Bell Labs Generates Squeezed Light

Quantum fluctuations set a minimum noise level in optical signals, but nonlinear optics provides a way to squeeze below this limit

Last month at the annual meeting of the Optical Society of America, researchers from AT&T Bell Laboratories reported the first experimental observation of squeezed states of light.* Details of the Bell Labs experiment and those of other groups also pursuing squeezed states were further discussed in a workshop on the subject at the Massachusetts Institute of Technology the following week†. Squeezed states are a purely quantum phenomenon with no classical analog (*1*). Since there are relatively few optical processes that require a quantum description of light, the observation of squeezed states is an important test for a fundamental theory.

Although the effect seen by the Bell Labs team comprising Richart Slusher, Leo Hollberg, Bernard Yurke, Jerome Mertz, and John Valley was small, it is possible that squeezed states may one day be of considerable technological importance. Foreseeing a day when sources of highly squeezed light will be routinely available, Jeffrey Shapiro of MIT, where another squeezed states project is under way, says, "It is apparent that a new era in quantum optics may be in the offing."

While not everyone working in the field is quite so optimistic, most agree that precision optical phase measurements, such as those made by interferometers and laser gyroscopes, are the most likely beneficiaries of squeezed states. Optical communications and memory systems could conceivably also benefit from the reduced noise that is the signature of squeezed states.

Mention the quantum theory of light, and photons come immediately to mind. At each frequency, the electromagnetic field is modeled by a harmonic oscillator whose energy levels are quantized. One photon is present when the harmonic oscillator is in the first excited state, two photons when in the second excited state, and so on. However, the energy of the ground state, which corresponds to no photons and hence no radiation, is not zero. The energy is due to quantum fluctuations, which may be imagined as the instantaneous appearance of photons out of the vacuum and disappearance back into it. Squeezing amounts to operating on these ephemeral photons. "We can't see them, yet we can manipulate them by garden variety nonlinear optics. That's amazing," says Marc Levenson of the IBM San Jose Research Laboratory, where a third squeezed-state search is in progress.

Interest in quantum fluctuations grew with the development of the laser, as exemplified by the theoretical work of Roy Glauber of Harvard University, George Sudarshan now at the University of Texas at Austin, and Leonard Mandel of the University of Rochester in the early 1960's, who studied the statistical properties of coherent light. The perfectly coherent light of an ideal laser, for example, has a poissonian distribution of photons rather than a single, well-defined number. From one measurement to the next, the number of photons may vary. In other words, a laser beam is noisy, though not so noisy as an incoherent beam, and the performance of any optical device using the laser's light will ultimately be limited by this noise.

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For squeezed states, the statistical variance of the photon number is not so important as those of the amplitude of the electric field, which is related to the photon number, and its phase. Consider a sinusoidally oscillating field that is characterized by an amplitude, a frequency, and a phase. Rather than explicitly writing the phase, one can express the field as the sum of a cosine and sine term with separate amplitudes called quadrature amplitudes whose values are related by the phase. For any light, the product of the variances of the quadrature amplitudes are related by an uncertainty principle; that is, the product must exceed a minimum certain value that is proportional to the energy of the vacuum.

For coherent light, the variances of the two quadrature amplitudes are equal, and their product equals the minimum. For squeezed light, the product of the variances again equals the minimum, but the variance of one quadrature amplitude may be decreased at the expense of an increase in the other; that is, one quadrature amplitude can be made less noisy than coherent light at the expense of making the other more noisy. By means of phase-sensitive measurement techniques, one can select one or the other quadrature amplitude. The interesting applications, of course, involve the less noisy one.

The idea of squeezing traces back to the early days of quantum mechanics. Current thinking about squeezing in a quantum optics context began to blossom following a 1976 publication by Horace Yuen, who is now at Northwestern University, in which he derived many of the properties of squeezed light (*2*). Yuen also coined the term two-photon coherent states, in analogy with the one-photon coherent states that make up laser light, but squeezed states has become the preferred nomenclature. Squeezing is also related to the so-called quantum nondemolition measurements that have been proposed as a way to measure smaller displacements in gravity wave detectors than the Heisenberg uncertainty principle would seem to allow. This is a kind of mechanical squeezing.

