

Glauber, Hall, and Hänsch Share the 2005 Nobel Prize in Physics

The work of these three helps today's optical researchers both measure and understand quantum phenomena.

The Royal Swedish Academy of Sciences has awarded the 2005 Nobel Prize in Physics to three physicists for their work at the frontiers of optics. Roy Glauber of Harvard University is to receive half of the \$1.3 million prize “for his contribution to the quantum theory of coherence.” John Hall and Theodor Hänsch will share the other half “for their contributions to the development of laser-based precision spectroscopy, including the optical frequency comb technique.” Hall is affiliated with JILA, NIST, and the University of Colorado, all in Boulder, and Hänsch is at the Ludwig Maximilian University of Munich and the Max Planck Institute for Quantum Optics in Garching. (See figure 1.)

The work by Glauber and others in the 1960s has led to the understanding of phenomena involving intrinsically uncertain numbers of photons, such as arise in quantum communications, quantum computing, and the recording of weak signals. The experimental tools of Hall, Hänsch, and collaborators continue to advance preci-

sion measurements, pave the way for tests of fundamental theories, and lead to such applications as the synchronization of large astronomical radio telescope arrays and enhanced particle accelerators.

The need for quantum optics

Although quantum electrodynamics is the well established and fundamental theory of electromagnetic interactions, it was initially applied only to the simplest of processes. Some of these processes could be described semiclassically even though that approach could not, in general, treat both the wave and particle natures of light. Examples of the semiclassical approach included emission and absorption of individual photons and some high-energy processes involving just one or occasionally two photons at a time.

In 1956, theorists were challenged by an intriguing experiment performed by Robert Hanbury Brown and Richard Twiss.¹ The two were lab testing an idea for using optical interfer-

ometry to measure the angular diameters of stars. Unlike a Michelson interferometer, which looks at the correlations in the amplitudes of two light beams, the Hanbury Brown–Twiss (HBT) apparatus measured the correlation in the intensities (the squares of the amplitudes). The experimenters sent two beam from the same thermal light source to different detectors and recorded the correlations between photocurrents from the detectors. Hanbury Brown and Twiss found that both detectors tended to fire at once. The photocurrents were apparently preserving the correlations present in the light beams themselves.

The HBT experiment really stirred things up. According to Marlan Scully (Texas A&M and Princeton University), it had been bred into the bones of many physicists that photons could interfere only with themselves. How, then, could one get correlations in the intensities as opposed to the amplitudes? Shortly after the HBT experiment, Edward Purcell explained the observations in terms of a semiclassical theory and suggested that the clumping of signals reflected the kind of fluctuations one might find in thermal radiation.² Other physicists, including Emil Wolf and

