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Experimental observation of a skewed X-type spatiotemporal correlation of ultrabroadband twin beams

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Parametric down-conversion (PDC) is a widely used source of entangled photon pairs, which are the key elements of several quantum communication and metrology schemes. At the heart of such quantum technologies is the quantum interference of photonic wave functions, which in turns depends crucially on the spatio-temporal structure of the biphotonic correlation. In recent investigations [PRL 102, 223601, PRA 81, 033808, PRA 82, 013835], we addressed the issue of controlling the biphoton spatio-temporal structure from a novel point of view, that is, the non factorability in space and time of the PDC entanglement. The idea came from the context of nonlinear optics, where in several media the angular dispersion relations impose a hyperbolic geometry, which characterizes the so-called X-wave. By turning our attention to the genuine quantum properties of PDC, we demonstrated that the hyperbolic geometry underlies also the spatio-temporal structure of the parametric down-conversion (PDC) entanglement and its non-factorability with respect to space and time, with the characteristics X-shape imposed by the phase-matching conditions.

To date the analysis of the PDC state has been mostly performed in a either purely temporal or purely spatial framework. Our approach, based on the non-factorability in space and time of the state points out relevant elements of novelty, namely i) the possibility of tailoring the temporal bandwidth of the biphotons by manipulating their spatial degrees of freedom, or viceversa and ii) the estreme relative localization of the X-entanglement in time and space, with biphoton correlation times and lengths in the femtosecond and micrometer range, respectively. In particular, by resolving the near-field positions of photons, the X-entanglement opens the access to an ultra-broad bandwidth entangled photonic source, with a temporal localization in the femtosecond range. From an experimental point of view, the disclosure of the strongly localized X-shaped biphotonic structure is extremely challenging because i) it requires a temporal resolution in the femtosecond range, together with the detection of huge temporal bandwidth of the PDC radiation and ii) both the spatial and the temporal degrees of freedom of twin photons have to be carefully controlled independently.

In this work we present—to the best of our knowledge- the first experimental observation of the X-type nonfactorable correlation, in space and time, of broadband twin beams [PRL 108, 253904, PRL109, 243901]. The experiment, performed in the high gain regime, relies on a nonlinear interferometric-type scheme based on the inverse process of PDC, i.e., sum frequency generation (SFG). The results, having their origin in the phase-matching mechanism which imposes a balance between group velocity dispersion and diffraction, suggest that signal and idler photons do not necessarily exit from the PDC crystal at the same time and in the same place, but that their emission out of the medium is correlated in space-time along skewed lines. The result is once more a clear evidence of the importance of accounting for space-time coupling in all those broadband processes governed by angular dispersion relations.

A similar scheme could be used to demonstrate the X correlation of biphotons in the low-gain PDC regime. This might open the relevant possibility of using the space-time coupling to tailor the spatiotemporal properties of biphoton entanglement in quantum technological applications.