2024 24th International Conference on Transparent Optical Networks (ICTON) | 979-8-3503-7732-3/24/$31.00 ©2024 IEEE | DOI: 10.1109/ICTON62926.2024.10647635

Unpolarized light: Poincaré Sphere Engineering - From natural light via quantum optics to applications

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ABSTRACT
We investigate the polarization properties of unpolarized light, first in the temporal domain realized by 1.55 µm ASE light emitted by an erbium-doped fiber amplifier and second in the spatial domain by exploiting the polarization dispersion of a Cornu depolarizer. We find novel Stokes parameter correlations and invariances for temporally unpolarized light and novel states on the Poincaré sphere for spatially unpolarized light. All these results give new fresh insight into the field of classical polarization with interesting promising quantum and sensing application perspectives.
Keywords: polarization, Poincaré sphere, polarization correlations, Stokes parameters, polarimetry, polarization metrology.

Richard Feynman:
"If the polarization changes more rapidly than we can detect it, then we call the light unpolarized, because all the effects of the polarization average out."
"Light is unpolarized only if we are unable to find out whether the light is polarized or not."

1. INTRODUCTION

Polarization is even 170 years after Sir Gabriel Stokes a fascinating topic in optics [1]. This is stimulated by recent developments in quantum optics and quantum technologies, e.g., in metrology and communication applications where novel fields with a new horizon for polarization emerged. These works comprise both, either a classical or a full quantum description of polarization in terms of Stokes vectors or Jones vectors with well-defined polarization states of linear, circular, or elliptical polarization [2,3].
The point-of-view of our work here, is based on traditional, classical polarization which is described and discussed in terms of Jones or Stokes formalism [2,3] and visualized in terms of the Poincaré sphere (PCS, see Fig. 1) [2,3]. On the other hand, besides fully polarized light, the rather surprising, amazing and at first glance, slightly counter-intuitive topic of unpolarized or randomly polarized light, both in the spatial and temporal domain, sometimes also called "natural light" due to its broad occurrence in nature, e.g. sunlight, has attracted attention accompanied by very interesting application perspectives, as e.g. ghost polarization communication (GPC) [4]. We start with the introduction of polarization in terms of Stokes vector, Stokes parameters and the Poincarè sphere. We then realize and investigate temporally unpolarized light

2. EXPERIMENTAL RESULTS ON THE GENERATION OF UNPOLARIZED LIGHT AND DISCUSSIONS

2.1 Temporally unpolarized light

We start by investigating temporally unpolarized light [5]. We investigate true unpolarized amplified spontaneous emission (ASE) light emitted from a broadband thermal light source, which we realize by an erbium-doped fiber amplifier, thus being an ideal source of true unpolarized light. We measure Stokes parameter correlations in analogy to the intensity correlation measurements in the original Hanbury-Brown & Twiss configuration by realizing an experimental setup combining a Schaefer–Collett or Berry–Gabrielse–Livingston polarimeter with a Hanbury-Brown & Twiss intensity interferometer.
We find that all Stokes parameter correlations $\langle S_n S_n \rangle$, n =1,2,3 are equal to 0.5 I^2 [6]. The proven invariance of the Stokes parameter correlations against retardation by wave-plates clearly shows for the first time, that our true unpolarized thermal light represents type I unpolarized light with Gaussian emission statistics [7] in accordance with a theoretical prediction for the classification of unpolarized light postulated more than 20 years ago [8, 9].