ROB HINES

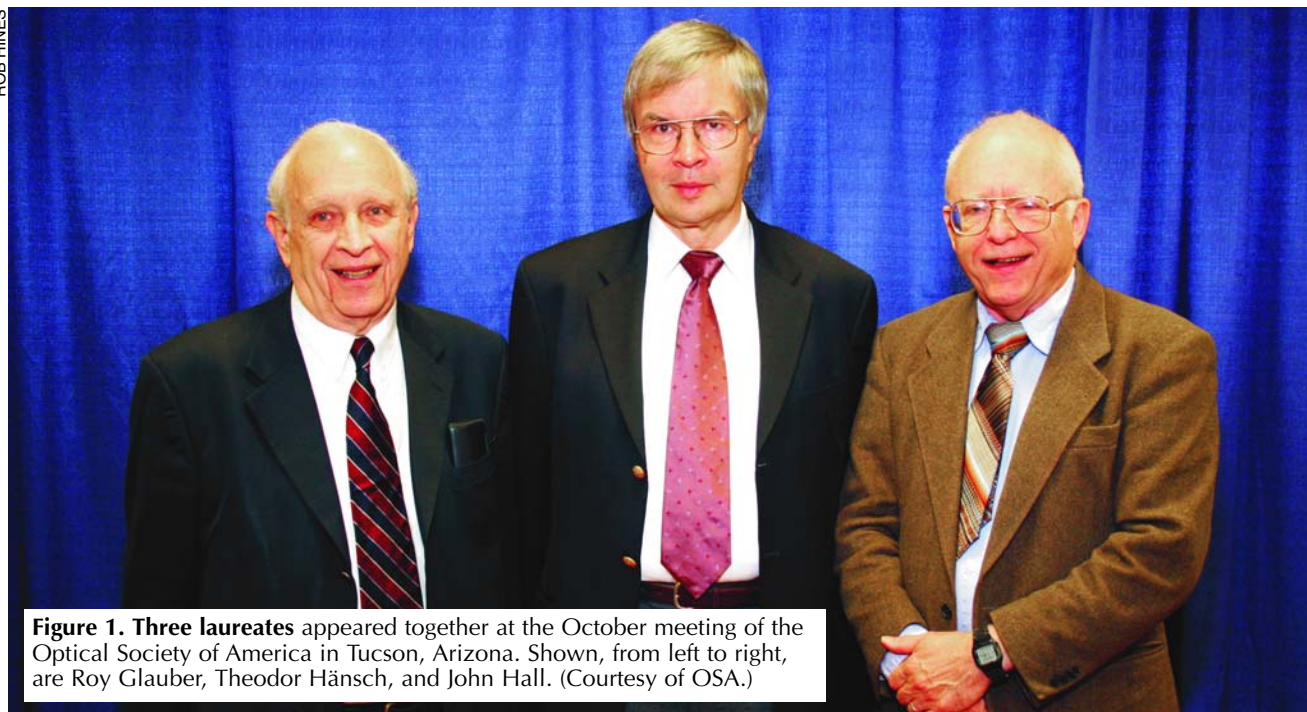


Figure 1. Three laureates appeared together at the October meeting of the Optical Society of America in Tucson, Arizona. Shown, from left to right, are Roy Glauber, Theodor Hänsch, and John Hall. (Courtesy of OSA.)

Leonard Mandel at the University of Rochester in New York, contributed ideas about how to treat the photon correlations, using primarily a semiclassical approach.

The development of the laser in 1960 further challenged theoretical understanding. Physicists needed a way to describe quantum coherence and photon statistics in a way that accounts for the wave-particle duality.

Glauber was motivated to formulate a fully quantum mechanical approach to these problems.³ He pointed out that once a photon has been absorbed—for example, by the photodetectors of the HBT experiment—the state of the field has been changed so that the next absorption event occurs against a different initial state than the previous one. For his purposes, Glauber adopted a set of coherent states and described systems in terms of a density matrix based on them.

Coherent states were first discussed by Erwin Schrödinger in the context of quantum mechanical harmonic oscillators. Joseph Eberly of Rochester comments that “the coherent states were an inspired candidate to describe light, for both technical and conceptual reasons. The theoretical framework is open to intuitive understanding because while highly excited coherent states are fully quantum mechanical, each still exhibits a fairly well defined phase and amplitude.”

The coherent states are particularly well suited to describe the detection process. Pierre Meystre of the University of Arizona credits Glauber for recognizing this link between theory and measurement. Glauber’s theory explained the HBT result, as did semiclassical approaches, but it also predicted, to the surprise of some, that there would be no such correlation in light from lasers well above lasing threshold. Later experiments confirmed that prediction.

In a contemporaneous paper, E. C. George Sudarshan,⁴ now at the University of Texas at Austin, also adapted the coherent-state description and asserted that any state of an optical field can be described exactly in terms of a density operator in diagonal form. Sudarshan discussed the generality and applicability of this representation from classical to nonclassical domains.

