Enpolarization of light by scattering media

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Abstract: The polarization of a coherent depolarized incident light beam passing through a scattering medium is investigated at the speckle scale. The polarization of the scattered far field at each direction and the probability density function of the degree of polarization are calculated and show an excellent agreement with experimental data. It is demonstrated that complex media may confer high degree of local polarization (0.75 DOP average) to the incident unpolarized light.

OCIS codes: (260.5430) Polarization; (260.2130) Ellipsometry and polarimetry; (030.6600) Statistical optics; (290.5855) Scattering, polarization; (030.6140) Speckle; (030.1640) Coherence.

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1. Introduction

The state of polarization is one of the main observable parameters of an optical field. Many practical situations exist that make the light polarization properties depend on the spatial location. Indeed the polarization state of a light beam [1–4] will change by propagation in free-space [5, 6], by propagation in turbulent atmosphere [7, 8], by beam combination [9], after scattering by a rough surface [10–15] or an inhomogeneous medium [16–20]. Most of these works are devoted to the loss of polarization that can take place on the incident light, considering a full polarization but different spatial and temporal coherence properties for the incident beam. Different formalisms were proposed including Mueller-Stokes [18], cross spectral density matrices [8] and electromagnetic theories. Such loss of polarization (or depolarization process) most often originates from a temporal average of uncorrelated polarization modes of the optical field [5, 7, 8, 12, 16, 18, 19], though spatial average may also be responsible for depolarization of a fully polarized incident beam [10, 11, 13, 14, 17, 21] when the state of polarization rapidly varies within the detection area.

Scattering by arbitrary inhomogeneous media is known to modify the polarization or depolarization properties of the illumination beam. Usually the incident polarization of a light beam is lost after scattering by a highly inhomogeneous medium, which reduces the interest of polarimetric techniques to probe complex media [14]. However one can have the benefits of a reversible effect in the sense that the same media may allow to significantly increase the polarization degree of a fully depolarized incident light. This is the scope of this paper where it is shown that unpolarized light can be "ordered" by a scattering process.

Repolarization of light has been observed by different authors; in particular Mujat and Dogariu [9] used beam combination inside an interferometer and emphasized a procedure to produce partial polarization at the system output, though the input was unpolarized light. In this work similar results are obtained with light scattering in the far field, though the scattering process is strongly different from that of specular beams. A phenomenological approach is first used to calculate the spatial repartition of the local degree of polarization (dop) of incident unpolarized light after transmission in the far field by a disordered medium. The average value and the probability density function (pdf) of the dop are investigated and an excellent agreement is obtained between numerical and experimental results. The high average polarization degree of light ($\approx$75%) compared with the incident one (<4%) allows considering that light has been locally *ordered* when passing through the disordered medium.

Emphasis must be given to the fact that this scattered-induced repolarization process is a local effect (ie. at one space location) which is here calculated and measured at the speckle scale in the far field. In other words, the polarization degree (dop) that we address is connected with a local temporal average of the scattered field and can be spatially distributed.

The modification of polarization is demonstrated at each position of space, and we then study its spatial distribution. Hence such effect would not be confused with another global DOP which describes the average polarization that can be measured when a great number of speckle grains are collected within the detector aperture. This last phenomenon includes an additional spatial average and was previously investigated through a multiscale approach [14] to take account of the detector aperture. Its value can be deduced from speckle histograms [13]. Therefore and contrary to the local dop, the global DOP remains equal to zero when the incident light is unpolarized. In other words, the spatial average of local dop is most often different from the global DOP.

2. Repolarization by a scattering process: principles

2.1 The incident unpolarized field

Let us consider a coherent and depolarized incident light beam characterized by the electric field $E(r,t)$ illuminating a scattering medium whose Jones matrix is denoted $M = (\nu_{uv})$, and r is the spatial coordinate. In the plane $z = z_0$ (Fig. 1), this field is written as:

$$E(r,t) = \sqrt{I(r)}\begin{pmatrix} e_s(t) \\ e_p(t) \end{pmatrix} \tag{1}$$

where $\sqrt{I(r)}$ and $\begin{pmatrix} e_s(t) \\ e_p(t) \end{pmatrix}$ describe spatial and temporal variations. The degree of polarization of E(r,t) is assumed to be zero whatever the r location. Therefore, at any point of the plane $z = z_0$, no temporal correlation exists between the Transverse Electric (TE or s) and the Transverse Magnetic (TM or p) modes, so that the complex modes correlation follows:

