Quiet Lasers, Cool Science

Trapping and cooling of atoms and nanoparticles is a growing area of laser-assisted research, with implications for quantum computing and ultraprecise sensing.

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In the 1960s, just a few years after the laser was invented, researchers contemplated its use as a precision tool to control the motion of neutral atoms. Early research focused on the use of an optomechanical force based on the scattering of light. In simple terms, it was found that when an object was irradiated with light from a single direction, the object could randomly re-radiate or scatter in all directions, causing a small net transfer of momentum from the photons to the object.

Eventually this led to the creation of "optical molasses" at a temperature of <50 µK. In 1995, scientists in the laboratory of Carl Wieman at JILA, a joint institute of the National Institute of Standards and Technology (NIST) and the University of Colorado Boulder, created the holy grail of cooling: the elusive Bose-Einstein condensate[1]. Specifically, they cooled roughly 2000 rubidium atoms to approximately 170 nK using a combination of laser cooling and magneto-evaporative cooling. In such condensate, extremely exotic effects, such as quantum interference and degeneracy, occur as the laws of classical physics begin to break down.

This early research was driven primarily by intellectual curiosity, but scientists soon recognized the possibility of interesting and potentially useful applications: ultraprecise (Doppler-free) spectroscopic measurements; more accurate atomic clocks; the ability to create and study "squeezed light"; ultrasensitive gravitational and magnetic field sensors; and faster quantum computing and communications.

Quiet NPRO lasers

Depending on the specifics of the atomic species being trapped and the target temperature range, several different laser cooling and trapping methods are now used. However, these methods generally require a laser with low phase noise and low amplitude noise. Depending on the technique, an acceptable definition of "low" can cover orders of magnitude.

In the case of cold atoms, conventional Doppler cooling laser techniques are used to reach millikelvin to microkelvin temperatures. For this, wavelength-tunable laser diodes, Ti:sapphire, or even dye lasers are typically used. To reach even lower temperatures by using evaporative cooling or to confine cold atoms, researchers often use stable off-resonant (i.e., with wavelength far from atomic transition) laser beams. Today, the gold standard in low-noise lasers for many atom-trapping experiments is the nonplanar ring oscillator (NPRO), because the