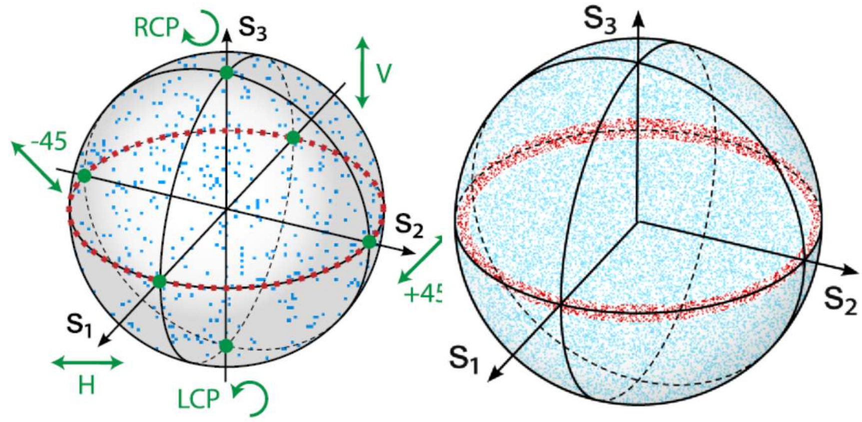


Fig. 1. Depiction of the Poincaré sphere, which is spanned by the three normalized Stokes vectors S_1, S_2, and S_3. Shown are the well-defined states of fully polarized light (green dots) and selected examples of spatial polarization distributions of randomly polarized light as fully randomly covered Poincaré sphere (type I unpolarized light, indicated by blue dots) and fully encompassed equator states (indicated by red dots).

2.2. Spatially unpolarized light

Next, we investigate spatially unpolarized light. We exploit the spatial depolarization properties of an optically active quartz double-wedge Cornu depolarizer [10] (as depicted in Fig. 2) with respect to the generation of spatially unpolarized light in terms of on-average randomly occupied states on the Poincaré sphere [11, 12].

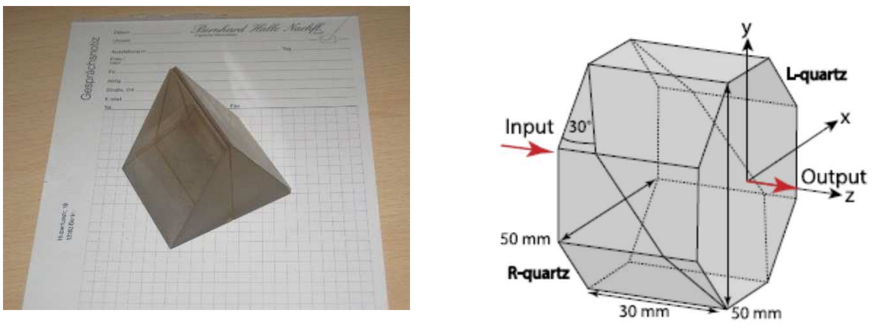


Fig. 2. Photograph and schematical illustration of the Cornu depolarizer manufactured by B.Halle Nachfl. GmbH.

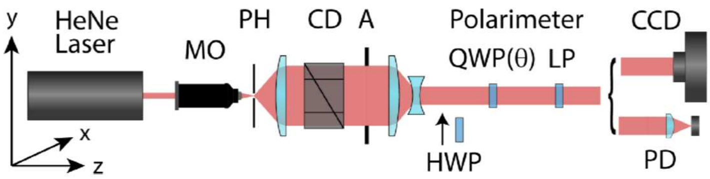
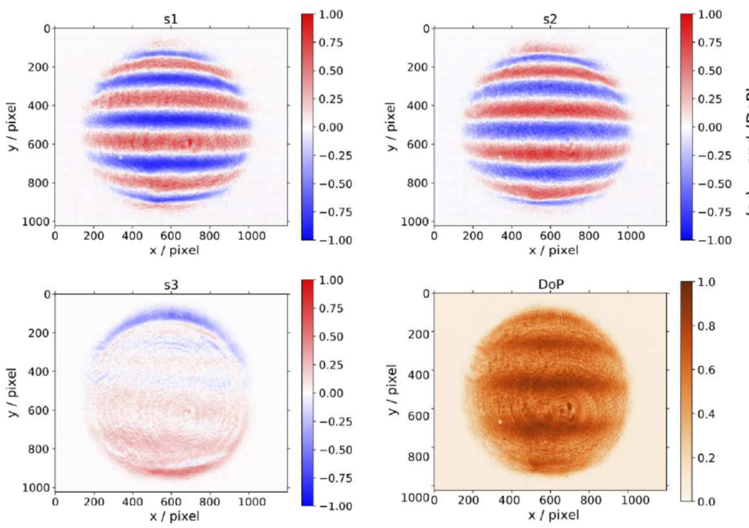
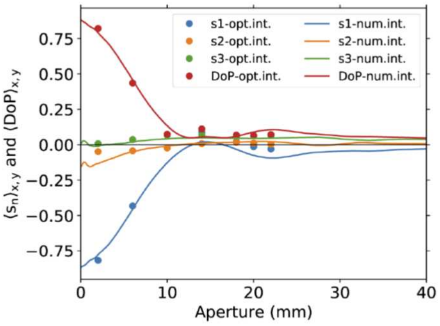


