Production of Entangled Images by Four-Wave Mixing

Alberto M. Marino, Vincent Boyer, Raphael C. Pooser and Paul D. Lett

One of the most important resources in quantum optics is entanglement, which is characterized by correlations stronger than allowed classically. As a result, it is the basis of applications such as quantum cryptography, quantum information processing and quantum teleportation.

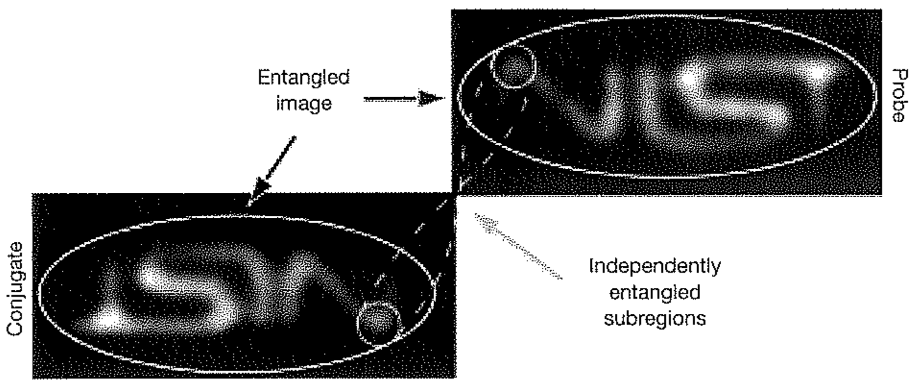
In particular, two beams of light can be entangled in their spatial degrees of freedom. The study of these quantum correlations, known as quantum imaging,[1-3] brings the intrinsic parallelism of image processing to these applications.

We have shown that nondegenerate four-wave mixing (4WM) in a ^{85}Rb vapor cell can produce highly multi-spatial-mode quantum-correlated "twin beams."[4] This has enabled us to generate complicated entangled images consisting of a pair of beams whose spatial cross-section is entangled not only as a whole but as individual subsections.[5]

The 4WM process is based on a double-lambda configuration, in which a strong pump field is mixed with two weak fields, the probe and the conjugate. Four-wave mixing is a parametric process, which means that the initial and final states of the atomic system are the same.

As a result, for each pair of pump photons that are absorbed, one probe and one conjugate photon are generated. This leads to the emission of probe and conjugate photons in pairs, and thus to quantum correlations between the two fields. The 4WM technology is remarkably simple, requiring about 400 mW of pump light and a 12 mm long Rb cell at 110° C. It can produce more than 8 dB of intensity-difference squeezing.

Beams of light entangled in the continuous variable regime display correlations between their phases and amplitudes. Specifically, a sufficient condition for entanglement is the presence of squeezing, or noise levels below the shot noise, for both the phase sum and amplitude difference between the beams. The measurement of these variables is done by homodyning each of the beams with a strong reference beam called the local oscillator (LO).



Entangled "NIST" images. The multi-spatial mode nature of the 4WM process makes it possible to generate complicated entangled spatial patterns. Entanglement is present between the two whole "NIST" images. In addition, smaller corresponding subregions (of the size of the coherence area) of the probe and conjugate should be independently entangled, as illustrated by the small circles and dashed lines.

The shape of the LO acts as a spatial filter that selects the spatial mode that is measured. We can use differently shaped LOs to analyze the spatial correlations between the probe and conjugate and verify that entanglement is present for a variety of LO shapes.

An example of entangled images is shown in the figure. Subregions of the images are independently entangled, such that the "N" in the probe is only entangled with the "N" in the conjugate and no other letter.

The spatial resolution of the process is determined by the phase-matching condition and the size of the pump beam in the medium. The phase-matching condition (determined by conservation of the momentum of light) gives the maximum angular spread, or spatial bandwidth, and the inverse of the size of the pump sets the smallest size of the correlations, or coherence area.

The large number of independently entangled areas makes the system an ideal source for parallel continuous-variable quantum information processing and quantum communication protocols. ▲

Alberto M. Marino (alberto.marino@nist.gov), Vincent Boyer, Raphael C. Pooser and Paul D. Lett are with the Joint Quantum Institute, National Institute of Standards and Technology and the University of Maryland, Gaithersburg, Md., U.S.A.

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