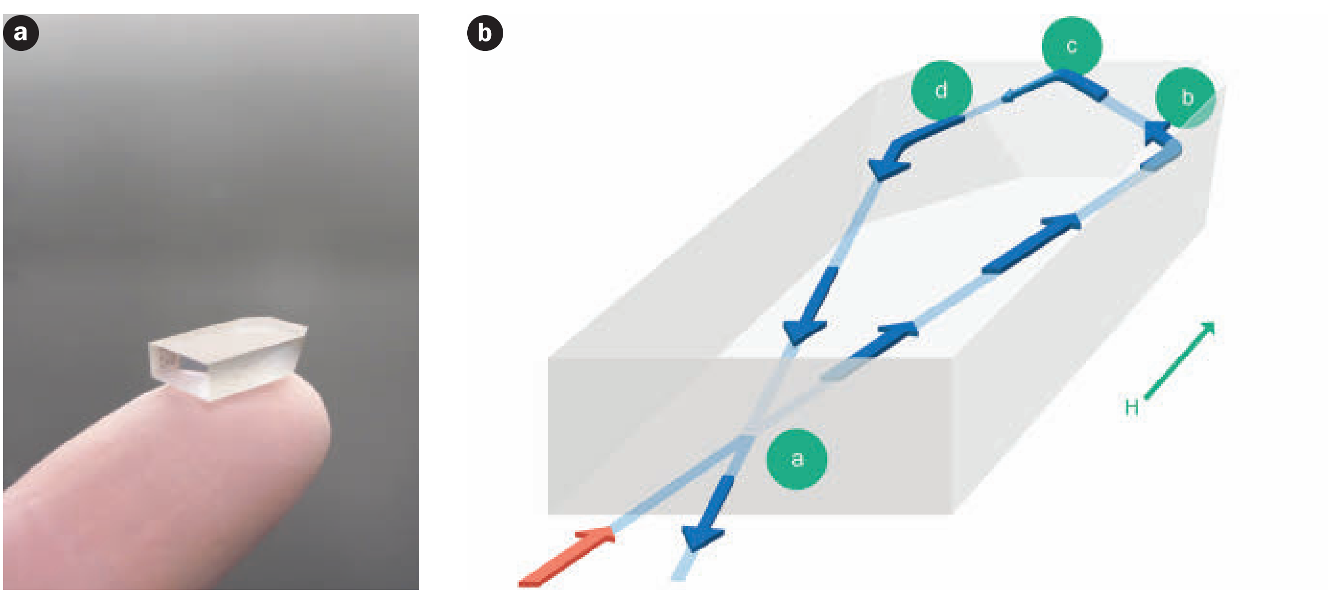

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Figure 1. The gain crystal forms a monolithic laser cavity in a nonplanar ring oscillator, where the facet angles ensure high reflectivity through total internal reflection (TIR) **(a)**. The facets are arranged so that natural intracavity beam polarization (due to TIR) in combination with an externally applied magnetic field preferentially supports unidirectional traveling-wave laser operation.**(b)**; H: magnetic field.

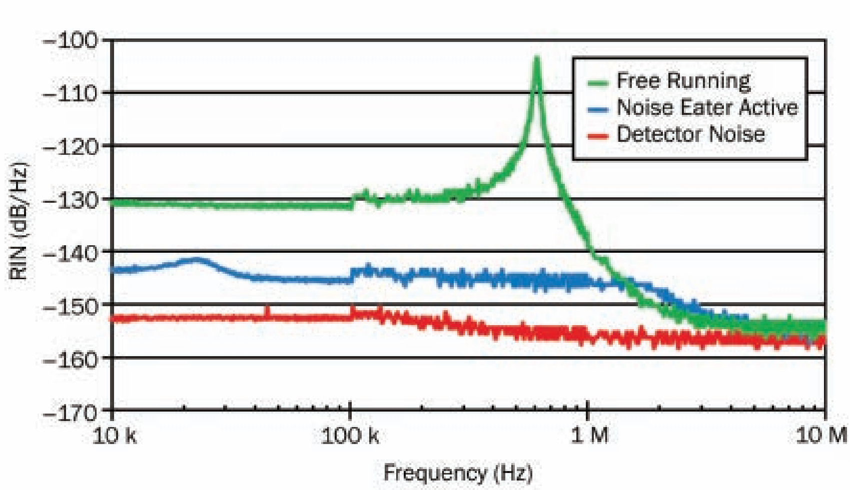

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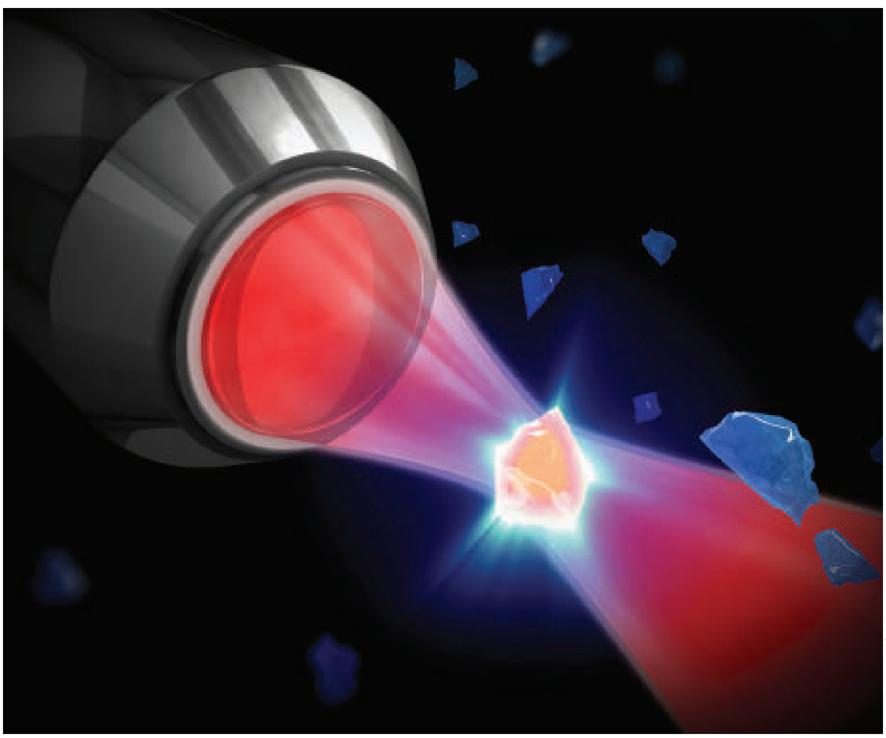
Figure 2. Mephisto amplitude noise, expressed as RIN (relative intensity noise). The noise eater circuit is effective in eliminating most of the pump-diode current noise and also the noise peak (at 0.7 MHz) caused by relaxation oscillations.



