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:

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

and the correlation:

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

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].

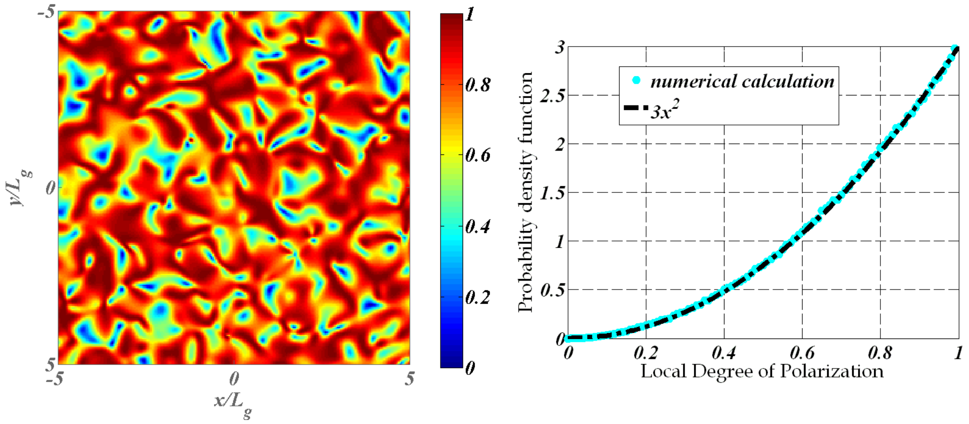

Fig. 2. (a-b): Calculation (left figure- a) of the local DOP in the far field with a random phasor matrix. The resulting dop average is 0.75. Lg is the mean speckle size. Probability density function (right figure- b) of the local degree of polarization.

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.

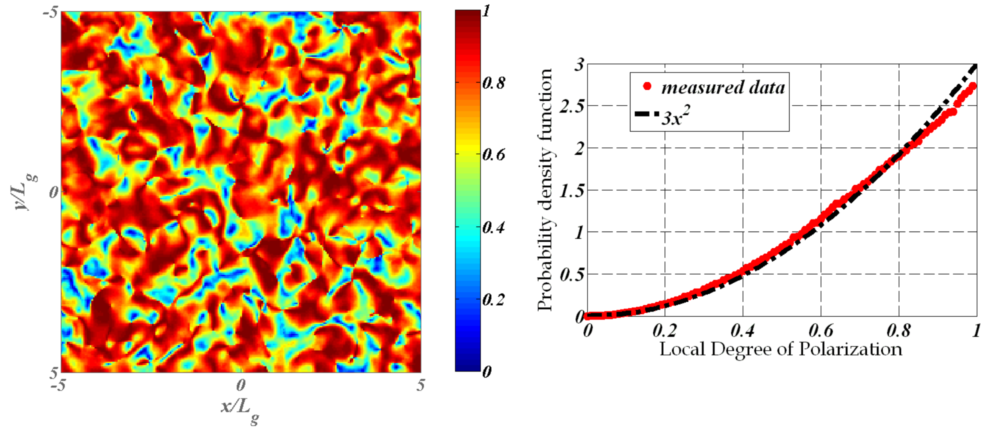

Fig. 3. (a) Measurement of the local dop in the far field. The resulting average is 0.75 Probability density function (right figure- b) of the local degree of polarization.

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:

$$v_{ss}v_{pp} = v_{sp}v_{ps} \qquad (10)$$

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:

$$\mu = 0 \Leftrightarrow DOP = |1-\beta| / |1+\beta| \qquad (11)$$

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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