Fig. 3 Experimental setup: Helium-neon laser followed by a spatial filter consisting of a microscope objective (MO) and a pinhole (PH), Cornu depolarizer (CD), variable iris aperture (A), optional half-wave plate (HWP), rotatable quarter-wave plate (QWP, angle θ with respect to the LP), linear polarizer (LP) and CCD camera. The CCD is replaced by a spatially integrating Si photodetector.

Spatially resolved Stokes parameter measurements with an experimental set-up as depicted in Fig. 3 for various input polarization states yield transformed polarization states and distinctive polarization-dispersed characteristic fringes of the spatially resolved Stokes parameters (see Fig. 4). Their spatial symmetry, the degree of polarization, and spatially integrated Stokes parameters as a function of the aperture-determined input diameter together with a Mueller matrix calculus model confirm the successful generation of equator states (see Fig. 4 bottom right) incorporating the ensemble of all purely linearly polarized states, thus on spatial average representing unpolarized light [13]. A global zero-value for S_3 and the zero-value for the spatial ensemble average of S_1 and S_2 over the full beam cross-section confirms that we have generated equator polarization states as type II unpolarized light.
This demonstrates the Cornu depolarizer's potential to produce well-controlled spatially randomly unpolarized light of high fidelity for an arbitrary orientation of the input polarization axis [14] and serves as guidance for the design and selection of appropriate parameters for a Cornu depolarizer for future applications





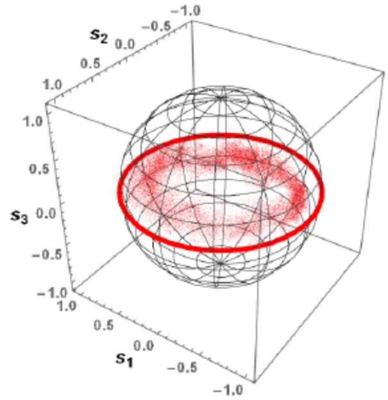


Fig. 4 Top left: CCD images illustrating the spatial distribution of the normalized Stokes parameters S_1 (x, y) (top left), S_2(x, y) (top right), S_3 (x, y) (bottom left) and DOP(x, y) (bottom right). Red colors indicate positive values, blue colors indicate negative values. **Top right:** Stokes parameters and DOP behind the Cornu depolarizer optically integrated (full dots) over a circular beam aperture with variable diameter *d* and numerically integrated via the CCD pixel data (full lines). **Bottom right:** Equator distribution generated by only the CD: the spatial Stokes parameter distribution of the corresponding CCD polarization distributions was mapped to the Poincaré sphere and is indicated by a red annular ring.

1.3 Poincaré Sphere Engineering: Generation of generalized meridian states

Next, we move to the Full Poincaré Sphere Engineering [15], i.e. creating unpolarized light states by using the experimental set-up in Fig. 5 with the additional waveplates for the manipulation of the polarization states. We demonstrate the experimental generation of "equator states", "meridian states," and arbitrarily positioned "great-circle states" of unpolarized light as depicted in Fig. 6 by exploiting the spatial depolarization properties of a Cornu depolarizer in combination with two subsequently following quarter-wave plates [16].