Peter Barker, UC London

Figure 3. Artist's conception of cavity optomechanical cooling of a nanocrystal.

low-noise experiments can make use of its intrinsic stability.

One of the keys to low-output noise is a stable laser cavity. The resonant cavity of a typical single-mode laser incorporates a gain medium and other individual optics, all held on precision mechanical mounts. In contrast, a monolithic NPRO crystal acts as both the gain medium and the cavity, which is defined by the crystal facets (Figure 1).

One of the prerequisites for narrow linewidth in any laser is stable operation on a single longitudinal mode. The NPRO naturally favors this single-mode operation because its short cavity length results in large frequency spacing between the longitudinal modes, relative to the gain bandwidth of the Nd:YAG crystal. The mode nearest the peak of the laser bandwidth thus has significantly higher gain than all other possible modes.

Just as important, the NPRO acts as a unidirectional traveling-wave ring oscillator because standing-wave oscillators typically exhibit spatial hole burning; a standing-wave pattern cannot efficiently use the gain located at the nodes of the sinusoidal electric field. This NPRO geometry also exhibits a clever trick: When the crystal is placed in a magnetic field, it acts as an optical isolator — a unidirectional device whose forward transmission is much higher than its transmission in the reverse direction. Thus, the strongest mode travels in this direction around the cavity, utilizing all of the gain and leaving no pockets of undepleted gain for any other mode to use.

Many trapping and cooling applications require feedback control (or locking of the laser output frequency), and the NPRO achieves this in two ways: (1) Fast response (up to 10 s of kHz) is supported by a piezoelectric actuator bonded to the crystal, which applies pressure to the crystal when a voltage is applied; and (2) long-term stability is supported by thermoelectric temperature control of the crystal.

An example of an NPRO-based laser is the Mephisto, which was developed and optimized specifically for LIGO (Laser Interferometer Gravitational-Wave Observatory); it is currently used as the master laser oscillator in all working LIGO instruments. Mephisto is an Nd:YAG laser that delivers a linewidth of ~1 kHz, far narrower than even the best commercial laser diode or fiber oscillator could achieve, even without any external locking. Thanks to its internal "noise eater" feedback loop, this laser also delivers very low amplitude noise (Figure 2).

Power scaling and lattice trapping

Different techniques and atoms have unique laser power needs. For example, heavier atoms can be trapped with <1 W of laser power. But lighter atoms, such as lithium, have much higher momentum for a given energy and require more laser power. In any situation where low-noise operation is critical, this need for power is best addressed with a modular MOPA (master oscillator power amplifier) design (e.g., Mephisto MOPA) where an NPRO is amplified by a second, third, or even fourth diode-pumped crystal, all integrated within a single package. In this way, a 2-W NPRO can be amplified to a choice of 8-, 25-, 42-, or 55-W output with no increase in phase noise.

One type of trapping that requires a high-power option is the optical lattice trap. Where two collimated counterpropagating beams are used, the dipole trapping field is a standing-wave pattern aligned along the laser beam axis.

In lattice trapping, the laser beams are collimated as narrow sheets, which creates an electric field pattern — consisting of maxima and minima — that looks like planar waves. A second pair of laser beams that are in the same plane, but at right angles, creates a standing-wave pattern in the shape of an egg crate, with each of the minima acting as a microtrap, which enables a tool for interesting experiments.

