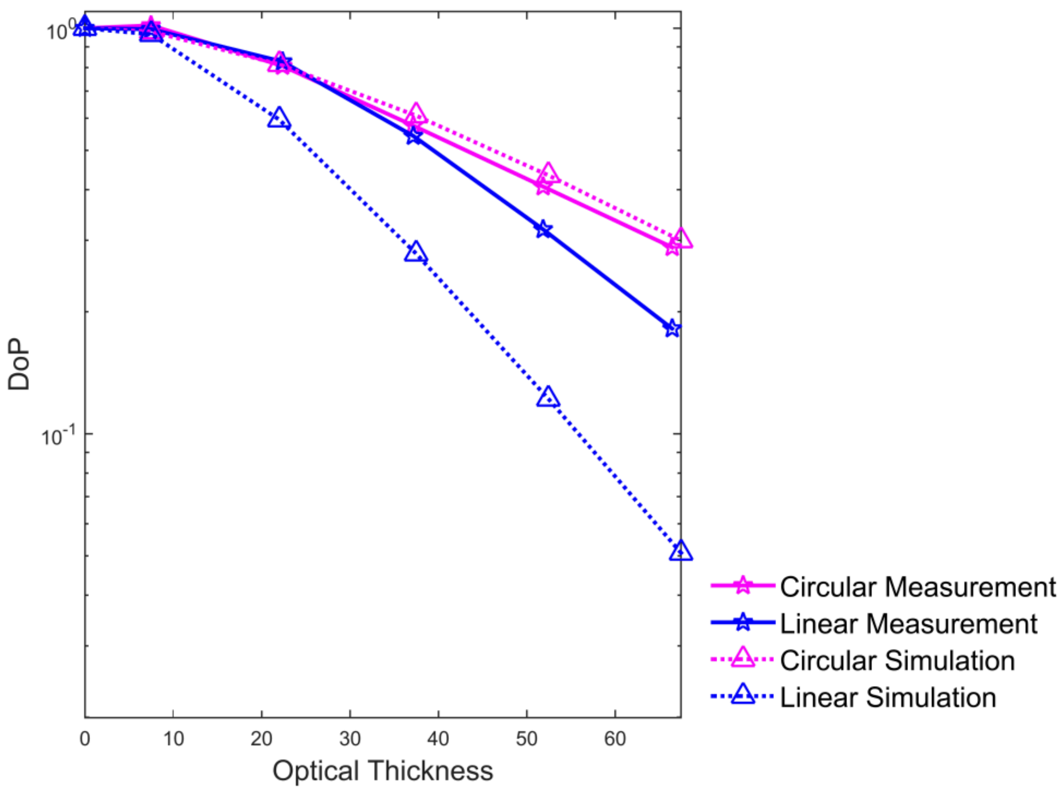

Figure 2 - Experimental and simulation results: DoP vs optical thickness for circular and linear polarizations in a forward scattering environment of 1 µm polystyrene microspheres in water.

7. SIMULATION RESULTS FOR VARIED COLLECTION AREA AND ANGLE

After observing the difference in linear and circular polarization's sensitivity to the experimental scattering environments lateral extent; simulations were performed to investigate variations in polarization persistence when the field of view and collection area of the simulated optical system were varied. This section shows simulation results for various angular field of views and collection areas for the 1 µm polystyrene microspheres in water forward scattering environment.

Figure 3 and Figure 4 show simulation results for variations in field of view and collection area for linear polarization (Figure 3) and circular polarization (Figure 4). Each figure consists of four separate plots. The individual plots correspond to increasing angular field of views: a) 10 degree HFOV, b) 30 degree HFOV, c) 50 degree HFOV, and

d) 70 degree HFOV. Within each plot there are four lines of data corresponding to different collection areas. The collection area is defined as a circular area with radii 0.25, 0.5, 1, and 2 cm.

For this forward scattering environment, the collected scattered light's DoP for linearly incident polarization decreases when either the field of view or the area of collection is increased. Increasing the field of view of the system has a smaller effect on the collected DoP than increasing the collection area. There is a loss in the DoP collected as the field of view increases, but the effect is small.

Collecting scattered light from a larger area causes a much larger change in the collected DoP. When the collection area's radius is 0.25 or 0.5 cm there is no significant change in the collected DoP. As the radius of the area collected increases beyond 0.5 cm there is more and more of a change in the collected DoP. Collected light from incident linearly polarized light scattered to larger areas have decreased DoP.