The diagonal representation of the coherent states, frequently called the Glauber–Sudarshan representation, is analogous in some situations to a classical phase-space density. But in other circumstances, it can take on negative or singular, and hence nonclassical, values. One consequence is

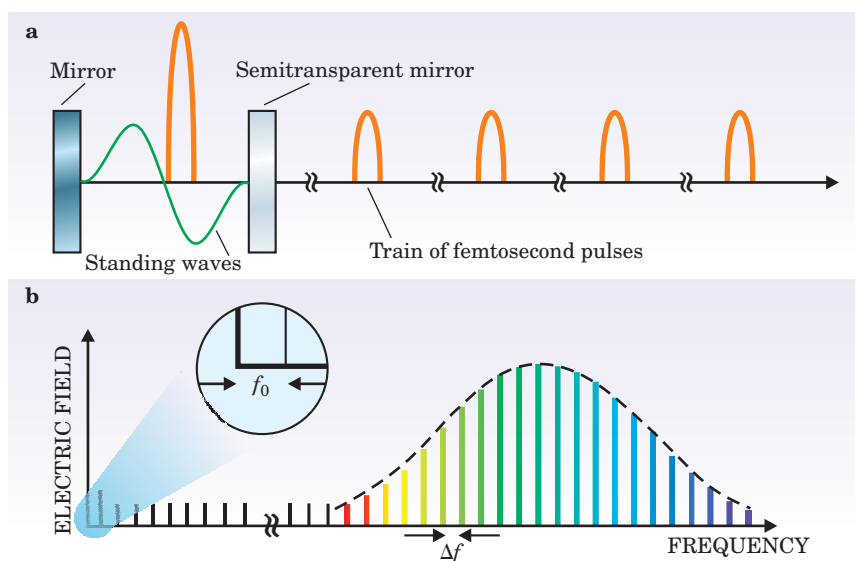


Figure 2. Optical frequency comb. (a) Between the mirrors (blue) of a mode-locked femtosecond laser, standing waves of different frequencies (such as the single blue wave) superpose to produce a traveling “ball” of light (orange). Light pulses escaping from the laser produce a pulse train. (b) Each pulse is a wide spectrum in the frequency domain. The comb’s sharp “teeth” result from interference between successive pulses. Note the presence of an offset frequency f_0 at the origin.

the prediction of photon antibunching—the tendency of photons to avoid one another.

Throughout the 1960s, independent groups led by Mandel at Rochester, F. Tito Arecchi at the University of Milan, and E. Roy Pike at the Royal Radar Establishment in Malvern, England, explored the quantum statistics of both laser and incoherent light. As experimental techniques improved, the researchers were increasingly able to draw the distinction between these two types of light.

It was not until the 1970s that experiments began to generate and observe some of the nonclassical effects that could only be described by a fully quantum mechanical treatment of light. In a 1977 experiment at Rochester, Jeffrey Kimble (now at Caltech), Mario Dagenais (Rochester), and Mandel observed photon antibunching.⁵ Nonclassical correlations in light beams were seen even earlier, in a 1974 experiment by John Clauser of the University of California, Berkeley.⁶

Seeking greater precision

Both Hall and Hänsch have been driven throughout their careers to push the limits of measurement accuracy, especially in laser spectroscopy. One motivation for their work is the measurement of fundamental properties, such as the frequency of the $1s-2s$ transition in the hydrogen atom. From this transition, one can deduce the Lamb shift. Repeating the measurement periodically can indicate whether

the fine structure constant varies with time. Measuring the transition can also yield the most accurate values of the charge radius of the proton and the structure radius of the deuteron, and help reveal possible asymmetries between matter and antimatter.

A second motivation is the development of better clocks. The most promising route is through the use of optical transitions, which are more stable than the microwave transitions that form the basis of the current time standard. Better clocks should lead to more capable global positioning systems, more accurate space navigation, and improved control of astronomical telescopes.

Frequency measurements have taken on even greater significance since 1983, when the 17th General Conference on Weights and Measures demoted the meter to a derived unit, defining it in terms of the distance that light travels in $1/c$ seconds. (See PHYSICS TODAY, March 2001, page 11.) The wavelength of light is now determined by measuring its frequency and dividing that into the now fixed value of c .

