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Dynamical charge inversion of polarization correlation vortex in propagating vector speckle field

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Abstract

A study on first-order polarization correlation in propagating vector speckle fields is carried out. Vector speckle field, generated by scattering of Poincare beam, is propagated through a spherical and a cylindrical lens. The first-order polarization correlation is experimentally constructed from intensity images of vector speckle fields at various planes before and after the focal plane. We have shown with supporting experimental and simulation results that polarization correlation vortex experiences charge inversion while vector speckle field propagates through a cylindrical lens. The importance of this study relies on the fact that it provides insight into one of the important properties of light, i.e. the phase between the orthogonal polarization components, how it evolves as the optical field propagates through various optical components. This study could find application in optical data processing, imaging, sensing, speckle meteorology, phase unwrapping, optical communication, etc.

Keywords: optical speckle, polarization, correlation optics, singular optics, vector-vortex beam, poincare beam

(Some figures may appear in colour only in the online journal)

1. Introduction

Optical speckles are, in general, classified as stochastic electromagnetic fields [1], having spatially varying intensity distribution. Speckle field consists of bright and dark intensity spots, arising due to the superposition of randomly scattered coherent light. This makes it unavoidable in the optical systems using coherent illumination as a source.

Optical speckles were considered as noise, limiting the performance of any well-corrected optical system, until 1963, when various studies related to speckle interferometry began with emerging holography techniques [2]. These studies lead to early applications of optical speckles in optical processing [3, 4] and data storage techniques [3–6].

With advancements in technologies, recent studies in the field revealed various potential applications of speckles in speckle interferometry [7, 8], speckle correlometry [7], speckle image velocimetry [9], optical speckle sensors [10–12], speckle myography [13], cardiovibration measurements [14], study of quantum transport phenomena [15], subwavelength imaging [16], subwavelength focusing [17], aberration-free imaging [18], etc.

Speckles being random electromagnetic fields, various statistical phenomenon involving its intensity, phase, and polarization have been studied [1, 3, 5, 6, 19–23]. Various statistical quantities calculated for speckle field have shown promising applications in the fundamental studies of optical singularities [24–26] to the advanced studies of optical holography [27–29] and object recognition techniques [30]. One such useful statistical tool that has promised extraordinary applications in information acquisition and data processing techniques is the

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Correlation function. Some of the advanced techniques such as ghost imaging [31, 32], correlation holography [32–34], super-resolution microscopy [35], etc become possible due to correlation techniques only.

Coherence singularities in propagating coherent and partially coherent optical fields have been studied [36–39]. In the recent past, technique for the controlled synthesis of coherence and polarization were investigated by making use of intensity correlations [40]. Also, first-order polarization correlation singularity and stokes field auto-correlation (fourth-order correlation) singularities were studied in the vector speckle far-field generated from the scattering of Poincare beam [41–43]. It was shown that the information about the topological properties of the input beam that was used to generate the vector speckle field can be obtained from these correlations [42, 43].

Moving further in this direction, in this paper, the first-order polarization correlation is studied in propagating vector speckle field. Vector speckle field can be considered as a special type of vector field having speckle intensity profile, whose spatially varying polarization states can not be analytically expressed by mathematical equations. Here, we have focused only on the correlation between the orthogonal polarization components of the scattered field. Which is, from now onwards, referred to as the polarization correlation. The singularity arising in this polarization correlation, the polarization correlation vortex, propagating through a spherical and a cylindrical lens is studied. It is experimentally realized and supported with simulation results that the polarization correlation vortex experiences charge inversion when propagated through a cylindrical lens. It is crucial to note that, majority of the previous studies have been done for either various types of intensity correlations or higher-order correlations and their applications [9, 27, 40, 43], which are relatively easy to obtain experimentally since the detectors are sensitive to the intensity of the incident field. Whereas, we have studied the first-order field correlation in vector speckle field, which are difficult to obtain experimentally. So, here we proposed a pragmatic approach for experimental determination of polarization correlation which is proven to give the analogous results as the exact polarization correlation.

2. Theory

Consider the input field as the Poincare beam, a coaxial superposition of x-polarized Gaussian beam and y-polarized Vortex beam of charge +1. Mathematically it can be expressed as

$$\vec{E}_{\mathrm{PB}} = E_x e^{i\phi_x}\hat{e}_x + E_y e^{i\phi_y}\hat{e}_y = \left(\hat{e}_x + \rho e^{i(|l|\theta+\delta)}\hat{e}_y\right)E_{\mathrm{GB}}. \tag{1}$$

Here, $\rho = \sqrt{x^2+y^2}$, $\theta = \tan^{-1}(y/x)$, E_{GB} is the field of Gaussian beam, l is the vortex charge and δ is the phase difference between $(\phi_x + |l|\theta)$ and ϕ_y.