As it happens, none of the properties of coherent laser light are inconsistent with an explanation in terms of classical electromagnetic radiation. The interpretation of their origin may be different, but given the fluctuations, a classical model will generate the same statistical properties. However, this is not true for squeezed states. Hence, the observation of squeezed light provides one of the few occasions to test the quantum theory of light. It is also important that, despite the popular conception of the photon as a little fuzzy ball or particle of light, this picture is of little help in understanding squeezed states. As the generation of squeezed light is a phase-sensitive phenomenon, points out Yurke at Bell Labs, it is also necessary to think in terms of waves.

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*Annual Meeting of the Optical Society of America, Washington, D. C., 14–18 October 1985.

†Workshop on Squeezed States of Light, MIT Endicott House, Dedham, Massachusetts, 21 October 1985.

The term two-photon coherent states suggests that nonlinear optics may provide the means of generating squeezed states. For example, consider second harmonic generation. Laser light passing through the nonlinear medium generates polarization waves at its own frequency and multiples of it (higher harmonics). The second harmonic polarization is proportional to a property of the medium called the second-order nonlinear susceptibility tensor and to the square of the amplitude of the laser electric field. The polarization wave can then reradiate coherent light having twice the frequency of the original laser light. It is as if the material absorbed two photons of one frequency and reemitted one photon of twice the frequency. The reverse process, called parametric downconversion, is also possible.

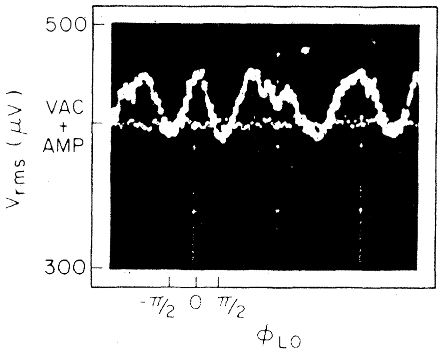
Parametric downconversion is a special case of the more general nonlinear optics process known as optical parametric amplification. A strong "pump" laser wave and a weaker input or signal wave enter the nonlinear medium. Coming out are a slightly attenuated pump, an amplified signal, and a third output or idler wave whose frequency is equal to the difference between those of the pump and the signal. In the case where the signal frequency is one-half that of the pump, the signal and idler have the same frequency, and the parametric amplifier is said to be degenerate.

It turns out that degenerate parametric amplification is a phase-sensitive process in that the quadrature amplitudes of the signal wave are not equally amplified, although with ordinary photodetectors that measure light intensity, the phase information is lost. A mechanical analog of the degenerate parametric amplifier that the Bell Labs researchers use to explain squeezing shows how this works.

Consider a playground swing that oscillates with a particular frequency. The occupant of the swing can increase or decrease the amplitude of the motion by standing and sitting at appropriate times. For example, if the occupant stands up when the swing is at the midpoint of its trajectory and is moving its fastest, and then sits down when the swing is at the end points of the motion and is not moving at all, the amplitude increases. Conversely, if the occupant sits at the midpoint and stands at the end points, the amplitude decreases.

In the swing example, the phase-sensitive amplification arises from the time-dependent moment of inertia due to standing up and sitting down, which oscillates at twice the swing frequency, and depends on the relative phase of the pump (standing and sitting) and signal (swing). A 90-degree phase shift in the pumping changes amplification to deamplification. In the degenerate parametric amplifier, the two quadrature amplitudes of the signal are always 90 degrees out of phase, so that the pump will tend to amplify one quadrature amplitude and deamplify the other.

So far, the effect of amplification and deamplification of the quadrature amplitudes is simply to shift the phase and increase the amplitude of the signal wave; that is, if one had an oscilloscope fast enough to follow an optical signal, the wave form would not change shape. Squeezing comes in when one looks at the noise due to quantum fluctuations associated with each quadrature amplitude; or equivalently, their variances.