In concert with the mission of his employer, NIST, Hall has focused on making better lasers and other devices to promote precise measurements. He explains, “I make tool kits for laser jocks.” Those tools have included the methane-stabilized helium–neon laser, mode-locked lasers, and frequency stabilization techniques.⁷

Hänsch has been measuring the

transition frequency between the 1s and 2s states of the hydrogen atom since he started that work with Arthur Schawlow in the early 1970s. Along the way, Hänsch has developed many innovative spectroscopic techniques, improving their precision by orders of magnitude.

Both Hall and Hänsch needed an easy and precise way to measure optical frequencies (around 10^{15} Hz). But to calibrate such frequencies, one must compare them to the microwave frequency (10^{10} Hz) of the time standard: the cesium atomic clock. Through the late 1990s, the standard comparison procedure, pioneered by Hall and coworkers, was to build a long chain of highly stabilized and phase-locked lasers whose frequencies were multiplied to span the huge gap between the optical and microwave signals. Unfortunately, such chains were cumbersome and expensive.

The frequency comb

In 1977, Hänsch and coworkers published an idea for generating a large set of evenly spaced peaks, or “teeth,” in the distribution of frequencies from a laser.⁸ The distribution is now aptly called a frequency comb. Independently, the late Veniamin P. Chebotayev and Ye. V. Baklanov of the Institute for Laser Physics in Novosibirsk, Russia, had the same idea.⁹ But a comb couldn’t be built with then-existing technology.

A frequency comb is generated by a very short-pulse laser, as sketched in figure 2a. If the laser is mode locked, many modes remain in step as they propagate within the cavity. The superposition of these modes is a tight “ball” of light that bounces between the mirrors. Each time this ball hits the semitransparent mirror, part of it escapes as a pulse of light, resulting in a train of pulses.

In the frequency domain, each of the femtosecond pulses transforms into a continuous broad peak (dotted lines in figure 2b) whose width is inversely proportional to the duration of the pulse. The magic of the comb is what happens when the detector looks at many such pulses: If the light source is suitably coherent, the successive pulses interfere, producing the comb’s sharp teeth. Their spacing Δf is the reciprocal of the cavity round-trip time. The absolute frequencies in the comb are not simply integer multiples of the comb spacing because of the offset frequency f_0 at the origin, caused by differences between phase and group velocity within the pulses.

Hänsch says that he saw a mode-

locked titanium-doped sapphire femtosecond laser at a trade show in 1994. The properties of the laser suggested to him that white light pulses from the laser would have the high degree of temporal coherence required for a frequency comb. Hänsch did not have time to pursue the idea, however, because of an ongoing hydrogen spectroscopy measurement (see PHYSICS TODAY, December 1997, page 19).

Hänsch returned to the idea in 1997. By then, Motonobu Kourogi, now at the Tokyo Institute of Technology’s Yokohama campus, was generating a comb by using cavity-enhanced phase modulators, but it was not nearly as broad as what one might get with a mode-locked femtosecond laser. After experimenting with a femtosecond laser with Marco Bellini at the University of Florence, Hänsch became convinced that a regular train of pulses would maintain a comb spectrum. He wrote down a confidential proposal for an octave-spanning optical frequency comb but did not publish right away because of patent considerations.

In 1999, Hänsch and his coworkers generated an optical frequency comb and reported that the teeth were very evenly spaced,¹⁰ to a few parts in 10^{17} . (See PHYSICS TODAY, June 2000, page 19.) With the comb, they determined the frequency of a spectral line of cesium relative to an infrared methane-stabilized helium-neon laser.¹¹ They also measured the absolute frequency of the hydrogen 1s–2s transition, comparing it to a commercial cesium atomic clock.¹² With Christophe Salomon of the Kastler–Brossel Laboratory and colleagues at the Paris Observatory, his group used a cesium atomic fountain clock to determine¹³ the 1s–2s transition to 1.4 parts in 10^{14} , besting the Munich team’s previous record by an order of magnitude.

