METROLOGY

Bright squeezed light reduces back-action

The use of amplitude-squeezed states of light as a probe is shown to yield superior measurements of the motion of a moving mirror at low frequencies. The demonstration offers a path to improving the sensitivity of gravitational-wave detectors.

Thomas Purdy

Since the early days of quantum mechanics, the Heisenberg microscope thought experiment has been a textbook example[1] of the basic mechanism of what we call today quantum measurement back-action. This hypothetical scenario attempts to provide an intuitive picture of what happens when a microscope is used to observe the position of an object, say an electron, by collecting photons that are scattered from it. The key realization is that the recoil force (back-action) due to randomly arriving photons bouncing off the object being observed causes excess motion of this object. This unpredictable jittering of the object is a direct consequence of the measurement process, thus limiting the precision of such a system as a sensor.

While this thought experiment was originally posed for individual subatomic particles, researchers have more recently been developing real-world experimental systems that come up against similar physics in nano- to macroscale mechanical systems. For example, the quantum sensitivity limits of gravitational-wave detectors have been considered for several decades, and in the current generation of laser interferometric gravitational-wave observatories such as LIGO, an appreciable fraction of the noise floor is due to quantum measurement back-action[2]. In future generations of LIGO, as optical power is increased and other sources of thermal and seismic noise are reduced, back-action should be a dominant noise source. Fortunately, for nearly as long as researchers have worried about quantum noise, they have also been devising clever techniques to sidestep its deleterious effects[3].

In the last decade, several small-scale optomechanical systems have been developed where quantum measurement back-action is experimentally accessible and schemes to combat it can be tested. Methods include periodically modulating the measurement strength[4], measurements employing an effective-negative-mass oscillator reference frame[5], probing with squeezed microwave fields[6], and using destructive interference of optomechanically induced optical quantum correlations[7]. These techniques employ a range of optical, microwave, atomic and nanomechanical systems, at cryogenic temperatures.

Now, writing in *Nature Photonics*, Min Jet Yap and co-workers report a reduction in the quantum back-action using amplitude-squeezed light to probe the motion of a cantilever-suspended micromirror forming one end of a Fabry–Pérot optical cavity[8]. In particular, a near-infrared squeezed light source is used to measure broadband motion at near audio frequencies of a suspended, room-temperature mirror. Importantly, the approach is potentially compatible with modern gravitational-wave detectors and its demonstration gives clear hope that such techniques may soon be available to extend the range and sensitivity of LIGO, potentially opening up new frontiers of gravitational-wave astronomy.

In their experimental set-up, Yap and colleagues use a low-loss, 70-μm-diameter dielectric micromirror patterned from a stack of alternating quarter-wavelength-thick

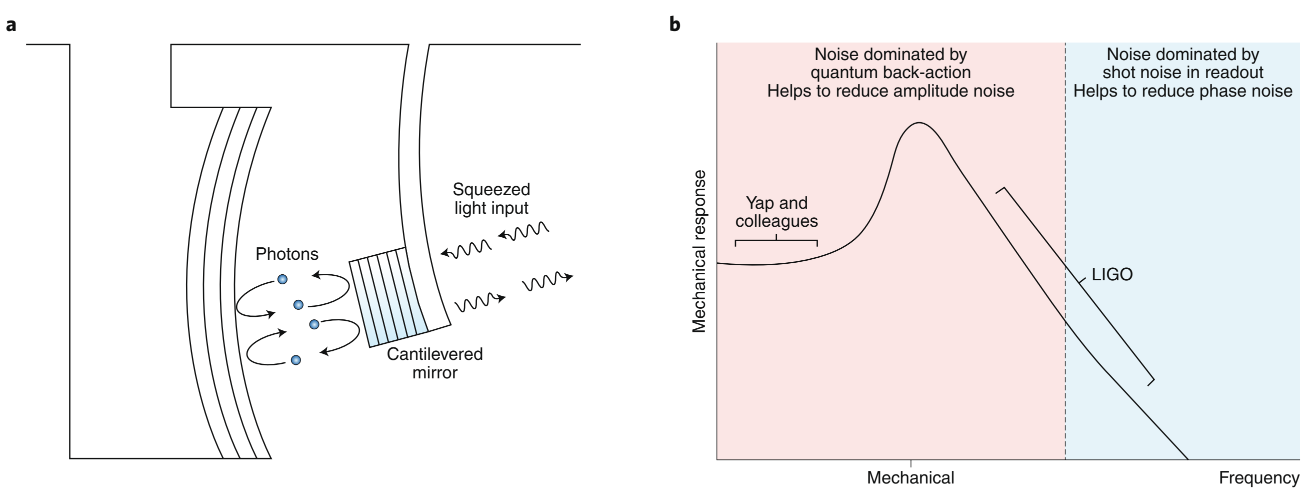

Fig. 1 | The principle and application of amplitude-squeezed light for mirror displacement measurements. a, Schematic of the experiment performed by Yap and co-workers. **b**, The mechanical response of the mirror measurements. At low frequencies, back-action quantum noise is more important and the use of amplitude-squeezed light like by Yap and colleagues improves sensitivity. At high frequencies, readout noise dominates and the use of phase-squeezed light improves sensitivity. At intermediate frequencies, squeezing of a quadrature between amplitude and phase can even more effectively reduce noise below standard quantum limits.