$$\mu = \frac{\left\langle e_s(t)\overline{e_p(t)}\right\rangle}{\sqrt{\left\langle \left|e_s(t)\right|^2\right\rangle \left\langle \left|e_P(t)\right|^2\right\rangle}} = \left\langle e_s(t)\overline{e_p(t)}\right\rangle = 0 \tag{2a}$$

with bars denoting the complex conjugation. In this relation, e_S (t) and e_P (t) are normalized as:

$$<| e_S(t) |^2> = <| e_P(t) |^2> = 1 \tag{2b}$$

The brackets <> stand for the temporal average. The spectral bandwidth $\Delta\omega$ of $E(r,t)$ is centered on the average frequency ω_0 and matches the quasi-monochromatic condition: $\Delta\omega/\omega_0 << 1$. Moreover this beam illuminates a scattering medium whose linear response is not frequency-dependent within the spectral domain, in order to preserve temporal coherence. In relation (2a) the correlation μ represents the non-diagonal term of the coherency matrix as defined in [22]

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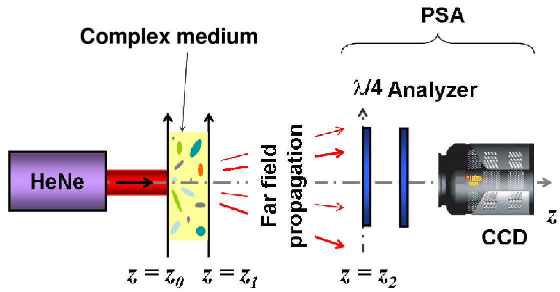

Fig. 1. Schematic view of the experiment.

2.2 The scattered field

Therefore, following the schematic view of Fig. 1, one can write the field E^{sc} scattered in the far field at one direction at infinity as $E^{sc} \approx M\, E$, that is:

$$E^{sc} = \begin{pmatrix} \nu_{ss} e_s(t) + \nu_{ps} e_p(t) \\ \nu_{sp} e_s(t) + \nu_{pp} e_p(t) \end{pmatrix} = \begin{pmatrix} E_S^{SC} \\ E_P^{SC} \end{pmatrix} \quad (3)$$

where the scattering coefficients (ν_{uv}) of the Jones matrix M are for the v-polarized scattered waves resulting from a u-polarized illumination. Notice here that relation (3) is for the field scattered at a particular direction at infinity in the far field; that is, the scattering coefficients ν_{UV} and the Jones matrix M are direction dependent. Notice also in this relation the absence of wave packet to take into account the propagation from z_1 to z_2; indeed we know from the stationary phase theorem [4] that in the far field at infinity, the wave packet (whose first-order approximation gives the Fresnel formalism) that describes the exact field at a particular direction can be reduced to a single Fourier component of the packet, here characterized by the (ν_{uv}) coefficients. In other words, the scattered field is described by a plane wave in the far field.

Therefore and as usually done in the light scattering community, the (ν_{uv}) coefficients can be predicted with exact electromagnetic methods [23–28] provided that the microstructure of the scattering medium is known [14]. However these numerical techniques are highly time-consuming for 3D arbitrary bulk structures and may not converge. For this reason we will use in the next section a fully developed speckle model [29] to predict the statistical angular behaviour of the (ν_{uv}) matrix. Within this approach and considering a bulk scattering process, the four (ν_{uv}) terms are known [13] to be mutually uncorrelated for a lambertian sample and to have similar average speckle patterns.

Notice also that these calculation methods take into account the whole illuminated area on the sample under study. Moreover, because the complex medium under study is perfectly identified, there is no need to average the electromagnetic calculation over multiple realizations; in other words, the sample has not to be translated or rotated, and the Jones matrix is perfectly identified and unique for one sample position. Indeed any motion of the sample would create a spatial average and cancel specific polarization signatures (the local dop would be turned into the global DOP). To summarize, the variation of scattering coefficients with direction or localization is deterministic and can be fully predicted with electromagnetism, whatever their derivatives.

