# Squeezed light reduces noise at a gravitational-wave observatory

**A decades-old idea—tinkering with light's quantum fluctuations to make a large interferometer even more sensitive—has now been implemented.**

There is little doubt that gravitational waves exist. Indirect evidence for them is compelling. But astrophysicists are keen to observe them directly for the information they can provide, and despite the efforts of teams of researchers working at extraordinarily sensitive interferometers (see, for example, the article by Barry Barish and Rainer Weiss in PHYSICS TODAY, October 1999, page 44), direct observation has yet to happen. The null result is not entirely unexpected. As sensitive as the current interferometers are, gravity is so weak that it would take a rare event, such as the merging of two black holes fairly close to Earth, to produce a wave strong enough to detect. Such events come along at most once every several years.

Any further increase in the interferometers' sensitivity would pay off rapidly. Reducing the noise by a factor of $x$ increases the volume of space from which an event can be detected by a factor of $x^3$. But the interferometers are running up against the shot-noise limit: Their main source of noise, at least at the high end of their frequency band, comes from the quantum fluctuations of light, which can be interpreted as the zero-point electromagnetic fluctuations of the vacuum itself. (At lower frequencies, seismic and thermal effects are the main contributors.)

Now, Roman Schnabel (University of Hanover) and colleagues have beaten the shot-noise limit of the GEO600 interferometer near Hanover, Germany.[1] GEO600 is closely connected with the Laser Interferometer Gravitational-Wave Observatory (LIGO) and is currently the only interferometer operated by the LIGO Scientific Collaboration while LIGO's two detectors are being upgraded to Advanced LIGO (see PHYSICS TODAY, December 2010, page 31). By using squeezed light, a team led by Schnabel, Hartmut Grote, and Henning Vahlbruch has improved GEO600's sensitivity at 3 kHz from 1 part in $10^{21}$ to 6.7 parts in $10^{22}$ and thereby increased the accessible volume of space by more than a factor of 3.

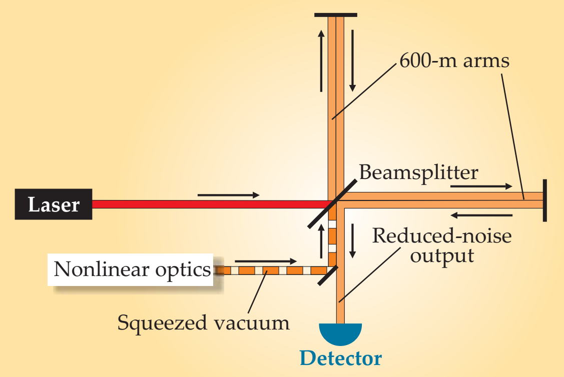


**Figure 1. Squeezed light** at the GEO600 observatory. As shown in this simplified layout, nonlinear optics generate a squeezed vacuum state, which is injected into the interferometer's output port. The squeezed vacuum alters the quantum fluctuations of the light traversing the two 600-m arms and reduces the noise of the interferometer output.

## Main squeeze

Squeezed light can be understood in terms of the Heisenberg uncertainty principle (see the article by Malvin Teich and Bahaa Saleh in PHYSICS TODAY, June 1990, page 26). Given two noncommuting quantities (such as the familiar example of a particle's position and momentum), quantum mechanics imposes a lower limit on the product of their uncertainties but no restriction on the uncertainty of either one by itself. For light, the noncommuting quantities are the so-called amplitude and phase quadratures, or the sine and cosine components of the wave. Squeezed states, in which one quadrature's uncertainty is reduced and the other's is increased, are allowed by theory; they can be produced in the lab by nonlinear optical elements such as optical parametric oscillators. When a detection scheme

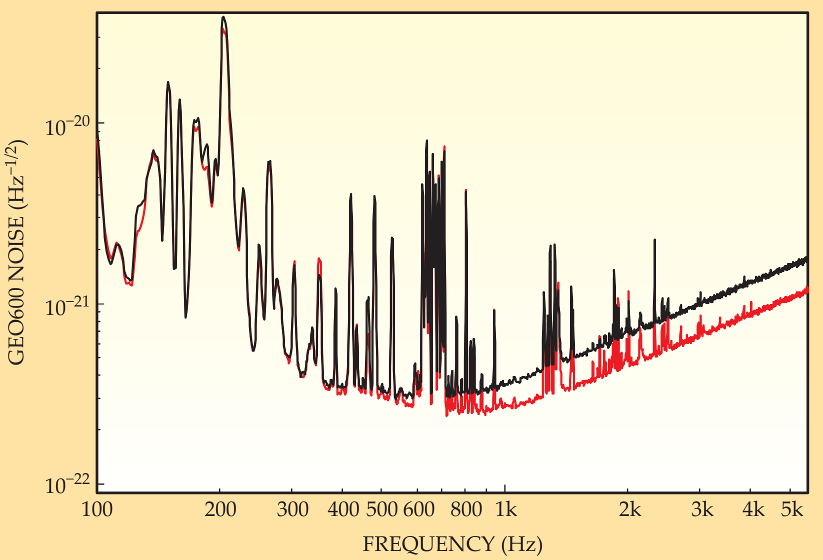


**Figure 2. Interferometer noise at GEO600** with (red) and without (black) the use of squeezed light. At frequencies above 700 Hz, where quantum fluctuations are the main source of noise, the noise is reduced by a factor of about 1.5. That reduction increases the accessible volume of sky by a factor of $1.5^3$, or 3.4. (Adapted from ref. 1.)

is sensitive to just one quadrature—the amplitude, say—squeezing that quadrature reduces the noise; the increased uncertainty of the other quadrature is irrelevant.

