PHYSICS

Let Quantum Mechanics Improve Your Images

Entanglement of light beams allows images to be transmitted and recorded in ways that surpass classical limits.

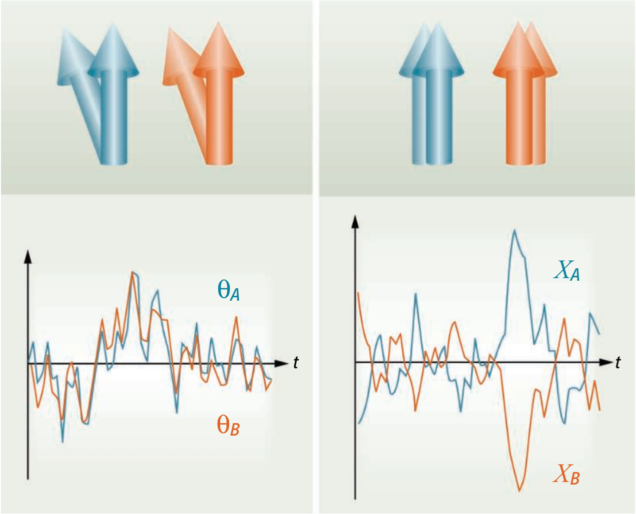
Robert W. Boyd

Images are superb conveyors of information. Recent research has shown how subtle quantum mechanical aspects of light can profoundly influence the nature of image formation.In this issue, two important advances in this emerging area of quantum imaging are presented. Wagner *et al.* (page 541) (*1*) report on the behavior of two beams of light that are quantum mechanically entangled in position and direction of propagation—that is, the outcome of measurements on one beam depends on what sort of measurements have been performed on the other beam. Boyer *et al.* (page 544) (*2*) show that two image-bearing light beams can be entangled such that strong quantum correlations exist both between the two beams and between individual image features within each beam. They find two sorts of quantum correlations: The intensities of the two beams fluctuate in unison, at a level not permitted by classical statistics, and the noise in one part of the light field can be reduced, or "squeezed," at the expense of another part.

The formation and manipulation of optical images is often treated classically, even though the light fields that carry images are quantum mechanical in nature. One well-known consequence of the quantum nature of light is the discreteness of the energy distribution within an image. Light arrives at each image point in the form of an integer number of photons. When light levels are low, the quantum nature of the light field thus leads to a grainy image (*3*), no matter how perfect the image-recording medium might be.

The field of quantum imaging (*4*, *5*) attempts to exploit these quantum effects to form images with finer detail or better sensitivity than those available with classical techniques. Examples of current research include the use of entangled photons to perform interferometric lithography with resolution exceeding the Rayleigh limit (*6*) and the possibility of performing interaction-free (*7*) and coincidence (*8*, *9*) imaging.

Wagner *et al.* present intriguing new results on the properties of entangled light beams. The authors first point out that the position X of a light beam (its geometric center) and its direction of propagation θ must obey a Heisenberg uncertainly relation: Either X or θ can be measured to high accuracy, but they cannot both be measured simultaneously. In the context of classical physics, this result is simply a statement that diffraction effects will cause a light beam of finite diameter D to diverge into a cone angle of approximately λ/D, where λ is the wavelength of the light—that is, there are limits to focusing a light beam based solely on its wavelength.



Entangled light beams. Entanglement is illustrated between two laser beams (A in blue and B in red). (**Left**) The direction of propagation fluctuates, but the fluctuations are highly correlated, so that the directions change in unison. (**Right**) Two beams whose positions are anticorrelated—as one beam moves left, the other moves to the right. For either beam studied individually, the position fluctuations ΔX and direction fluctuation $\Delta\theta$ are related by diffraction laws and obey an uncertainly relation $\Delta X \, \Delta\theta > \lambda/4\pi$, where λ is the wavelength of light. However, because of the correlations between the two beams, the uncertainty product of the differences $[\Delta(X_A + X_B)][\Delta(\theta_A - \theta_B)]$ can be much smaller than $\lambda/4\pi$

However, the situation is much richer when viewed quantum mechanically, and some of these limits can be beaten up to a point. Two separate light beams can be constructed so that they are entangled—the properties of either beam cannot be described independently, so one can speak meaningfully only of the combined properties of the total system.

Using some sophisticated tricks developed during the past two decades, Wagner *et al.* produce two light beams, A and B, that are entangled in that the propagation directions of the two beams are correlated—their directions fluctuate in unison. Thus, the variance of the difference in propagation directions, which we designate as $V(\theta_A - \theta_B)$, is much smaller than the variance of either of the individual propagation directions (see the figure). Simultaneously, the beam positions are anticorrelated in the sense that $V(X_A + X_B)$ is much smaller than the variance of the position of either beam. In classical physics, either of these conditions can occur, but it is not possible to achieve both simultaneously.