By the late 1990s, Hall and his coworkers at NIST Boulder had also started working with a titanium-doped sapphire laser. The Boulder group was able to obtain a nonlinear optical fiber with very low dispersion that had been developed by Bell Labs. By sending femtosecond pulses through the optical fiber, Hall and company spread apart the frequencies within the comb.¹⁴ In particular, they generated an optical frequency comb that spans an “octave”—that is, it includes the frequencies f_n of a given mode n and the frequency f_{2n} of the higher mode $2n$.

Because of the offset frequency f_0 , f_{2n} is not exactly twice f_n . As Hall’s NIST team showed, the octave-spanning comb provides a particularly

Spectrometers and Lasers for your Application Needs

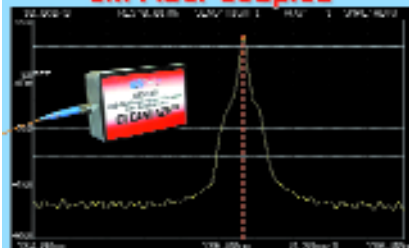
**The compact laser
with a big brain!**



Self-Healing Functionality

- Real-time performance Monitoring
- Low noise, Stable Output
- Excellent Beam Quality ($M^2 < 1.1$)

**0.02 nm FWHM @ 785 nm
SM Fiber Coupled**



- Up to 100 mW @ 0.02 nm
- Up to 1200 mW @ 0.25 nm FWHM
- Diffraction Limited Spatial Mode
- Excellent Sideband Extinction



**Contract Manufacturing and
Engineering for Bio-Medical
Instruments and Lasers**

BWTEK INC.

19 Shoa Way, Newark, Delaware 19713 USA
Phone: (302) 368-7824 Website: www.bwtek.com

simple way to determine f_0 . It's the beat frequency between f_{2n} and $2f_n$.

Octave-spanning optical frequency combs have revolutionized the world of precision measurement. Researchers can now set up optical combs to do precision spectroscopy in their own labs. The comb technique has now been extended into the VUV and XUV regions by both the Hänsch group¹⁵ and the JILA lab of Jun Ye,¹⁶ a former student of Hall. Although practical limits still challenge researchers, neither Hall nor Hänsch sees any fundamental limit to the precision that can be obtained.

Biographies

Born in 1925, Glauber entered Harvard as an undergraduate in 1941. Due to the war, the graduate courses were being taught for the last time, so he took most of them in his first 2½ years. Then, at the age of 18, he was recruited for the Manhattan project at Los Alamos, where he worked in the theory division. Returning to Harvard, he earned his PhD in physics under Julian Schwinger in 1949. After two years at the Institute for Advanced Study in Princeton, a half

year with Wolfgang Pauli in Zürich, and one year at Caltech, he became a postdoc at Harvard. He has remained at Harvard, where he is now a Mallinckrodt Professor of Physics.

Hall was born in 1934 and earned his PhD in 1961 from the Carnegie Institute of Technology in Pittsburgh, Pennsylvania. There, he worked with Robert Schumacher on electron-spin resonance (his first job was to stabilize the microwave frequency source). Upon graduation he got a National Research Council postdoctoral fellowship at what is now NIST. He stayed at NIST, becoming a JILA fellow in 1964 and a NIST senior scientist in 1971. He has been affiliated with the University of Colorado's Boulder campus since 1962 and retired from NIST in 2004.

Born in 1941, Hänsch earned his PhD under Peter Toschek at the University of Heidelberg, Germany, in 1969. After two years as a postdoc with Schawlow at Stanford University, he joined the Stanford faculty. In 1986, he became director at the Max Planck Institute for Quantum Optics and a professor at the University of Munich.