For example, optical lattices are widely used in optical atomic clocks, phase transition experiments, quantum simulators, and work with cold molecules. The motion in each well is quantized in a classic particle-in-a-box situation. Spectral transitions between the different levels can be studied in isolated atoms, but with a large enough sample for detectable signal-to-noise ratios. A key factor here is low laser intensity noise, which would otherwise cause heating of the trapped atoms.

Levitating the refrigerator

A particularly dynamic area of trapping research that currently involves nanoparticles is quantum optomechanics. Even though matter is both a particle and a wave, the wave effects cannot be seen in larger objects. Nanoparticles typically encompass billions of atoms, which present an excellent opportunity to study quantum effects in a macroscopic setting, if they can be trapped and cooled. With small numbers of atoms, such as a condensate, stopping the translational motion of the atoms both traps and cools the sample at the same time. Some atom-trapping techniques can be extended to trap nanoparticles by reducing the center of mass motion, but this will not simultaneously cool the internal temperature of these particles.

Professor Peter Barker of University College London is a leading researcher in the field. He is now studying at what point quantum mechanics breaks down as particles get larger. From a practical applications viewpoint, one of the materials Barker is studying is nitrogen-vacancy (NV) diamond, where nitrogen doping causes vacancy centers. This material has all kinds of potential uses in photonics. He plans to study its fundamental properties, such as photoluminescence, when quantum conditions dominate.

Trapping alone often serves to actually heat the particles under ultrahigh vacuum conditions. This means any heat that is accidentally introduced cannot escape, except as blackbody radiation. For example, in silica spheres trapped at a nonresonant wavelength, Barker has seen a small amount of absorption rapidly push the internal temperature as high as 1800 °C. The spheres start to shrink by vaporization until they reach a size where absorption is no longer relevant. Trapped nanodiamonds have even been seen to completely disappear with this effect.

The trick is to use one laser mechanism to trap the particles and another to cool their internal temperature, referred to as "laser refrigeration"[2]. Researchers have only recently been successful with laser refrigeration, where dropping the particle temperature by 100 K was considered state of the art just a couple of years ago.

In this work, researchers trap silica particles in an optical cavity with an extremely high finesse — about 200,000 (Figure 3). They trap the particles and cool the center of mass motion using 1064-nm light from a Mephisto oscillator. The Barker team calls this approach "cavity optomechanics," where the high-finesse cavity is tuned so that blue-shifted scattered light escapes, but red-shifted light does not. Repeated scattering of the 1064-nm nonresonant light therefore systematically drains center-of-mass kinetic energy from the particle.

So far, they've reached the millikelvin regime in this way and are hoping to reach 10 µK soon. The technique depends on maintaining a small offset between the laser wavelength and a resonant mode of the cavity, with a precision and stability of ±1 MHz. They actually use the cavity itself as a reference for locking the laser. Only low (<1 W) laser power is needed for this method because the high numerical aperture (NA) creates very high intensity at the cavity waist.

According to Barker, in related work where 1031 nm from another laser is used, they can trap and cool down the internal temperature of the nanoparticles by resonant absorption of embedded Yb ions, which re-emit with nearly 100 percent quantum yield.

Here, they use a laser diode controlled by a fiber Bragg grating (FBG) tuned so that the narrowband excitation light is red-shifted from the absorption line center. The long excited-state lifetime of the Yb atoms allows the nanoparticles to thermalize before re-emitting (fluorescing), so that on average, depleted photons are blue-shifted from the laser, leading to net cooling. To date they have reached an internal particle temperature of 130 K with this method, and they are working on bringing these two techniques together to cool both the center of mass motion and the internal temperature.

Barker said the research team used linearly polarized light at 1064 nm to control the orientation of the trapped crystals, which allows them to maximize the efficacy of the 1031-nm-driven internal cooling. Both lasers have to exhibit extremely low noise for all of this to work. Heating is caused by the shot noise of the laser, which must be overcome by the cooling mechanism.

Very cool research by any measure.

Meet the author

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