Shielding Quantum Light in Space and Time

A way to create single photons whose spatiotemporal shapes do not expand during propagation could limit information loss in future photonic quantum technologies.

By **Giuseppe Fumero**

When enjoying the sight of a rainbow, information loss might not be the first thing that comes to mind. Yet dispersion, the underlying process that makes different colors travel at different speeds, also hampers scientists' control of light propagation—a crucial capability for future photonic quantum technologies. As they move, short laser pulses tend to lengthen through dispersion and widen and dim through diffraction. Together, these effects limit our ability to make light reach a target, although mitigation strategies have been developed for classical pulses and, recently, for quantum light. Now Jianmin Wang at the Southern University of Science and Technology in China and colleagues have realized a quantum source of single photons that are impervious to spreading out during propagation, potentially safeguarding against the loss of information encoded in the photons' spatiotemporal shapes [**1**].

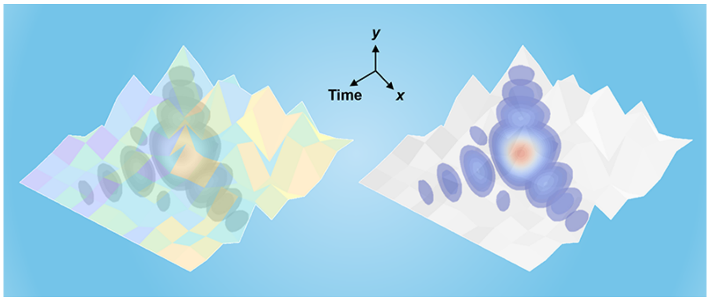

Figure 1: Wang and colleagues produced single photons whose spatiotemporal profiles, known as Airy patterns, do not spread out during propagation [**1**]. (Left) Such a pattern can be concealed by classical photon noise, represented here by a random surface. (Right) The pattern dominates over this noise when only quantum-correlated photons are selected using a technique called coincidence detection.
Credit: J. Wang *et al.* [1] (Airy pattern); G. Fumero/National Institute of Standards and Technology and West Virginia University (noise surface)

In 2007, physicists demonstrated light beams, known as Airy beams, whose spatial profiles make them resilient to spreading out [**2**, **3**]. These profiles consist of a pattern of bright and dark lobes surrounding a central bright component, with each feature propagating along a parabolic trajectory. Recently, scientists created quantum Airy beams, which are technically challenging to realize [**4**, **5**]. The goal of Wang and colleagues' work was to extend this principle to the temporal domain, producing quantum Airy single photons that do not spread out in both space and time. Such quantum "light bullets" could offer exciting possibilities for quantum technologies, much like their classical counterparts did for applications in areas from plasma physics to optical trapping [**3**, **6**]. Describing the spatiotemporal shapes of single photons may seem counterintuitive, but quantum mechanics works probabilistically: the Airy pattern emerges after averaging the spatiotemporal distributions of many photons.

Wang and colleagues leveraged a recently introduced method to generate entangled pairs of photons and simultaneously shape each pair's temporal profile [**7**]. The researchers induced a nonlinear optical process in a cloud of cooled rubidium atoms using a femtosecond laser beam whose spatial profile displayed an Airy pattern along only one dimension. This optical process caused the atomic cloud to emit entangled photon pairs—each comprising a "trigger" photon shortly followed by a "signal" photon—with a probability dependent on the beam's intensity and modulated by the beam's bright and dark lobes. The beam's one-dimensional spatial Airy pattern was transformed into a temporal Airy pattern, which was encoded in the probability distribution for the time interval between the emission of the two photons in each pair. The researchers then spatially shaped the signal photons directly so that these photons exhibited spatial Airy patterns, in addition to the temporal one.

Manipulating single photons is difficult because they have very low intensities and highly fragile quantum correlations. Wang and colleagues alleviated the first issue by realizing the space-to-time transfer of the one-dimensional Airy pattern from the femtosecond laser beam to the single photons—rather than directly shaping both the spatial and temporal profiles of the photons after pair generation.

To verify the survival of the quantum correlations, the researchers tested two quantum properties of the photons. First, they used an interferometer to determine the signal photons' so-called second-order self-correlation, obtaining a value below one, which is considered a signature of nonclassical light. Second, they investigated the ability of these signal photons to be retrieved from background noise using their temporal correlations with the trigger photons—a concept known as quantum illumination (Fig. **1**). To this end, the researchers mixed the signal photons with a random pattern of classical light. They then measured the spatial distribution of all the photons arriving at a camera, capturing the images formed by the photons at different distances from the atomic cloud. An observer without access to the trigger photons would not recognize any structure in these images but that of a spreading random cloud. However, when including only the photons arriving in coincidence with the trigger photons, the spatiotemporal Airy patterns and their trajectories are revealed.

The researchers' proof-of-principle demonstration of quantum spatiotemporal Airy photons opens intriguing application scenarios. For example, if used in superresolution microscopy, these photons would provide the high imaging depth and large field of view offered by Airy beams while achieving the lower-than-classical measurement uncertainties that are peculiar to quantum sensing [8]. Another possibility is in increasing the range and information capacity of quantum communications, for example, in the context of quantum key distribution—a secure communication method in which cryptographic keys are shared between parties. Encoding these keys in the spatial and temporal profiles of the demonstrated photons would allow many keys to be simultaneously transmitted in a single communication channel, while protecting their quantum states from environment-induced decoherence over longer distances than would otherwise be possible [**9**].

More generally, Wang and colleagues' work provides a path toward full spatiotemporal control of single photons that is not necessarily restricted to Airy patterns. It will be interesting to see whether the researchers' strategy can be generalized to other kinds of beam shaping, while maintaining the same efficiency, and how it can be merged with existing protocols for creating quantum states.

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