Some aspects of entanglement in paraxial light fields

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by

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Abstract

The detection and estimation of entanglement in the optical domain have been extensively explored, drawing inspiration from formal methods developed in quantum theory and quantum information. However, these approaches often introduce complexities in terms of achieving entanglement and necessitate the use of additional devices in the experimental setup. We aim to study entanglement in optics using elementary interferometric setups.

First, we focus on investigating polarization-spatial Gaussian entanglement in a coherent vectorial paraxial light field. We outline a method for detecting polarization-spatial Gaussian entanglement through fringe movement when a linear polarizer is rotated, with the light field passing through the polarizer. The fringe movement is identified as a sufficient condition for detecting polarization-spatial entanglement in coherent paraxial vector light fields. We demonstrate that two Gaussian light fields exhibiting a small relative tilt, substantial spatial overlap, and orthogonal polarizations possess close to 1 ebit of polarization-spatial entanglement. Furthermore, we experimentally demonstrate tunable polarization-spatial Gaussian entanglement using a folded Mach-Zehnder interferometer.

We then move on to address bipartite entanglement in partially coherent paraxial vector light fields. A generalized uncertainty principle suited for the polarization-spatial degrees of freedom is introduced. Partial transpose is implemented through the obtained generalized uncertainty principle. Partial transpose is shown to be necessary and sufficient in detecting entanglement for a class of partially coherent vector light fields which have their spatial part to be Gaussian. Also, an experimental realization of the studied entangled states using classical optical interferometry is outlined.

Next the study delves into the detection of polarization-spatial entanglement by implementing partial transpose on measured intensities. A sufficient criterion for polarization-spatial entanglement in partially coherent light fields based on intensities measured at various orientations of the polarizer, as implied through partial transpose, is outlined. Furthermore, we experimentally demonstrate the detection of polarization-spatial entanglement through the proposed method, using a Mach-Zehnder interferometer setup.

Finally, though a scalar singular paraxial light field does not possess polarization-spatial entanglement, it could possess entanglement between other degrees of freedom such as radial-angular entanglement. Detection and estimation of the same requires the knowledge of both amplitude and phase of the light field. While the amplitude can be easily measured, the phase has to be retrieved from intensity measurements. Once the phase is successfully retrieved, important properties such as mode expansion, orbital angular momentum, and radial-angular entanglement of the light field can be directly determined based on the estimated field amplitudes. We demonstrate the estimation of the phase of a singular paraxial light field from experimentally measured intensities using a Gerchberg–Saxton type algorithm. A combination of cylindrical lenses which does not conserve the orbital angular momentum of the light field is used in obtaining the measured intensities. Consistent extraction of the phases in regard of the orbital angular momentum is demonstrated both at the input and output transverse planes, using the measured intensities.