2.3 Polarization parameters

The degree of polarization is defined from the coherence matrix in [[22], Eq. (4), 3-36, p136]. It is connected with the time averages of the modes squares and to their cross-correlation. For the scattered light this quantity is local and varies with location or direction. Comparison of theory and experiment can be immediate when the speckle is resolved.

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Let us now express this dop^{SC} of the scattered field E^{sc} as a function of the correlation μ^{sc} between its polarization modes:

$$dop^{sc} = \sqrt{1-4\beta\left(1-\left|\mu^{sc}\right|^2\right)/\left(1+\beta\right)^2} \tag{4}$$

with β the polarization ratio:

$$\beta = \frac{\left\langle \left|\nu_{SS}e_S(t)+\nu_{PS}e_P(t)\right|^2\right\rangle}{\left\langle \left|\nu_{SP}e_S(t)+\nu_{PP}e_P(t)\right|^2\right\rangle} = \frac{\left\langle \left|E_S^{SC}\right|^2\right\rangle}{\left\langle \left|E_P^{SC}\right|^2\right\rangle} \tag{5}$$

and the correlation:

$$\mu^{sc} = \frac{\left\langle \left(\nu_{SS}e_S(t)+\nu_{PS}e_P(t)\right)\overline{\left(\nu_{SP}e_S(t)+\nu_{PP}e_P(t)\right)}\right\rangle}{\sqrt{\left\langle \left|\nu_{SS}e_S(t)+\nu_{PS}e_P(t)\right|^2\right\rangle\left\langle \left|\nu_{SP}e_S(t)+\nu_{PP}e_P(t)\right|^2\right\rangle}} = \frac{\left\langle E_S^{SC}.\overline{E_P^{SC}}\right\rangle}{\sqrt{\left\langle \left|E_S^{SC}\right|^2\right\rangle\left\langle \left|E_P^{SC}\right|^2\right\rangle}} \tag{6}$$

Provided that all media are static (the scattering coefficients are time constants), and taking into account relations (2a), (2b), relations (5) and (6) are turned into:

$$\beta = \frac{\left|\nu_{SS}\right|^2+\left|\nu_{PS}\right|^2}{\left|\nu_{SP}\right|^2+\left|\nu_{PP}\right|^2} \tag{7}$$

and

$$\mu^{sc} = \frac{\nu_{ss}\overline{\nu}_{sp}+\nu_{ps}\overline{\nu}_{pp}}{\sqrt{\left(\left|\nu_{ss}\right|^2+\left|\nu_{ps}\right|^2\right)\left(\left|\nu_{sp}\right|^2+\left|\nu_{pp}\right|^2\right)}} \tag{8}$$

Therefore and because the *(ν_{uv})* coefficients are independent in the general case of arbitrary scattering media, Eq. (8) ensures that the temporal correlation μ^{SC} will not be identically equal to zero, but will be distributed in modulus within the interval [0;1] depending on space location and sample microstructure. Extreme situations may occur when this correlation is zero or unity. The first situation (zero correlation) is that of slightly inhomogeneous samples (polished surfaces or transparent bulk substrates) that are known [28] to exhibit negligible cross-scattering coefficients ($\nu_{UV} \approx 0$) in the incidence plane; with these samples the temporal correlation remains zero ($\mu^{SC} = 0$) and the scattered light remains unpolarized ($dop^{SC} = 0$) if the polarization ratio is unity ($\beta = 1$). On the other hand, in the general case of arbitrary samples, the presence of cross-scattering coefficients will make the temporal correlation and the dop^{SC} not to be zero. So, even though the illumination beam is perfectly unpolarized, relation (8) shows that the scattered light can be partially or totally polarized in the far field depending on the scattering samples and the space direction.

3. Comparison of experiment and numerical calculation

3.1 Numerical calculation

Numerical simulation has first been performed to illustrate this phenomenon. We did not use exact electromagnetic theory because time-consuming is prohibitive for 3D bulk calculation. Instead of that we used a fully developed model from Goodman [29] where each speckle pattern *(ν_{uv})* is obtained via the Fourier Transform of a random phasor matrix [29]. Here, the non-zero domain is a square of 2^7 points length within a square of 2^{10} points length.