Scattering of this field from the rough surface having wavelength scale irregularities generates vector speckle field following Gaussian statistics. This scattered field can be mathematically expressed as

$$\vec{E}_{\mathrm{sc}}(\vec{r}) = F\left(\vec{E}_{\mathrm{PB}} e^{i\phi_R\left(\vec{r'}\right)}\right) = \vec{E}_{\mathrm{Sc}(x)}(\vec{r}) + \vec{E}_{\mathrm{Sc}(y)}(\vec{r}) \tag{2}$$

using Fourier optics concepts [44]. Where, $\phi_R\left(\vec{r'}\right)$ is the random phase introduced by the rough surface.

Vector speckle field, being electromagnetic stochastic field, is characterized by a 2×2 Coherence-Polarization matrix [1]. For statistically stationary ergodic process, this matrix is given by

$$J(\vec{r}_1;\vec{r}_2) = \begin{bmatrix} J_{xx}(\vec{r}_1;\vec{r}_2) & J_{xy}(\vec{r}_1;\vec{r}_2) \\ J_{yx}(\vec{r}_1;\vec{r}_2) & J_{yy}(\vec{r}_1;\vec{r}_2) \end{bmatrix} \tag{3}$$

where,

$$J_{\alpha\beta}(\vec{r}_1;\vec{r}_2) = \langle E^*_{\mathrm{Sc}(\alpha)}(\vec{r}_1) E_{\mathrm{Sc}(\beta)}(\vec{r}_2)\rangle. \tag{4}$$

Here $\langle\cdot\rangle$ denotes the ensemble average.

Now, denoting x- and y-polarized components of the speckle field in its complex representation, $E_{\mathrm{sc}(x)} = E_{0\mathrm{sc}(x)} e^{i\varphi_{E_{\mathrm{sc}(x)}}}$ and $E_{\mathrm{sc}(y)} = E_{0\mathrm{sc}(y)} e^{i\varphi_{E_{\mathrm{sc}(y)}}}$. The first-order exact polarization correlation between x- and y-polarized components of the speckle field is, then, defined as,

$$J_{xy}(\vec{r}_1;\vec{r}_2) = \left\langle E^*_{\mathrm{Sc}(x)}(\vec{r}_1) E_{\mathrm{Sc}(y)}(\vec{r}_2)\right\rangle = \left\langle E^*_{0\mathrm{Sc}(x)}(\vec{r}_1) e^{-i\varphi_{E_{\mathrm{sc}(x)}}(\vec{r}_1)} E_{0\mathrm{Sc}(y)}(\vec{r}_2) e^{i\varphi_{E_{\mathrm{sc}(y)}}(\vec{r}_2)}\right\rangle. \tag{5}$$

For a particular observation plane, this exact polarization correlation is a function of four variables and hence, difficult to measure experimentally.

One can take various approaches for the experimental determination of polarization correlation [45, 46]. We took the pragmatic approach and defined our *pragmatic polarization correlation* as:

$$S_{xy}(\vec{r}_1;\vec{r}_2) = \left\langle \left\{\left|E^*_{0\mathrm{Sc}(x)}(\vec{r}_1)\right|\right\}\left\{\left|E_{0\mathrm{Sc}(y)}(\vec{r}_2)\right| e^{i\Phi_{xy}(\vec{r}_2)}\right\}\right\rangle = \langle\{E^*_1(\vec{r}_1)\}\{E_2(\vec{r}_2)\}\rangle \tag{6}$$

where, $\Phi_{xy}(\vec{r}_2) = \varphi_{\mathrm{Sc}(y)}(\vec{r}_2) - \varphi_{\mathrm{Sc}(x)}(\vec{r}_2)$ contains all the relative phase information in a single phase term. Equation (6) can be physically interpreted as the correlation between $E_1(\vec{r}_1)$ and $E_2(\vec{r}_2)$ fields. Here $E_1(\vec{r}_1)$ is x- polarized field having real amplitude which is speckle in nature and constant (zero) phase, therefore can be called as *speckle plane wave*. The $E_2(\vec{r}_2)$ is the field having amplitude of the y-polarized speckle field with phase equal to the relative phase difference between the x- and y-polarized components of the scattered field. This polarization correlation function (equation (6)) can be easily measured [42]. Therefore, the whole experimental procedure