If the system had complete quantum correlation, $V(\theta_A - \theta_B)$ and $V(X_A + X_B)$ would both vanish. However, imperfections in the laboratory setup prevent the correlations from being complete. Wagner *et al.* apply two of the standard criteria for demonstrating quantum correlation and find that their data meet each of them. One is inseparability—the two-beam wave function cannot be factorized into the product of individual wave functions (*10*). The second is the Einstein-Podolsky-Rosen (EPR) limit (*11*). This condition states that the system displays an EPR paradox, in that the collapse of the two-particle wave function occurs instantaneously (the aspect that troubled Einstein). EPR entanglement between two individual photons has been observed previously (*12*), but this experiment demonstrates entanglement between entire beams of light.

In a second advance in quantum imaging, Boyer *et al.* describe two related laboratory experiments that investigate the properties of entangled image-carrying beams. In the first

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CREDIT: ADAPTED BY K. WAGNER ET AL.

Published by AAAS

experiment, the authors impress an image onto a probe beam by passing it through an amplitude mask. They then pass this beam through an optical amplifier with a gain of ≈4.5 that operates by means of four-wave mixing in an atomic rubidium vapor. The four-wave mixing process converts two pump photons into signal and conjugate photons. Thus, in addition to amplifying the probe beam, this process generates a conjugate beam that is the twin of the probe beam. This conjugate beam mimics the properties of the probe beam, even to the extent of replicating its quantum fluctuations.

To demonstrate this behavior, the authors measured the intensities of the two beams and the difference in their intensities. Fluctuations in the intensity difference are smaller by a factor of 3.5 than are the quantum fluctuations in either individual beam. This strong quantum correlation exists not only for the entire beam but also for the individual parts of the image carried by the beam.

Their second experiment explores some of the more subtle aspects of the quantum correlations between two entangled beams. For this experiment, no probe beam is injected into the optical amplifier. Only the zero-point fluctuations associated with the electromagnetic "vacuum" that occur spontaneously are allowed to seed the amplification process. In this case, the two output beams are in the form of pure noise fields, but the noise properties are strongly correlated and can be studied by measuring each of the beams with homodyne detection. These measurements show that certain linear combinations of the two beams possess strong quadrature squeezing (for example, the noise of the part of the field that oscillates as cos ωt can be very much smaller than that of the part that oscillates as sin ωt.)

Remarkably, this squeezing persists even if an arbitrary image is impressed on each of the local oscillators used in the homodyne detection process. By impressing an image onto the local oscillator's field, the homodyne detection process sees only that part of the noise field that possesses the same spatial structure as the local oscillator field. This procedure demonstrates that strong quantum correlations exist between the probe and conjugate fields, even when they are projected onto nearly arbitrary spatial modes.

The work of Wagner *et al.* and Boyer *et al.* illustrates the richness of the phenomena that can occur when quantum effects are studied in the context of image formation. Such quantum effects may find use in enhancing the process of image formation. These studies complement recent progress in using the transverse nature of the light field (*13*) to increase the information it carries per unit time, which is of interest in the related field of quantum information science.

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10.1126/science.1161439

MATERIALS SCIENCE

Bulk Metallic Glasses

Improved testing and a better understanding of the properties of bulk metallic glasses will lead to new avenues for commercial use.

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Metals and alloys generally exist as crystalline materials. Around 1960, it was discovered that rapid cooling of the melt resulted in the formation of alloys in glassy states. About 30 years later, multicomponent alloys were discovered that could be solidified as glasses at much lower cooling rates (~1 to 100 K/s or lower), resulting in samples larger than ~1 mm. Compared to their crystalline counterparts, these bulk metallic glasses (BMGs) often exhibit high compressive strength, good corrosion resistance, and large elasticity (*1*). Despite the identification of a vast range of BMGs and applications including sporting goods and electronic casings, the development of methods for rationally designing BMG alloys is still an important task.

BMGs with the best glass-forming abilities are Zr- and Pd-based, often reported in terms of a "critical casting diameter." Critical casting diameters up to 70 mm have been reported in Pd alloys with cooling rates lower than 10^{-1} K/s (*2*). In many systems, microalloying has been found to improve the glass-forming ability (*3*). For example, aided in part by microalloying, BMG steels have generated interest because of their strength and cheaper constituent materials than the traditional Pt, Pd, and Zr classes of BMGs (*4*, *5*).

Small changes in composition can lead to large changes in properties. Several empirical rules exist correlating a single physical parameter with glass-forming ability, but only some of these correlations are useful for predicting universal glass-forming ability (*6*). These rules still require knowledge of properties of the alloy to allow prediction of glass-forming ability. Models that only require information about the constituent elements as inputs remain a challenge.

A better understanding of the atomic structure of BMGs is developing, primarily through analyses of the simplest binary alloys. The popular portrait of the BMG structure is a randomly packed assembly of the different atoms. However, although BMGs lack long-range atomic order, they do exhibit short- and medium-range order over several atomic lengths (*7*). The identification of polyamorphism (different amorphous phases) indicates some of the inherent complexities involved in any atomistic-scale investigation of multicomponent BMGs (*8*).

Compared to other engineering materials, BMGs are used in small volumes. Most are quite strong in compression, and several optimized alloy compositions show notable compressive ductility (*9*, *10*). Many engineered

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