Space-time wave packets & classical non-separability

A classically non-separable state of light involves entanglement of, at least, two degrees of freedom of a light field. For instance, one can have a superposition of two orthogonal polarizations and two orbital angular momentum (OAM) states of light, such that the optical field, expressed in a vector Hilbert space notation, reads

$$|\Psi\rangle \propto |H\rangle|l\rangle + |V\rangle|-l\rangle, \tag{1}$$

where H (V) stands for a horizontal (vertical) polarization and $\pm l$ denotes the corresponding OAM value. Eq. (1) implies that if the light field is horizontally/vertically polarized, its OAM must have the value $+l/-l$. This is the essence of classical entanglement which is **local** because we speak of non-separability (entanglement) of different degrees of freedom of **the same optical field**. Employing classical fields of the type given by Eq. (1) makes it possible to simulate many quantum communications/imaging protocols with classical fields so long as no **quantum non-locality** is required.

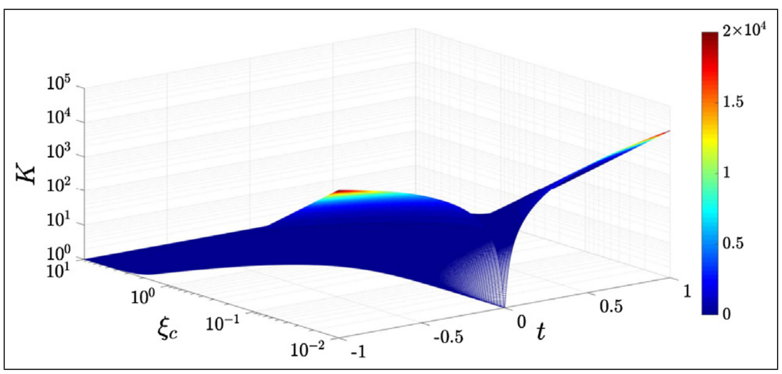

FIG. 1. Schmidt number K as function of the coherence parameter ξ_c in the log-log scale and of the twist parameter t: the greater t and smaller ξ_c, the larger the twist phase and the lower the coherence of light.

In this connection, we have discovered a novel type of classical non-separability between phase-space degrees of freedom of an ensemble of partially coherent light beams induced by a twist phase of the cross-spectral density function of the ensemble [1]; the twist phase vanishes in the fully coherent limit. Hence, the discovered type of classical entanglement is peculiar to random (partially coherent) light fields. To quantify the extent of such entanglement, we have explicitly evaluated the degree of entanglement, quantified by a so-called Schmidt number, in the case of twisted Gaussian Schell-model beams and shown that it dramatically increases in the low-coherence limit (see Fig.1). In other words, the noisier the beams, the more they are entangled! This conclusion stands in sharp contradiction to the conventional quantum wisdom that predicts precipitous loss of entanglement due to exposure of any quantum system to a noisy environment. Our work can have applications to quantum-like communications with classically entangled light through a noisy environment, such as open-air communications in presence of atmospheric turbulence [2].

We have also shown that classical non-separability of spatial and temporal degrees of freedom of a wave packet undergirds a fundamentally new type of space-time wave packet revivals whereby a periodic in either space or time wave packet at the source initially disintegrates on propagation in free space, only to self-reconstruct in both space and time over multiples of a certain revival distance [3].

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[1] S. A. Ponomarenko, "Twist phase and classical entanglement of partially coherent light [**Editor's Pick**]," Opt. Lett. **46**, 23, 5958 (2021).

[2] S. A. Ponomarenko, "Classical entanglement of twisted random light propagating through atmospheric turbulence [**Invited**]," J. Opt. Soc. Am. A, **39**, C1 (2022).

[3] L. A. Hall, M. Yessenov, S. A. Ponomarenko, and A. F. Abouraddy, "The space-time Talbot effect [**On Cover**]," APL Photonics **6**, 056105 (2021).