TUTORIAL

Better Sensors via Squeezed Light

Some quantum-mechanical sleight-of-hand can boost detector sensitivity

The sensitivity of laser-based detectors has dramatically improved, with multiple techniques to hammer down classical noise sources such as laser intensity fluctuations. But eventually, these systems run up against the seemingly intractable shot-noise limit—the noise from statistical quantum fluctuations in the photons making up the beam.

To go below that noise floor, researchers are turning to an elegant bit of quantum-mechanical sleight-of-hand: "squeezed" states of light. Here's a look at how it works, based on a setup for a squeezed-light-enhanced plasmonic biosensor published last year in *Optica* by researchers at the Oak Ridge National Laboratory (ORNL) and the University of Oklahoma, USA.

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1. The basics of squeezing

Exotic as the name seems, squeezed states are just Heisenberg's uncertainty principle in action. In quantum optics, a light field is described by two "quadratures," one for phase (P) and one for amplitude (X). Per Heisenberg, the minimum uncertainty of those two quadratures in a given measurement is given by the relation $\Delta X \Delta P = \hbar/2$. In other words, for a given measurement, the better you know the phase, the more potential error there is in the amplitude, and vice versa.

For a coherent state, such as a laser field, the phase and amplitude uncertainties are equal, giving rise to a circularly symmetric "fuzzball" of potential error between the two quadratures. But using nonlinear-optics techniques, the circle can be "squeezed" into an ellipse. That means that uncertainty in one quadrature—the one that's relevant to your sensor—can be reduced, while the uncertainty in the other, less relevant quadrature are increased.

2. Pump and probe beams

State-of-the-art plasmonic biosensors already reduce classical noise to the shot-noise limit. The ORNL–Oklahoma setup takes the noise-reduction performance further by using four-wave mixing to create a squeezed state of light that can drive the system below the shot-noise limit.

The system begins with two beams from a 795-nm Ti:sapphire laser—a strong (550 mW) pump beam, and a weaker, frequency-downshifted probe beam. The pump and probe beams are sent, at a 0.5-degree angle to one another (to ensure phase matching), into a hot vapor cell containing ^{85}Rb atoms.

3. Squeezing the uncertainty

Inside the vapor cell, the presence of the pump and probe beams leads to a "double-Λ" four-wave mixing process, in which two pump photons spur creation of another photon at the probe wavelength and of a "conjugate" photon at a different wavelength.

As the process cycles over and over, each new probe photon beefs up the probe beam strength. And since the number of photons generated in the probe and conjugate beams is correlated over time, the noise statistics are correlated, too. The correlation reduces the quantum uncertainty of the intensity difference between the probe and conjugate beams—in effect squeezing the intensity difference.

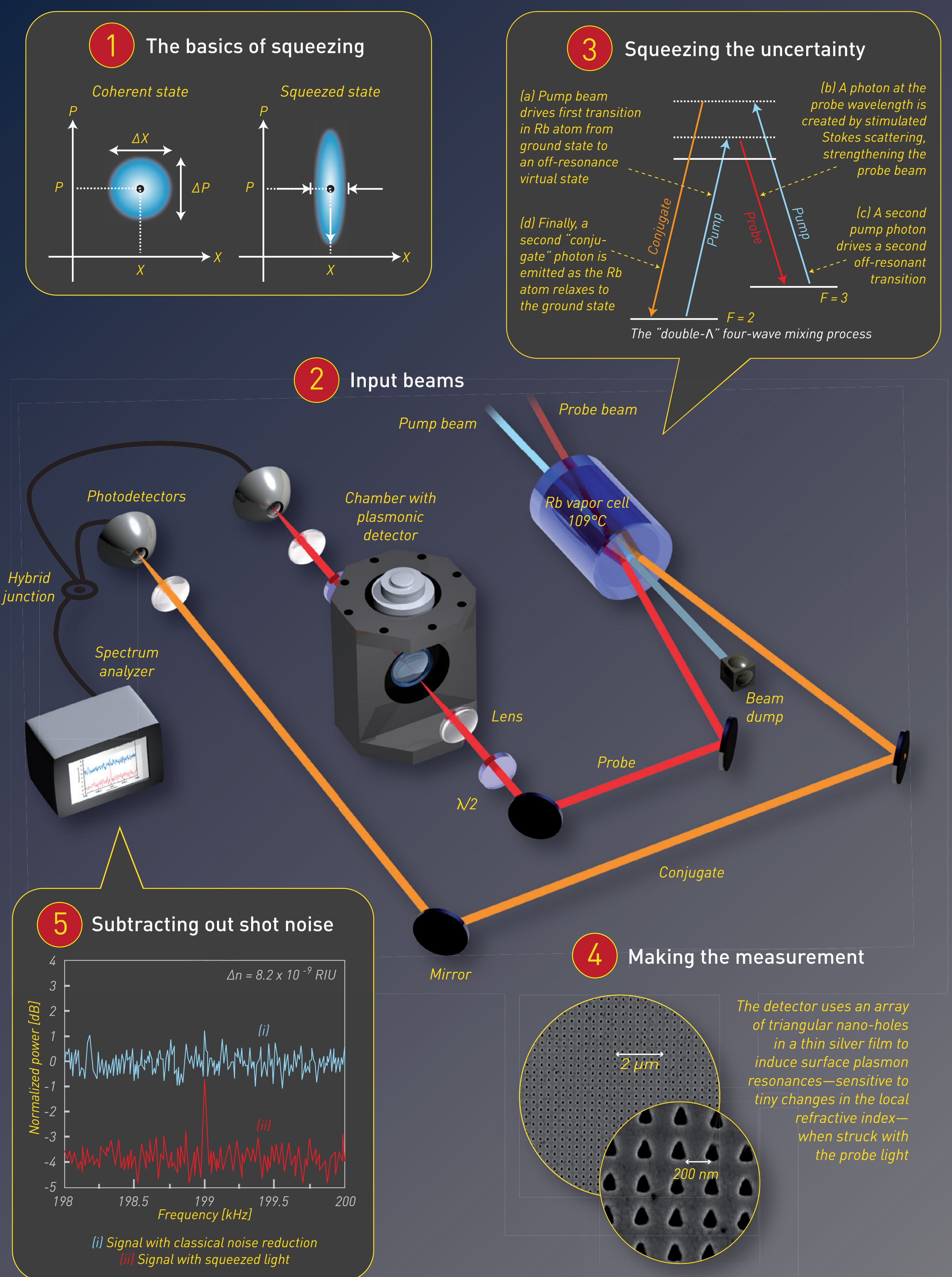
4. Making the measurement

Because of conservation of momentum, the probe and conjugate beams exit the ^{85}Rb cell at an angle to one another. (The pump beam, its work done, is shunted to a beam dump.) The conjugate beam is routed to a photodetector for a reference intensity measurement; the probe beam passes through the plasmonic sensing module for the actual sample measurement, and on to a second photodetector.

5. Subtracting out quantum noise

Finally, the intensity difference between the quantum-correlated probe (measurement) and conjugate (reference) beams is subtracted out at hybrid junction. The signal passes to a spectrum analyzer to demodulate and measure the refractive-index shift from the plasmonic sensor. The ORNL–Oklahoma team found that squeezing the intensity difference cut the quantum noise of the sensor by 4 dB, allowing the system to detect a ~10^{-10} refractive-index change at the plasmonic sensor that, in the classically optimized system, would have been lost in the shot noise. OPN

OPN thanks Ben Lawrie and Raphael Pooser of ORNL for assistance with this tutorial. For references and more information on squeezed light, go online: www.osa-opn.org/tutorials/squeezed-light.



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