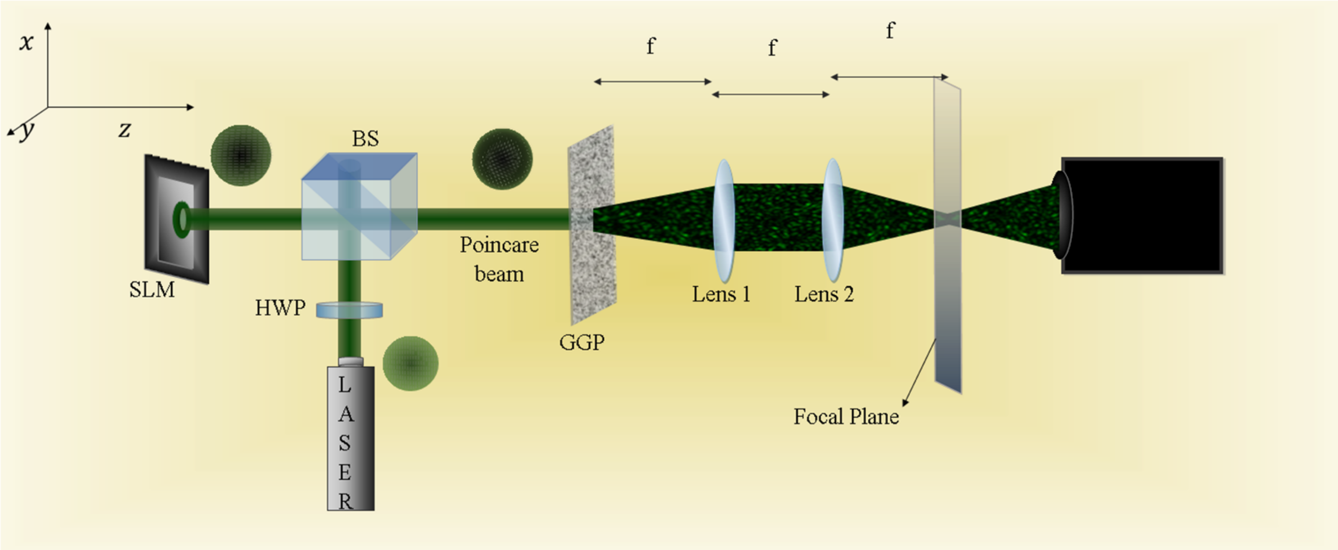

Figure 1. Experimental set-up to study polarization correlation in propagating vector speckle field. SLM: spatial light modulator, HWP: half wave plate, BS: beam splitter, GGP: ground glass plate, CCD: charged couple device.

becomes feasible to study polarization correlation in vector speckle fields.

We know that, $E_{sc(x)}$ and $E_{sc(y)}$ being components of an electromagnetic field, satisfy the wave equation. It has already been theoretically proven that the first-order exact polarization correlation function obeys a pair of wave equations [22]. Propagation of pragmatic polarization correlation function defined in equation (6) is reported in this paper. Which is, from now onwards, referred as a polarization correlation function.

3. Experimental method

The experimental setup to study the propagation of polarization correlation vortex through a spherical and a cylindrical lens is as shown in figure 1. As shown in the figure, a vertically polarized Gaussian beam of light from a diode-pumped solid-state laser, *Coherent-Verdi-V10*, operating at 532 nm, is incident on a half wave plate (HWP). The orientation of HWP is so adjusted that its output contains an equal amount of horizontally and vertically polarized components of light. It is then allowed to fall onto a y-polarization sensitive spatial light modulator (BNS SLM, model P512-0532, pitch 15 $\times$ 15 μm), which is fed with an on-axis vortex hologram. Therefore, y-polarization component of the input light from the beam splitter will be encoded with the vortex phase while the x-polarized component remains unaffected by the SLM. This vortex beam will co-axially superpose with the x-polarized Gaussian beam, giving a poincare beam (PB) [38]. The PB is allowed to pass through a ground glass plate, *DG20-220*, obtained from Thorlab, which is having wavelength scale irregularities. Therefore, the ground glass plate (GGP) will scatter the input PB, giving vector speckle field as an output [41].