AT&T Bell Laboratories

Squeezed light

Noise voltage from the homodyne detector as a function of the local oscillator phase shows peaks and valleys 90 degrees apart. The valleys, which represent squeezing, do not dip as much as the peaks rise partly because of noise due to spontaneous emission in the sodium vapor and phase jitter in the laser [from (4)*].*

Amazingly, these are amplified and deamplified in the same way as the signal quadrature amplitudes themselves. Amplifying and deamplifying the variances does not, however, result in a uniform change in the noise. Where once the noise was the same at all points along the wave form, now it is increased and decreased at 90-degree intervals.

Optical frequency oscilloscopes do not exist. In 1979, Yuen and Shapiro suggested that an optical homodyne detector would provide the needed phase sensitivity to see squeezed states. In brief, there are two light waves, the squeezed signal and a reference (local oscillator). The two waves have the same frequency, but the relative phase of the local oscillator can be adjusted by a phase shifting device. The two waves beat together on the surface of a photodetector. When the maxima of the reference wave form are in phase with the minima of the signal wave quadrature having decreased noise, the noise at the photodetector is reduced. Similarly, the photodetector noise is enhanced when the reference wave is in phase with the signal quadrature with increased noise. When the minimum of the phase-dependent photodetector noise goes below the noise level seen when the squeezed wave is blanked off, squeezing has been detected.

The parametric amplifier is a three-wave device (pump, signal, and idler). But proposals for realistic squeezing experiments concentrated on another nonlinear optics process called four-wave mixing, which offers several experimental conveniences. In 1979, for example, Yuen and Shapiro proposed generating squeezed states by means of degenerate backward four-wave mixing. The operation of a four-wave mixer is similar to that of the parametric amplifier except that there are two strong pump waves.

In the general four-wave mixer, the frequency of the idler wave is the difference between the sum of the pump frequencies and the signal frequency. In the degenerate case, the pumps, the signal, and the idler all have the same frequency. Backward means that the two pump waves travel in opposite directions. Moreover, the signal and idler also propagate through the interaction region in opposite directions. All the squeezing schemes require that the amplified signal and idler waves be brought together in some way. There are also forward four-wave mixers that are directly analogous to the parametric amplifier.

Actually achieving squeezing by means of four-wave mixing or some other nonlinear optical process is considerably more difficult than it sounds. One difficulty is eliminating all sources of instrumental noise, such as frequency jitter in the lasers. Another is finding a nonlinear medium with a large enough susceptibility tensor to generate a measurable effect. A recent microscopic quantum theory of squeezing by means of degenerate four-wave mixing by Margaret Reid and Daniel Walls of the University of Waikato in Hamilton, New Zealand, points to some of the trade-offs that must be balanced (*3*).

For example, to increase the nonlinearity in an atomic vapor, researchers must set the frequency of the pump close to that of an electronic transition in the medium, a so-called resonant enhancement. But, operating too close to a resonance also means that some of the light will be absorbed and reemitted as fluorescence (spontaneous emission), which is a source of noise that can mask any squeezing effect. Another way to boost the squeezing is to increase the pump beam intensity, but this runs into the same difficulty.

By this summer, three groups in the United States had progressed to the point where they were reporting at conferences phase-sensitive reduction in noise. The Bell Labs group used sodium vapor to obtain four-wave mixing, as did an MIT team comprising Mari Maeda, Prem Kumar, and Shapiro, although the experiments differed in the way they brought the two outputs together. The third group, consisting of Levenson, Robert Shelby, and Stephen Perlmutter of IBM, used an optical fiber as the nonlinear medium in its four-wave mixing experiment. None of the three, however, could push the noise below the quantum fluctuations limit.

The Bell Labs group has now succeeded, although just barely, with a 7 percent noise reduction below the quantum fluctuations limit (*4*). In brief, calculations of Yurke (*5*) had shown that imbedding the nonlinear medium in an optical cavity with only one entry/exit port would enhance the squeezing. When a resonant frequency of the cavity nearly matches that of the pump, light passes many times through the medium, effectively increasing the interaction. At the same time, this allows operation at lower pump intensities and at a frequency not so close to that of the atomic resonance (the higher frequency line of the sodium D doublet), thereby reducing spontaneous emission noise.