From the very beginning, gravitational-wave interferometry was one of the anticipated applications of squeezed light. In 1981, four years before squeezed states were first observed in the lab, Carlton Caves worked out the theory of quantum noise in a gravitational-wave detector.[2] As he showed, the interferometer's shot noise depends critically on the zero-point fluctuations of the vacuum state entering the interferometer's output port (the side of the beamsplitter opposite where the laser light goes in, as shown in figure 1). Injecting a squeezed vacuum state—a state of alternating regions of high and low electric-field uncertainty but with zero average electromagnetic amplitude—affects the quantum fluctuations of the light traversing the interferometer's two arms and can ultimately reduce the noise of the output.

To implement that scheme at GEO600, Schnabel and colleagues needed to vastly improve their light-squeezing capability. Squeezing degrades rapidly as light is attenuated, so squeezing by the usual 3–6 decibels (reducing the electric field variance by a factor of 2–4) would not suffice. The researchers used a squeezing factor of 10 dB—a milestone they'd reached in the lab in 2008—and the squeezing needed to be specially tailored to reduce noise over a broad range of potential gravitational-wave frequencies.

The researchers found that squeezing the vacuum by 10 dB gave an output noise reduction of 3.4 dB as measured by the variance, or a factor of 1.5 as measured by the standard deviation. As figure 2 shows, that factor is nearly constant over the high-frequency part of the band. A planned upgrade to GEO600 should more than halve the optical losses and almost double the benefit of squeezing. And an international team, led by researchers at MIT and the Australian National University and including Schnabel and his group, is working on testing squeezed light at one of the two LIGO detectors.

Of all the envisioned applications of squeezed light, enhancement of a gravitational-wave observatory is the first to be implemented on a large scale. Others, including quantum communication and quantum computation, remain at the proof-of-principle stage. Says Aephraim Steinberg of the University of Toronto, "When I started learning about squeezed light about 20 years ago, I thought the original motivation of improved gravitational-wave sensitivity was a beautiful idea that would probably always remain in the realm of science fiction. This is a landmark paper."

**Johanna Miller**

## References

1. LIGO Scientific Collaboration, *Nat. Phys.* (in press), doi:10.1038/nphys2083.
2. C. M. Caves, *Phys. Rev. D* **23**, 1693 (1981).

# Phase-shifting surfaces bend the rules of ray optics

**Researchers have outlined a recipe for fashioning subwavelength optical components from plasmonic antennas.**

One way to arrive at Snell's law of refraction is to assume, as Pierre de Fermat did nearly four centuries ago, that light rays travel the fastest path between two points. If the points lie on opposing sides of the interface between optically different materials, then that path likely isn't a straight line.

Richard Feynman likened the problem to that of a lifeguard—presumably a faster runner than swimmer—tasked with rescuing a drowning swimmer. The astute lifeguard, rather than make a beeline to the swimmer, would run toward a point on the shoreline that extends the length of the run in exchange for shortening the length of the swim. Likewise, when a light ray passes from a medium with a low refractive index $n_i$ to one with a high refractive index $n_t$, its angle of incidence $\theta_i$ is larger than its angle of refraction $\theta_t$, as formalized by Snell's law: $n_t \sin\theta_t - n_i \sin\theta_i = 0$. The fastest-path assumption also leads to the law governing the angle of reflection $\theta_r$: $\sin\theta_r - \sin\theta_i = 0$.

Now, Harvard University researchers led by Federico Capasso have posed a question that Fermat, Feynman, and Willebrord Snell likely never considered: How would a light ray's trajectory change if, at the surface of reflection and refraction, it experienced a position-dependent phase shift?

Combining theory and experiments, they've arrived at a conclusive answer: A carefully constructed phase-shifting surface—implementable with plasmonic antennas or other small optical resonators—can bend light in ways that defy the traditional laws of reflection and refraction.[1]

## Rethinking Snell's law

Fermat's principle works not because light is in a particular hurry to get from one place to the next, but because the fastest path lies at an extremum, where the derivative of the optical path length with respect to small deviations in trajectory is zero. Light waves that hew closely to the fastest path arrive at their destination at nearly the same time and with nearly the same phase and thus interfere constructively. Away from the extremum, neighboring trajectories of light arrive out of phase and cancel each other.

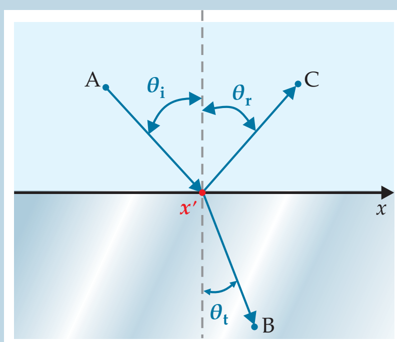


**Figure 1. According to Fermat's principle,** light that departs from point A refracts and reflects so as to arrive at points B and C with phases $\phi_B$ and $\phi_C$ that are constant with respect to small perturbations of the point of incidence $x'$. By imposing a position-dependent phase shift $\Phi(x)$ along the surface, the location of the paths of stationary phase—and the attendant relationships between the angles of incidence $\theta_i$, refraction $\theta_t$, and reflection $\theta_r$—can be altered arbitrarily. (Adapted from ref. 1.)