Vector speckles obtained in this way, are then allowed to pass through two lenses, lens 1 and lens 2, respectively, having the same focal length f and placed at distance f apart. Here, the Fourier transform property of the lens is used for mathematical simplicity of the analysis [44]. Lens 2 is the element of our interest. We have used a spherical and a cylindrical lens of focal length $f = 20$ cm in place of lens 2 to record experimental data.

Intensities of the polarization components of the propagated speckle field are recorded at various planes before and after the focal plane of lens 2 using a CCD detector. The CCD camera with pixel pitch 4.65 μm $\times$ 4.65 μm is used to capture intensity images of 1392 $\times$ 1040 pixels. The relative phase, $\Phi_{xy}(\vec{r}_2)$, can be determined using Stokes polarimetry [42, 47]. The speckle field obtained in this way will have spatial stationarity at the observation plane [48]. Hence the polarization correlation is obtained using spatial averaging to evaluate equation (6) for respective planes.

4. Results and discussion

The experimental images of the transverse intensity profile of the speckle field propagated through lens 2 is shown in figure 2. Here, the intensity images are shown with hot colormap in order to make the speckles properly visible. Polarization correlations obtained for various planes before and after the focal plane of lens 2 along with their simulation results are as shown in figures 3 and 4. Taking into account the statistical stationarity of the field, the analysis is performed utilizing 250 $\times$ 250 pixels near to the centre of the recorded image (figure 2). It can be noticed from these figures that, the experimental results are matching very well with the simulation results, except for a constant phase difference, which is arising due to different initial relative phase of x- and y-polarized components of the experimental and simulated input fields (equation 1).

Now, considering figure 3 only, it can be noticed that the polarization correlation vortex is uniformly squeezing in both the transverse directions as the field propagates towards the

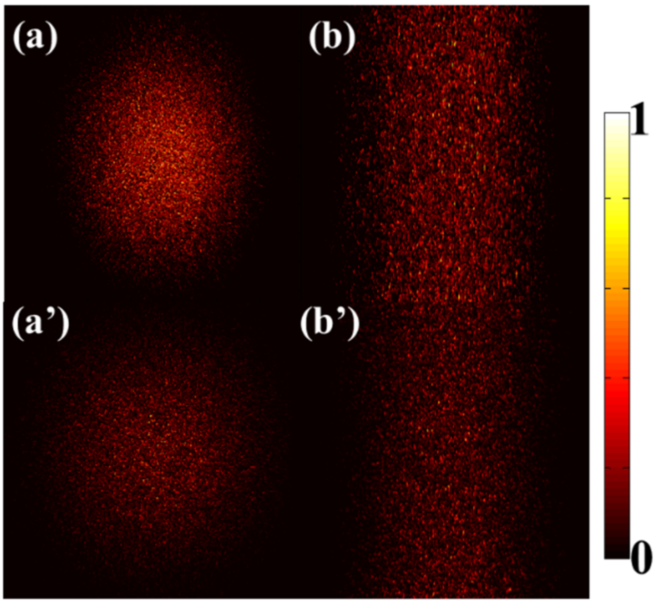

Figure 2. (a), (b) Experimental images of the transverse intensity profile of vector speckle field at $z = +4$ cm plane for focusing using spherical lens and cylindrical lens, respectively. z being the direction of propagation. (a′), (b′) Simulation results corresponding to (a) and (b), respectively. Colorbar is the same for all the images.

focal plane and uniformly expanding as the field propagates away from the focal plane of lens 2, which is the effect of spherical lens focusing. Here, 0 cm denotes the focal plane, negative numbers denote planes before the focal plane and positive numbers denote planes after the focal plane of lens 2. Also, the charge of the polarization correlation vortex before and after the focal plane remains the same. Which is the similar behavior observed when an optical vortex beam propagates through a spherical lens [49].

Now, considering figure 4, it can be noticed that size of the polarization correlation vortex along the vertical direction is the same for all the observations, while it is decreasing in the horizontal direction as we move towards the focal plane and again starts increasing as we move away from the focal plane. i.e. the polarization correlation vortex is non-uniformly squeezed in the transverse direction. This can be understood by the asymmetry introduced by a cylindrical lens. Also, charge inversion in the polarization correlation vortex is observed as it propagates through the cylindrical lens, which is the similar behavior when an optical vortex beam propagates through a cylindrical lens [49].

Thus, we have observed from the experimental and corresponding simulation results that, the polarization correlation vortex is behaving in a similar manner to the optical vortex beam while propagating through lenses and hence we can conclude that the polarization correlation defined in equation (6) propagates satisfying the wave equation.