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Figure 2(a) shows the spatial repartition of the local dop^{SC} of the scattered far field at infinity in a plane perpendicular to propagation. Depending on the space location (or direction), the dop varies from 0 to 1. Therefore it is different from that of the incident light, which was zero at any location. Such result is in agreement with the prediction of relation (8) given in the preceding section.

One can also address statistical properties of the local dop of the scattered light. Taking all data of Fig. 2(a), we extracted the dop spatial histogram and plotted the resulting probability density function (see Fig. 2(b)). We notice that the pdf dop function follows a $p(u) = 3u^2$ law, and the resulting spatial average of local dop is found to be:

$$\int_0^1 up(u)du = 3/4 \tag{9}$$

Such value emphasizes a significant increase of local polarization. Notice that the pdf function and the average are here deduced from numerical simulation and not by theoretical analysis of the statistical properties of the scattering process. Equation (9) indicates that light scattered by a highly inhomogeneous sample under unpolarized illumination will exhibit a 75% average of local polarization degree. In other terms, polarization modes have recovered partial order at the speckle size when passing through the disordered medium.

Notice again that these results would not be confused with the global DOP which is different from the spatial average of the local DOP; in our configuration the global DOP is close to zero, due to the spatial independence of the scattering coefficients, and to their quasi-identical spatial mean squares [14].

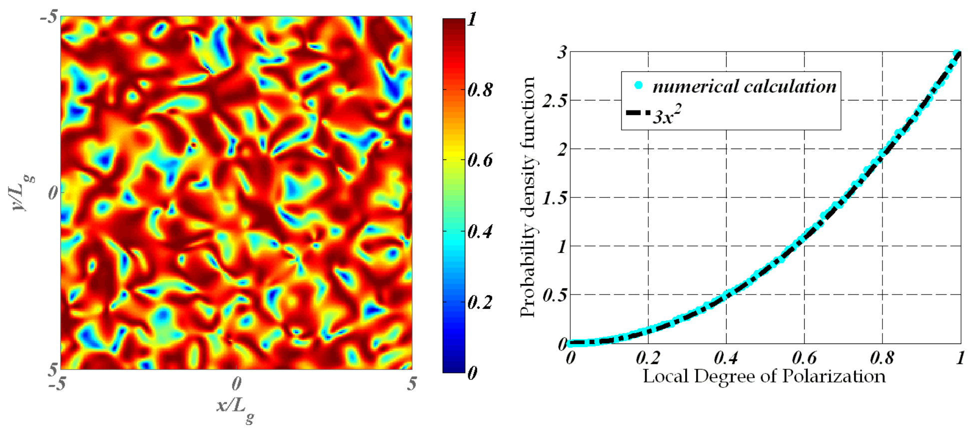

Fig. 2. (a-b): Calculation (left figure- a) of the local DOP in the far field with a random phasor matrix. The resulting dop average is 0.75. Lg is the mean speckle size. Probability density function (right figure- b) of the local degree of polarization.

3.2 Experiment

To go further, experiment has been used to confirm the process of local repolarization by a scattering medium. For that we used a MgF_2 sample often used for calibration in scattering apparatuses. This means that the sample scatters all the incident light and that its angular pattern follows a lambertian law (cosθ curve, with θ the scattering angle). Moreover, previous experiments [13] have shown that scattering from this sample originates from its bulk, due to the transparency of MgF_2.

The sample was illuminated with a collimated He-Ne (λ = 632.8 nm) unpolarized (incident dop ≈4%) laser beam of 3 mm diameter. The mean speckle size at the 1m distance associated to the measurement is L_g = 0,2mm. The local dop^{SC} of the light scattered in the far field is classically measured [22] via the four Stokes images measurement. No lens is present in the system (Fig. 1). The optical elements of the PSA are a quarter wave plate, a linear analyzer and a high sensitivity 1024*1024 pixels CCD array. Figure 3(a) shows the transverse variations of the local dop^{SC} recorded in the far field, which varies from 0 to 1 depending on space location. Again the measured spatial average of this dop is 0.75, and the pdf law follows $3u^2$ (see Fig. 3(b)), in excellent agreement with prediction. Notice that this result is intrinsically related to the random phasor model [29], and thus should hold for most high scattering media. On the other hand, samples with lower scattering will surely emphasize different pdf laws.