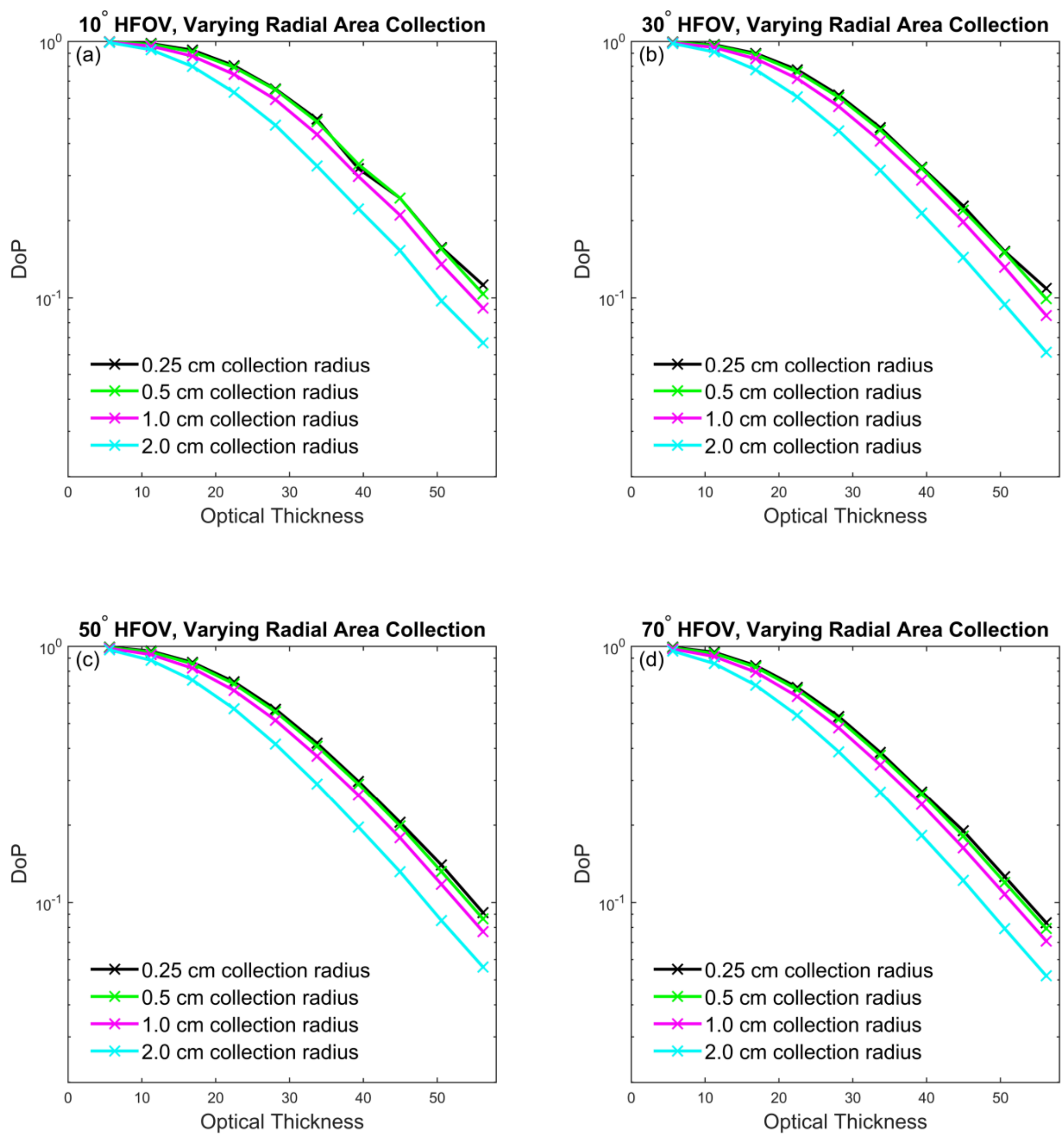

Figure 3 - DoP vs optical thickness: incident linear polarization, varied field of view and collection area

Compared to linear polarization, circular polarization shows a very different behavior. For circularly incident polarized light, varying both the collection field of view and area result in almost no real change in the collected scattered light's DoP. In Figure 4, the four subplots look nearly identical. Increasing the field of view collected shows no change in the collected DoP. Even photons multiply scattered at large angles are highly polarized for incident circular polarization.

When the collection area is increased there is a small variation in the collected light's DoP. As the collection area is increased the collected DoP decreases less than 0.1, a very small and insignificant change. Circular polarization's transmitted DoP is not affected largely by changes in the field of view or collection area for this forward scattering environment.