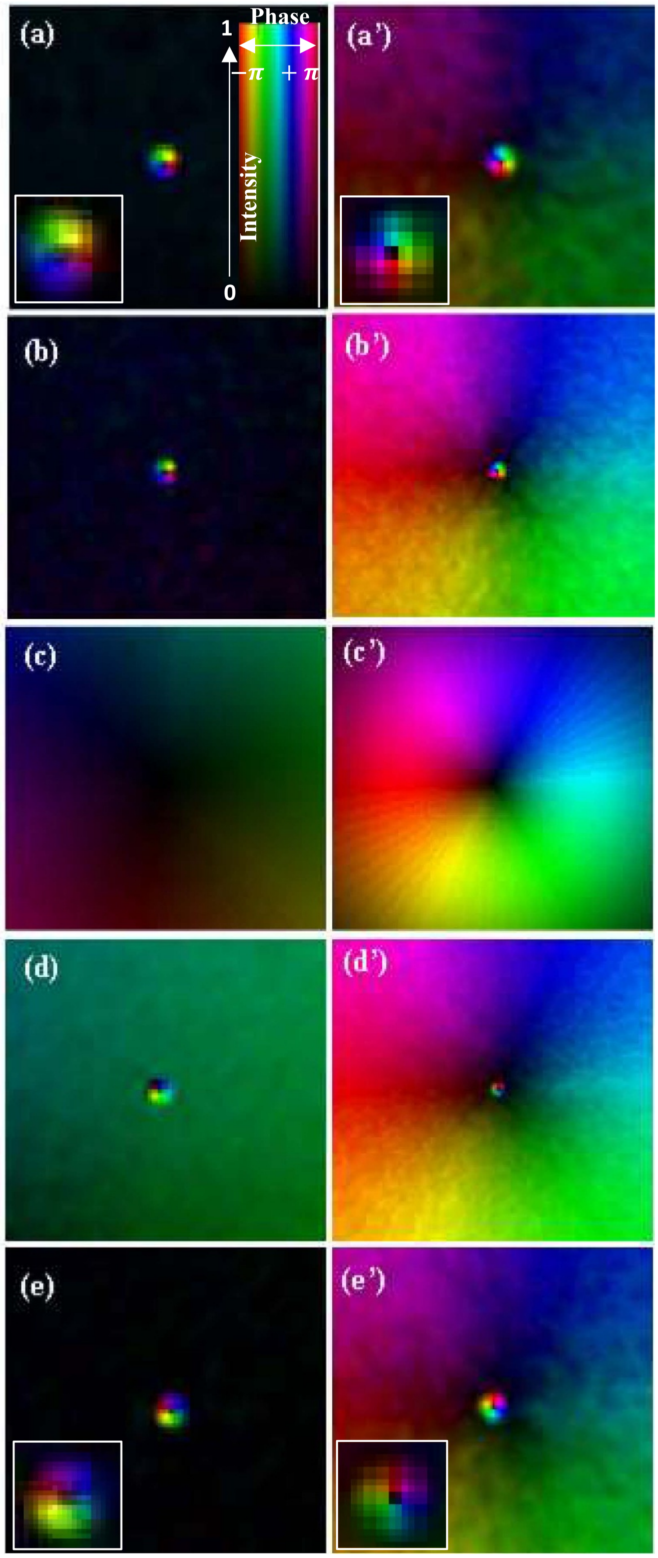

Figure 3. Intensity modulated polarization correlation vortex at $z =$ (a) -6 cm (b) -3 cm (c) 0 cm (d) $+3$ cm and (e) $+6$ cm distance away from the focal plane of spherical lens. (a′)–(e′) are corresponding simulated results. Colorbar is the same for all images as shown in figure (a). Insets show zoomed and cropped images of correlation vortex.