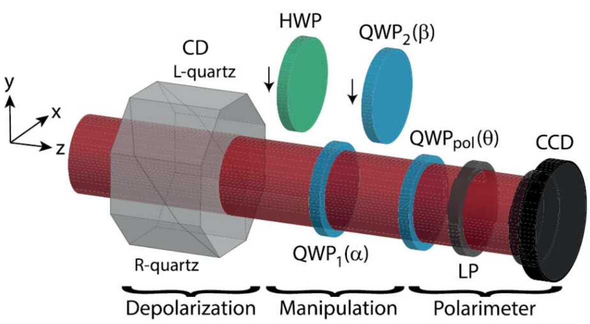


Fig. 5 Experimental setup: Cornu depolarizer (CD) followed by an optional half-wave plate (HWP), two rotatable quarter-wave plates (QWP1 and QWP2, angles α and β with respect to the *y*-axis), a polarimeter consisting of a rotatable quarter-wave plate (QWPpol), angle θ with respect to the LP), and linear polarizer (LP), allowing to tailor the desired output polarization state. A CCD camera acquires spatially resolved polarization properties.

We have presented a robust method of tailoring type II unpolarized light on the Poincaré sphere, together with a high level of control over these polarization distributions by varying the rotation angles of both quarter-wave plates.

3. CONCLUSIONS

In this paper we have investigated temporally unpolarized light emitted by an EDFA and spatially unpolarized light by using a Cornu depolarizer in terms of Stokes parameters and their temporal correlations and their spatial structure. We have generated spatially randomly polarized light by exploiting the optical activity of a so-called Cornu depolarizer and demonstrate tailored, spatial polarization distributions on the Poincaré sphere. We have investigated the generation, manipulation and invariance properties of spatially unpolarized light in the context of classical optics. These results complement the model of classical polarization, leading to a better, deeper understanding but also to novel applications, e.g. in imaging or metrology.

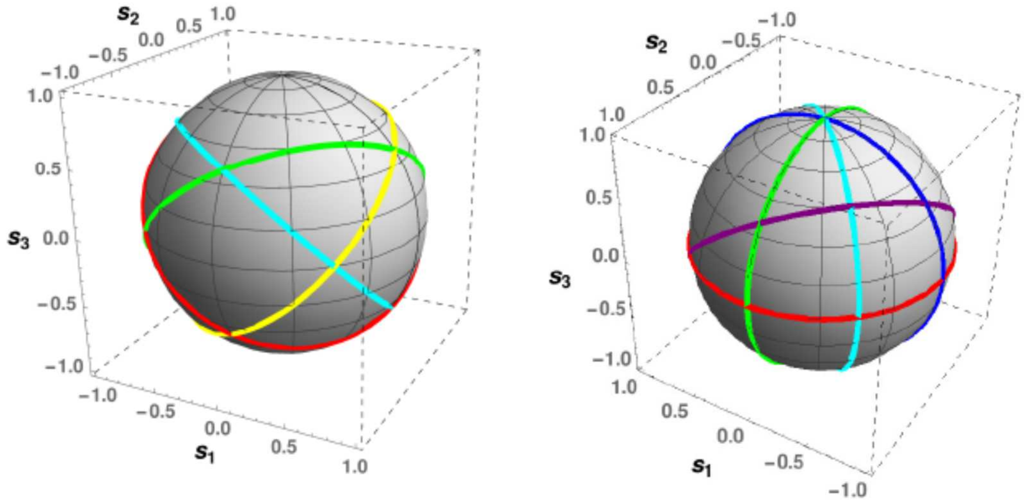


Fig. 6 Left: Schematic depiction of exemplary generalized great circle states (shown as circles in green, yellow, red, and cyan) of unpolarized light on the Poincaré sphere, which is spanned by the three normalized Stokes vectors S_1, S_2, and S_3. **Right:** Shown are an equator state (solid red circle), three meridian states for QWP1(α) rotation angles of 0◦ (blue circle), −22.5◦ (cyan circle), and −45◦ (green circle) as well as a great-circle state (QWP1(α = 0◦) and QWP2 (β = 67.5◦), magenta circle).

ACKNOWLEDGEMENTS

The authors thank Andreas Herdt for fruitful and stimulating discussions and experimental support and Th. Führer for the loan of a CCD camera. We gratefully acknowledge discussions on the CD with Dr. Götz Zinner (B. Halle Nachfl. GmbH (Berlin)) and the innovative craftsmanship of this extraordinary optical manufacture.

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