Finally, having only one open port minimizes the loss of signal while it prevents entry of extra quantum fluctuation noise into the cavity. In quantum optics parlance, even if no light shines into an open port, the vacuum along with its fluctuations does, thereby introducing extra noise. And one port solves the problem of how to combine the two four-wave mixer output waves, since they both must exit through it.

In their experiment, the Bell Labs researchers first measured and optimized the amplification and deamplification of the quadrature amplitudes of the laser light that was injected into the four-wave mixer. Since the quantum noise amplitude was about 1000 times smaller than that of the injected light, it could not be seen in this measurement. To resolve squeezing effects, the investigators closed off the input beam to the mixer. In this way, the vacuum, which consists only of noise, became the input signal, and the squeezed noise spectrum was detectable.

The researchers used a nearly degenerate four-wave mixer rather than an exactly degenerate one; that is, the frequency of the signal beam was slightly different from that of the pump beams. However, the results are quantitatively in agreement with an updated version of the theory of Reid and Walls by John Klauder, Samuel McCall, and Yurke of Bell Labs.

To ever be useful, the amount of squeezing should be more like a factor of 10 than one-tenth. Should such a performance eventually be achieved, high-sensitivity interferometry could be the first beneficiary. The minimum phase difference measurable with conventional interferometers is proportional to $1/\sqrt{N}$, where N is the number of photons passing through the interferometer during the measurement. Ring laser gyroscopes now operate at this limit. Carlton Caves at the California Institute of Technology has calculated that, by feeding squeezed rather than coherent light into an interferometer with two input and two output ports, the minimum measurable phase difference would be proportional to $1/N$, if the photodetectors were 100 percent efficient (*5*). Since N is typically about 10^{12}, this represents a large improvement. More recently, Yurke, McCall, and Klauder have proposed an interferometer based on four-wave mixers rather than beam splitters that could achieve the same sensitivity with only coherent laser light and the ubiquitous vacuum as the inputs. Mixing of vacuum fluctuations with the laser light internally generates the squeezing that gives rise to the sensitivity. —**Arthur L. Robinson**

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Finding Biological Clocks in Fetuses

Researchers are finding that animal fetuses have functioning biological clocks and that the clocks are set by the mother

Newborn animals and humans do not immmediately express circadian rhythms. But, researchers began to ask, is it possible that the brain's pacemaker cells that ultimately direct circadian rhythms are working even before daily rhythms are apparent in such things as sleep-wake cycles and hormone outputs? And, if so, how early does an animal's biological clock start to work?

The answer seems to be that, in rats and squirrel monkeys at least, a biological clock is oscillating during fetal life, and the timing of the fetal clock is set to the light-dark cycles of the outside world by the mother. Immediately after birth, while the young animal's neural pathways are maturing, the mother continues to coordinate the biological clocks of her offspring. This raises the question of why biological clocks develop so early in life, whether these findings apply to humans, and what the biological significance of the finding might be.

Animals have an intrinsic biological clock with a cycle that is approximately 24 hours long, but is reset to an exact 24-hour day by the light cycle to which the animal is exposed. A number of investigators working over the past 13 years established that the pacemaker cells for a biological clock in mammals are located in the brain, in the suprachiasmatic nucleus, which is part of the hypothalamus. Nerve connections between the eye and the suprachiasmatic nucleus provide the pacemaker cells with information on light-dark cycles, which keeps the clock ticking correctly. This hypothalamic tract is independent of the pathways used for vision. And since it is not in place at birth in rats, neurobiologists thought that newborn animals could not have functioning biological clocks that are in tune with daily light-dark cycles.

Then, 9 years ago, Takeo Deguchi of the Tokyo Institute for Neurosciences reported the first hint that young rats have functioning circadian clocks before their retinohypothalamic pathways are in place and before they have daily hormonal and enzymatic rhythms or regular sleep-wake cycles. What he learned was