Barbara Goss Levi

References

1. R. Hanbury Brown, R. Q. Twiss, *Nature* **177**, 27 (1956).
2. E. M. Purcell, *Nature* **177**, 1449 (1956).
3. R. J. Glauber, *Phys. Rev. Lett.* **10**, 84 (1963).
4. E. C. G. Sudarshan, *Phys. Rev. Lett.* **10**, 277 (1963).
5. H. J. Kimble, M. Dagenais, L. Mandel, *Phys. Rev. Lett.* **39**, 691 (1977).
6. J. F. Clauser, *Phys. Rev. D* **9**, 853 (1974).
7. J. L. Hall, *IEEE J. Selected Topics of Q. Electron.* **6**, 1136 (2000).
8. R. Teets, J. Eckstein, T. W. Hänsch, *Phys. Rev. Lett.* **38**, 760 (1977).
9. Ye. V. Baklanov, V. P. Chebotayev, *Appl. Phys.* **12**, 97 (1977).
10. Th. Udem et al., *Opt. Lett.* **24**, 881 (1999).
11. Th. Udem et al., *Phys. Rev. Lett.* **82**, 3568 (1999).
12. J. Reichert et al., *Phys. Rev. Lett.* **84**, 3232 (2000).
13. M. Niering, *Phys. Rev. Lett.* **84**, 5496 (2000).
14. D. J. Jones et al., *Science* **288**, 635 (2000).
15. C. Gohle et al., *Nature* **436**, 234 (2005).
16. R. J. Jones et al., *Phys. Rev. Lett.* **94**, 193201 (2005).

Targeted Ultrasound Mediates the Delivery of Therapeutic Genes to Heart Muscle

Rats exposed to ultrasound and injected with tiny DNA-coated bubbles grow new blood vessels.

If you start a program of vigorous exercise, your muscles will sprout new capillaries. Behind that performance-enhancing response lies an elaborate interplay of genes and proteins. Conceivably, the same molecular machinery could be switched on to make new blood vessels in a diseased heart. Then, doctors could induce heart muscle to grow arteries that bypass life-threatening blockages, sparing their patients the sliced flesh and cracked bones of open-heart surgery.

That's one of the hopes for cardiovascular gene therapy. If realized, it would work roughly as follows. Identify a protein whose presence causes blood vessels to form. Produce and package strands of DNA that contain the gene for making the protein. Deliver the DNA to heart muscle.

Of those steps, the last is the most challenging. The heart lies within the rib cage and behind the lungs. With each beat, it fluctuates in volume by about 25%. Directly injecting DNA into that well-defended moving target is

dangerous. Delivering the DNA in specially modified viruses—a standard technique in experimental gene therapy—is also dangerous. Even if they don't cause infection, modified viruses still provoke the body's immune system, and they don't necessarily end up where the DNA is needed.

In the late 1990s, physicians and physicists hit on the idea of using ultrasound contrast agents to deliver DNA. The contrast agents consist of micron-sized gas-filled bubbles encased in shells made of lipids, proteins, or sugars. When exposed to ultrasound, the bubbles pulsate resonantly, reflecting the ultrasound and boosting the detected signal.

If the ultrasound is intense enough, the bubbles can burst with sufficient force to breach the membranes of nearby cells. And if the bubbles are coated with DNA, their destruction releases the DNA, enabling it to enter the cells through the holes forced open by the burst. The accompanying figure depicts the process.

Early experiments proved that ultrasound-targeted microbubble destruction (UTMD) does indeed breach cells.¹ Followup work successfully transferred genes that encode readily detectable markers, such as luciferase, a protein responsible for the glowing abdomen of the male firefly.

Now, a team led by Paul Grayburn of Baylor University Medical Center in Dallas, Texas, and Ralph Shohet of the University of Texas Southwestern Medical School, also in Dallas, has demonstrated that UTMD can deliver genes that stimulate the growth of new blood vessels in rat heart.² UTMD, they hope, could lead to minimally invasive treatments for heart disease, diabetes, and other diseases.

Making DNA-coated microbubbles is surprisingly simple. The Dallas researchers shake DNA, in the form of short circular strands called plasmids, in a saline solution with the other ingredients: lipids for the shell and a hydrocarbon for the gas. DNA-coated bubbles then self-assemble and can be sorted by size.

The bubbles should be small enough that they can pass through