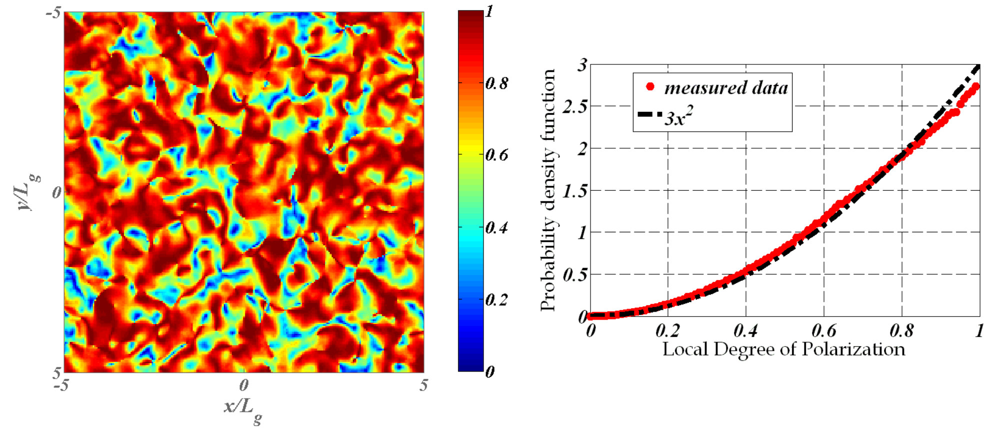

Fig. 3. (a) Measurement of the local dop in the far field. The resulting average is 0.75 Probability density function (right figure- b) of the local degree of polarization.

4. Conclusion

Calculation and measurements have shown excellent agreement to emphasize the process of light repolarization by scattering media at the speckle scale. An illustration was given with a highly inhomogeneous bulk and the result is a 0.75 average degree of local polarization and a $3u^2$ pdf probability local dop function.

One may wonder whether specific media could allow to confer full local polarization to the scattered light resulting from unpolarized illumination. Following relation (8), one can show that such media would exhibit scattering coefficients following the condition:

$$v_{ss}v_{pp} = v_{sp}v_{ps} \tag{10}$$

Such condition cannot be fulfilled in the framework of first-order theories [29], but could occur when multiple reflection dominates scattering. Because it cancels the determinant of the Jones matrix, relation (10) would allow different incident waves to create the same speckle pattern. However keeping the condition for all speckle grains does not appear realistic a priori. Relation (10) addresses inverse problems outside the scope of this paper.

It is also necessary to notice one key difference in the repolarization processes obtained by beam combination inside an interferometer [9] and by light scattering. In the first situation and though the beams are combined, there is no mixing (S with P) of the polarization modes, which means that only the S modes (resp. P modes) are superimposed for each beam. Therefore the modes cross-correlation is not changed (remains equal to zero) and temporal disorder is not reduced: the repolarization process only results from the relative weight of energy carried on each axis, which was modified by the interferometer; to be complete, in such experiment repolarization of light is connected with the polarization ratio β and vanishes in the case β = 1, due to the relationship:

$$\mu = 0 \Leftrightarrow DOP = |1-\beta| / |1+\beta| \tag{11}$$

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On the other hand, light scattering allows a spontaneous mixing of the polarization modes (see relation (3)), due to the presence of cross-scattering coefficients. Such mixing of S and P modes describes a linear combination of random variables (the polarization modes) on each axis. Hence the resulting variables on each axis may exhibit new cross-correlation values, though the initial ones were totally uncorrelated: the temporal disorder can be reduced, which allows the repolarization process. This result is valid whatever the β value. Notice also that this scatter-induced repolarization process would vanish in the absence of cross-scattering coefficients, what can occur at low scattering levels predicted with perturbative theories [23, 30] and characteristic of slightly inhomogeneous media.

All results provide new signatures for the identification of disordered media under unpolarized illumination; indeed the average dop value and its histogram are microstructure-related and can be calibrated versus structural parameters of samples. In other words, and provided that the dop histogram has been calculated for different bulk inhomogeneities, direct comparison to experiment will help in the identification of samples.

Applications concern security and remote sensing, biophotonic and biomedical optics, lighting, microscopy and metrology.

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