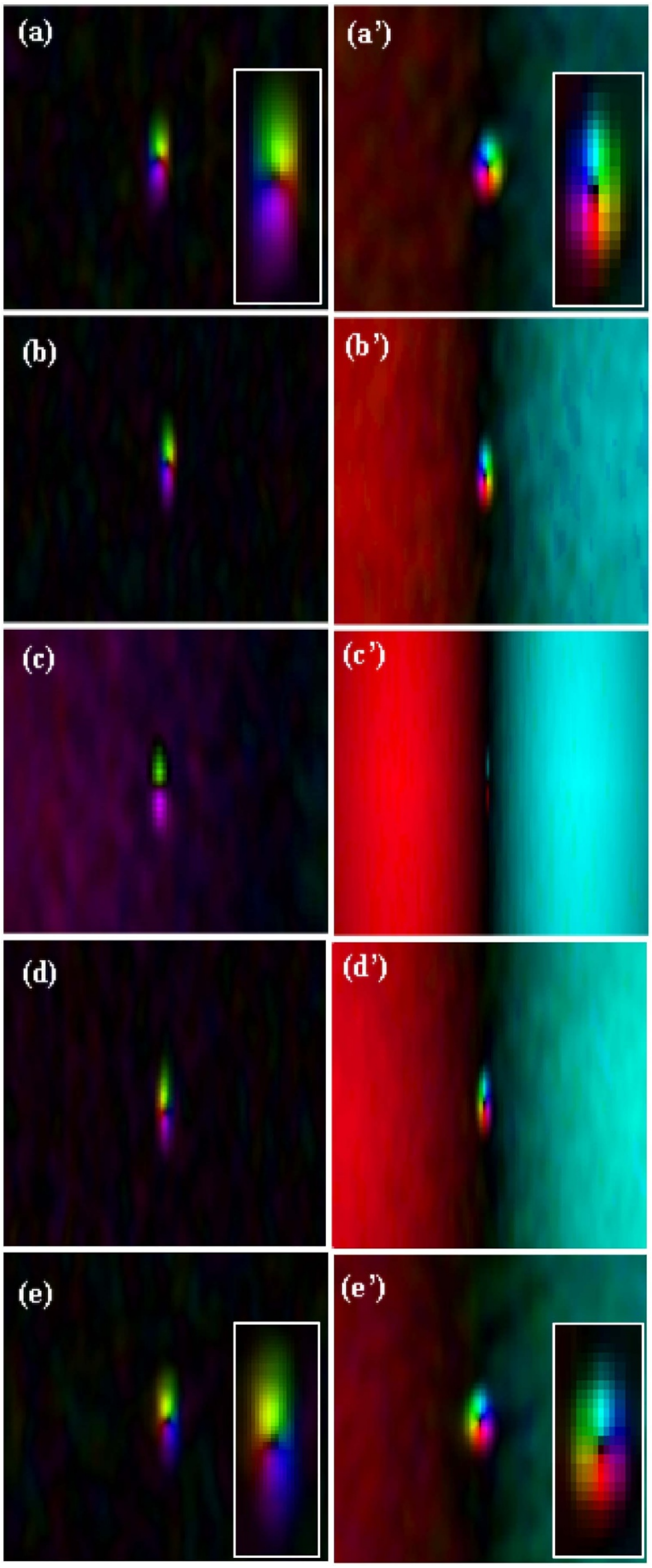

Figure 4. Intensity modulated polarization correlation vortex at z = (a) −6 cm (b) −3 cm (c) 0 cm (d) +3 cm and (e) +6 cm distance away from the focal plane of cylindrical lens. (a′)–(e′) are corresponding simulated results. Colorbar is the same for all images as shown in figure 3(a). Insets show zoomed and cropped images of correlation vortex.

5. Conclusion

To conclude, we discussed a method to study polarization correlation in propagating vector speckle field in detail. Here the vector speckle field is generated by scattering of the Poincare beam using GGP. The first-order polarization correlation is defined and studied in the propagating vector speckle field. The behavior of the polarization correlation vortex is observed as it propagates through a spherical and a cylindrical lens. The experimental results supported with simulations show the dynamic charge inversion of the polarization correlation vortex propagated through a cylindrical lens.

It is also shown that the correlation function defined under certain constraints (equation (6)) is exhibiting the same properties as an exact polarization correlation function, which validates our assumptions for practical implications. Here, the approach we adopted is a general one. But, being an experimental investigation, we restricted ourselves to the particular cases only. We believe that a rigorous mathematical analysis can show the generality of the proposed concept.

Also, being a pragmatic approach, validated for practical application, it is important to know about the quality of the correlation. So, a quantitative analysis [50, 51] to reveal the quality of the correlation along with some mathematical modeling to generalize the discussion, can be taken as a future scope of research. This study shows that the information about the input field before scattering is preserved during propagation of the field correlation, therefore, being a fundamental experimental study on the propagation of field correlation in vector speckle field, its applications in the fields of sensing, imaging and data processing could be exploited in future.

Data availability statement

The data that support the findings of this study are available upon reasonable request from the authors.

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