layers of GaAs and AlGaAs (Fig. 1). This mirror is suspended from a thin GaAs cantilever and forms one end of a high-finesse Fabry–Pérot optical cavity. When the mirror vibrates, the length of the optical cavity, and thus its resonance frequency is modulated, creating an optomechanical coupling, and a simple, and high-sensitivity method to optically detect the mirror motion. While the cantilevered mirror is fairly floppy on its own, an optomechanical effect known as an 'optical spring' uses optical forces to stiffen the system so that it oscillates at a higher frequency above 100 kHz, over 100 times faster than in the absence of light. The optical spring creates a flat mechanical response at frequencies below 100 kHz and importantly reduces the response to thermal and other mechanical noise from the environment. In a recent paper[9], some of the authors demonstrated in a similar system that the noise from quantum measurement back-action was visible above other mechanical noise sources over a broad region in the audio frequency band below mechanical resonance.

In their current work[8], a state-of-the-art squeezed light source is added to probe the optomechanical cavity. One of the basic assumptions of the quantum measurement paradigm discussed above is that the photons scattering from the mirror arrive at it at random, uncorrelated times. This is the case for so-called coherent states of light, such as those generated by an ideal laser source, which are governed by Poissonian statistics.

However, by using an optical parametric oscillator, squeezed states of light can be generated by parametric down-conversion, with correlations between pairs of photons. These correlations can lead to reduced amplitude noise and thus reduced levels of optical force noise and quantum back-action. In many optical systems, such as the LIGO interferometers, squeezed light and a strong coherent optical probe are injected into different interferometer ports. However, here, Yap and colleagues create a so-called bright squeezed state where the squeezed light and coherent probe are combined and injected into the single input port of the Fabry–Pérot cavity. Such bright squeezed states created via nonlinear crystals had never previously been produced at such low frequencies.

The result was a reduction in the quantum back-action noise in the audio frequency band. To accomplish this feat, the authors employed a separate coherent locking laser to reduce excess low-frequency noise via servo control. The system provided added control of the squeezed state correlations. The authors were able to demonstrate not only reduced back-action noise by probing with the amplitude-squeezed state, but also saw increased back-action if they adjusted their squeezing source to probe with light that had amplified amplitude noise.

One could ask the question — if it is the strong probe light that is causing excess noise in the system, why not just turn down the probe power? Indeed, in the present demonstration, the overall noise floor would actually improve slightly by lowering the probe power. However, in large-scale gravitational-wave interferometers — the intended application of this prototype quantum technology — the story is more complicated. In such interferometers, quantum measurement back-action may dominate the measurement noise floor at low frequencies while readout noise dominates at higher frequencies.

The readout noise consists of phase fluctuations in the input light and can be reduced by increasing the probe laser power or by creating squeezed light correlations that reduce phase noise. Indeed, such phase-squeezed light has been shown to reduce the high-frequency noise in gravitational-wave interferometers[10], and is employed in current LIGO observational runs.

However, the catch is that the correlations that reduce phase noise actually amplify the laser amplitude noise and increase quantum back-action noise. This hasn't been a big problem for LIGO so far because its low-frequency noise is dominated mainly by seismic and thermal noise, not by quantum noise. However, as technical noise sources are reduced and the available optical power continues to grow for the next-generation detectors, a more sophisticated squeezed light source will be required. Sources with a frequency-dependent squeezing, reduced amplitude noise at low frequency and reduced phase noise at high frequency, may be the preferred solution and are currently under development. But, in the meantime, Yap and co-workers have provided a crucial experimental demonstration and an important piece of the quantum noise reduction puzzle. ❐

Thomas Purdy
University of Pittsburgh, Pittsburgh, PA, USA.
e-mail: tpp9@pitt.edu

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IMAGING AND SENSING

Ultrafast time-of-flight 3D LiDAR

Time-of-flight 3D imaging is an invaluable remote sensing tool, but raster speeds are currently limited by pulsed-laser scanning rates. By adapting techniques from ultrafast time-stretch imaging, a new LiDAR platform scans orders of magnitude faster than today's commercial line-scanning pulsed-LiDAR systems.

Daniel J. Lum

Three-dimensional (3D) imaging is an invaluable remote-sensing tool utilized by numerous fields from robotics research[1] and aerial mapping[2] to commercial autonomous navigation[3]. With the race to perfect autonomous vehicles[3,4], development of high-speed 3D imaging utilizing light detection and ranging (LiDAR) has taken centre stage to make autonomous vehicles a reality. Current 3D imaging systems can generate high-resolution point clouds of the surrounding