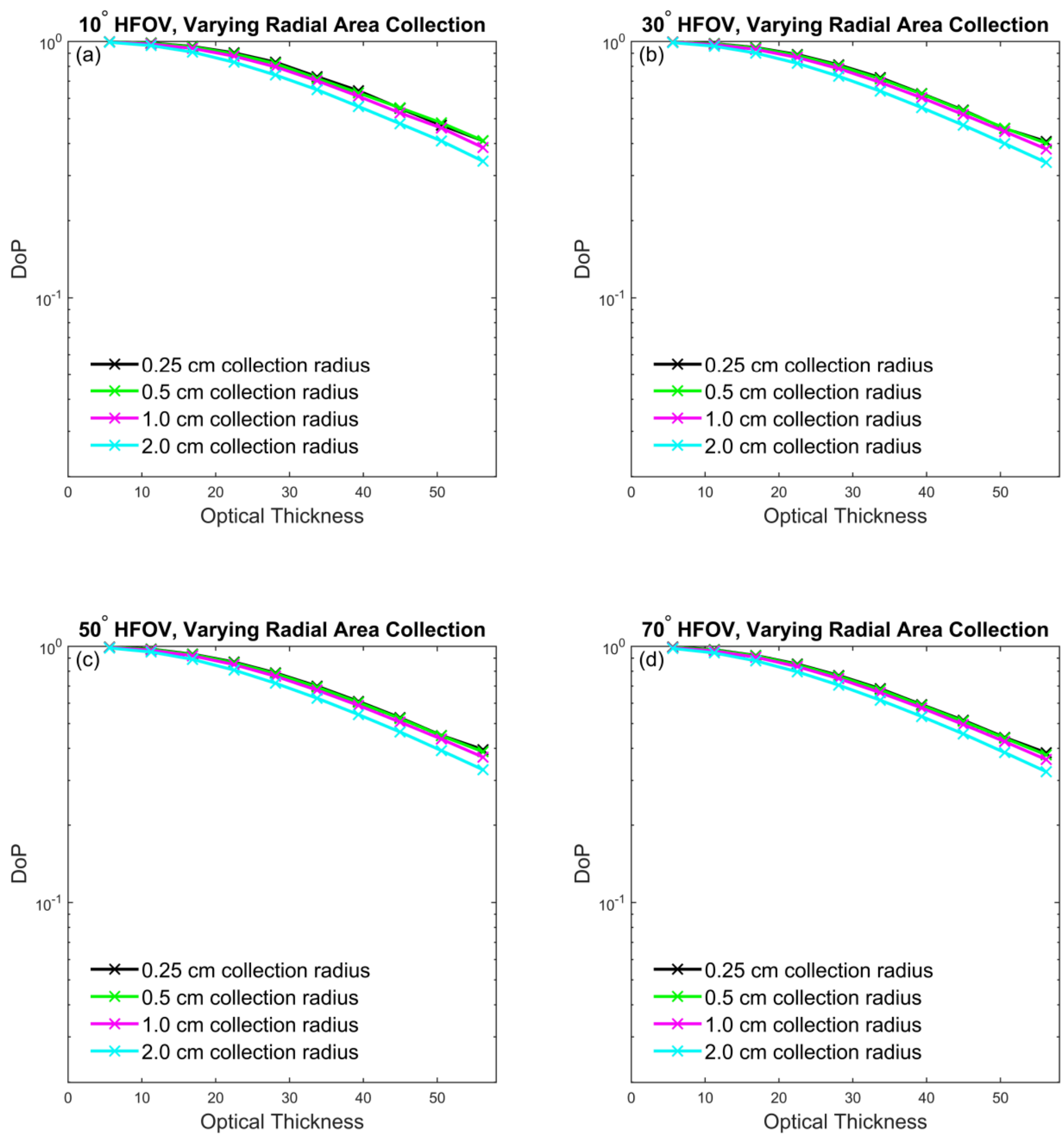

Figure 4 - DoP vs optical thickness: incident circular polarization, varied field of view and collection area

For this forward scattering environment of 1 μm polystyrene microspheres in water, circular polarization is more tolerant to changes in the collected field of view and collection area than linear polarization. These simulation results for varied field of view and collection area add to the evidence why the linear polarization experimental results do not match the original simulation. Linear polarized light is more susceptible to variations in the collection area and photons that are scattered off the original axis of the beam. The experimental cuvette used interfered with the off-axis polarized photons more than the circularly polarized photons. Since circular polarization is indiscriminate of the collected field of view and collection area, the effects of the cuvette walls is not as detectable compared to linear polarization.

8. CONCLUSIONS

Circular polarization maintains its DoP through increasing optical thickness better than linear polarization for a forward scattering environment of 1 μm polystyrene microspheres in water. Circular polarization's better performance was shown in measurements made through the scattering environment with a laser illumination wavelength of 543.5 nm. The experimental and simulation results show the same trend of circular polarization outperforming linear polarization, but experimental results for linear polarization deviated from those predicted in simulation. It was hypothesized that the limited lateral extent of the experimental cuvette compared to the infinite extent of the simulation accounts for the deviation in the measured DoP and the simulated DoP for linear polarization. This hypothesis was investigated in subsequent simulations for varied field of view and collection area. Linear polarization is susceptible to the variation of both the field of view and collection area, although the variation due to field of view changes are small. Uniquely, the effect of changing the field of view and collection area for incident circular polarization is nearly non-existent. Circular polarization is much more tolerant to changes in the field of view or collection area of the optical collection system compared to linear polarization. This characteristic of circular polarization makes it ideal and flexible for use in a wide range of optical sensing systems.

9. REFERENCES

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