correlated in a particular way with the signal. Finally, the signal and idler are brought together to create an output wave, one of whose quadrature amplitudes has reduced noise at the expense of increased noise in the other. Whether squeezing is in fact observed depends on whether the nonlinear interaction is strong enough to overshadow sources of noise, such as spontaneous emission of light (fluorescence) in nonlinear atomic vapors.

The Texas group adopted a particularly simple (in concept if not necessarily in practice) nonlinear optical system called a degenerate parametric oscillator. Degenerate means that the signal and idler waves have the same frequency, while the single pump wave has twice that frequency. The oscillator has an optical cavity resonant at particular frequencies and operates somewhat like a laser. When the pump intensity exceeds a threshold, the idler wave is intense and coherent, but the Texas researchers operated below the threshold. This system was the first to be considered and subsequently has received much attention by theorists in their treatments of squeezed light, but experimentalists have concentrated on related systems with two pump waves.

For phase-sensitive detection, all the waves must be referenced to a common source, which at Texas is an infrared laser (Nd:YAG emitting at 1.06 micrometers). Part of the infrared wave, all of which passes through a barium sodium niobate nonlinear crystal, is converted to a visible (0.53 micrometer) wave by second harmonic generation. The unconverted infrared wave is split off to serve as the reference wave (local oscillator) at the photodetector, while the frequency-doubled wave serves as the pump for an optical cavity containing a lithium niobate nonlinear crystal (see figure).

At this point, there is an important departure from the standard optical parametric oscillator. There is no input signal wave (or equivalently, the vacuum furnishes the signal). In the lithium niobate, the 0.53-micrometer wave is reconverted to 1.06 micrometers by the process of parametric down conversion. One can think of it in two ways. For each 0.53-micrometer photon it absorbs, the lithium niobate emits two 1.06-micrometer photons, or the nonlinear interaction of the pump and the vacuum generates output signal and idler waves. Only these output waves are transmitted by the cavity, which is resonant at both pump and output frequencies, because the exit mirror is partially reflecting for the output but perfectly reflecting for the pump. The advantage of the cavity is that all the waves are reflected many times through the nonlinear medium, which effectively enhances the length of the medium and, hence, the strength of the interaction.

Finally, the reference (local oscillator) and output waves are brought together on a beam splitter, which passes half of the light into each arm of a phase-sensitive detector called a balanced homodyne detector. By means of a phase-shifting device, the phase of the local oscillator relative to the output can be adjusted so that the detector is sensitive to one or the other quadrature amplitude. In brief, the noise recorded by the detector drops when light from the squeezing cavity is allowed to enter. "It is as if the detector is illuminated by a source that is darker than the darkness of the vacuum," says Kimble.

Slusher and his co-workers at Bell Labs used sodium vapor in an optical cavity as the nonlinear medium in a nondegenerate backward four-wave mixing system. In backward four-wave mixing, there are two pump waves of the same frequency propagating through the nonlinear medium in opposite directions. Nondegenerate means that the pump, signal, and idler waves have somewhat different frequencies. At MIT, Kumar and his colleagues also worked with sodium vapor as the nonlinear medium, but they eschewed the cavity and used a degenerate forward mixing geometry with the two pump waves traveling in the same direction.

As for the relative merits of solid nonlinear media, such as lithium niobate, and atomic vapors, such as sodium, Slusher notes that spontaneous emission in vapors is hard to avoid because it is necessary to pump near an atomic resonance in order to have a strong nonlinear effect, whereas this is considerably less of a problem in solids. As a result, solids are less noisy in principle.

Other effects may intervene to change the balance, however. At IBM, for example, Shelby, Levenson, and their associates tried a unique approach to nondegenerate forward four-wave mixing involving an optical fiber as the nonlinear medium. The 114-meter length of the fiber obviates the need for an optical cavity. Unfortunately, in practice, scattering of light waves by acoustic vibrations (Brillouin scattering) in the fibers swamped the squeezing effect in early experiments. By cooling the fiber in superfluid liquid helium to a temperature below 4.2 K, the researchers damped the scattering enough to see their 12% effect.

All in all, the once arcane subject of squeezed light now seems to have a bright (or dark) future ahead of it. ■

Arthur L. Robinson

ADDITIONAL READING

A. L. Robinson, "Bell Labs generates squeezed light," *Science* **230**, 927 (1985).

Briefing:

Faster Division with Computers

Multiplication on a computer is easy and fast. There are standard methods that simply feed in the digits of the numbers to be multiplied and, as the digits are going in, the answer starts coming out. But division is a different matter. There simply are no shortcuts and one of the best methods, used on Cray computers, is actually to take the reciprocal of the divisor and multiply it by the dividend. This method is five times slower than multiplying two numbers of similar sizes.

Yet the development of fast methods for dividing is of practical importance. Ernest Brickell, a computer scientist at Bell Communications Research, says he became interested in the problem in part because the clumsiness of existing methods made it very difficult to design computer chips to implement the cryptography scheme called RSA, for the last initials of its inventors. Now, Brickell reports that he has developed a fast method of dividing.

Brickell says that the new method's main advantage is that it allows high-precision division. Thus investigators can quickly get answers that are accurate to a high number of decimal places.

The existing methods of dividing are slow because they require global communications. If you think of each digit as being in a register of the computer, then the top register must communicate with every other register during the division process. Multiplication, in contrast, takes place with what computer scientists call a systolic array—each register talks only to its neighbors.

Recently, Charles Leiserson of the Massachusetts Institute of Technology found a way to take certain algorithms that use global communications and convert them to local communications. Brickell used this result to develop a division method that uses systolic arrays.

The method seems strange. It resembles the multiplication algorithms, because the dividend and divisor are fed into the computer and, simultaneously, an answer comes out. But because of the problem of carrying in division, this answer is continually altered until the division is complete.

Brickell and his associates at Bell Communications Research are now attempting to build a prototype computer chip to implement the method. Brickell says he will publish details of the algorithm and, at the same time, Bell Communications is applying for a patent on the process. ■ **Gina Kolata**