Laser Physics

All-atom parametric oscillator

Using a 1D optical lattice to precisely control and confine the location of cold ^{87}Rb atoms has made it possible to create a distributed Bragg reflector and an optical parametric oscillator from nothing but atoms.

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The standard picture of a laser or an optical parametric oscillator is composed of a gain medium placed between two mirrors that create an optical cavity. Steady-state oscillation of the output optical field is achieved once the gain equals the round-trip optical loss within the cavity. Historically, the first lasers were constructed using gain media relying on optically active centres in solid-state crystals (such as chromium ions in a ruby crystal) and room temperature gases of atoms (such as mixtures of helium and neon). While a pair of parallel end mirrors is the most straightforward way to create an optical cavity, there is also a class of lasers, called distributed feedback (DFB) lasers, where the optical feedback comes from the spatial structure of the medium through which the light propagates. A one-dimensional, periodic patterning of the medium's refractive index creates a resonant scattering (Bragg scattering) condition at a particular wavelength and angle. The strength of this feedback depends on the number of periods as well as the strength of the refractive index modulation. If the feedback and gain are strong enough, lasing can occur without the use of conventional mirrors. This interesting type of lasing is popular in semiconductor systems where the gain medium can be easily grown or etched at periodic intervals, and such semiconductor DFB lasers are standard commercial products that play an important role as high performance transmitters in telecommunications systems.

On page xxx of this issue[1], Alexander Schilke and co-workers extend the concept of DFB lasing to systems in which gas phase atoms are the gain medium. Of course, atomic media have been used in lasers for the last half-century, but the implementation of distributed feedback within them is daunting for several reasons. Firstly, the real part of the index of refraction of a single atom like ^{87}Rb only differs from the vacuum near an optical transition (where there is significant absorption due to the imaginary part of the index), and it doesn't differ by much, so that a large number of atoms is required in a near-resonant condition. Secondly, the achievement of distributed feedback requires the modulation of the refractive index to be periodic, which is extremely difficult to arrange with room temperature atomic vapours as the atoms are constantly in motion.

Fortunately, this obstacle can be overcome by developments in laser cooling and trapping technology. Previously, atoms have been cooled and slowed to velocities of a few hundred mm/s and used as the gain medium in lasers employing end mirrors[2,3] , however, these velocities of a few hundred mm/s are still too large to allow for effective DFB oscillation. The answer is to use an optical lattice (a periodic potential made by interfering several laser beams) to pin the atoms at precise locations required to form a periodic index modulation. Schilke and colleagues have now done just that by cooling ^{87}Rb atoms in a magneto-optical trap and then subsequently loading them into a 1D optical lattice (Figure 1a). The team make their optical lattice by retro-reflecting a far red-detuned laser (not shown), creating a standing wave that determines the lattice and thus sets up the DFB system and gain medium. Roughly 5×10^7 atoms are distributed over 7700 lattice periods (~3 mm length in total) to induce a change in the refractive index of about 10^{-3} at each lattice site. Although, the average index over the lattice differs from the vacuum value by only 2.2×10^{-4} the variation is still sufficient to obtain stable optical feedback. A slightly off-axis, near-resonant pump laser beam is passed through the lattice and reflected off a mirror (not essential to the feedback) so that the atoms are effectively pumped by two degenerate, counterpropagating fields (see Figure 1a). Gain in this system is generated through a nonlinear optical process called four-wave mixing (FWM). In this case, the FWM converts the two pump fields into two new and nearly degenerate fields (often called the signal and idler fields). The combination of gain due to FWM and optical feedback produces optical parametric oscillation. As this feedback is produced without conventional end mirrors, such a configuration is sometimes referred to as "mirrorless." In addition to the aforementioned semiconductor DFB lasers, mirrorless optical parametric oscillations has recently been demonstrated in a nonlinear semiconductor material (cite NPhoton 2007 paper).

The interplay between FWM and feedback in the work of Schilke *et al*. is quite elegant. The optimal angle (with respect to the lattice) for efficient Bragg reflection is determined by the periodicity of the lattice, which is half of the wavelength of the laser that creates the optical lattice and is therefore tunable, and the average index of the atomic gas. Such Bragg reflection couples fields E_1 and E_3 as well as E_2 and E_4 as shown in Figure 1b. However, as shown in Figure 1a, multiple reflections result in the beam walking off from its original position, and because the atomic cloud has a finite extent, this limits the number of reflections achievable in practice. This is where an important property of the degenerate FWM comes in. The two new fields generated by FWM are phase-conjugates, which means they are emitted in exactly opposite directions (one field is the time-reverse of the other)[4]. In Figure 1, fields E_1 and E_4 as well as E_2 and E_3 are phase conjugate pairs. The addition of this phase conjugation thus completes the feedback cycle and generates stable oscillation above a threshold pump power. This stable oscillation generates four beams exiting the atomic cloud at the Bragg angle. The cylindrical symmetry of the setup dictates that the Bragg angle can be satisfied in any plane about the lattice axis, which means the output fields can be emitted into a cone exiting either side of the atomic cloud.

In such a complex system, proving that stable oscillation has been achieved is non-trivial. The researchers perform several measurements supporting their claim of DFB parametric oscillation. Firstly, by measuring the frequency of the output field using a beat-note technique, they show that the frequency of the output field matches (or nearly matches) that of the pump frequency, indicating that FWM is taking place. In addition, FWM is known to be more efficient when the output fields are orthogonally polarized to the input; an effect they also observe. Lastly, if the pump field is made a travelling wave rather than a standing wave, they do not observe stable oscillation as FWM can no longer take place. To verify that the optical feedback was due to Bragg reflection, the researchers adjusted the lattice periodicity by changing the wavelength of the lattice laser. As discussed earlier, the angle for Bragg reflection depends only on the lattice period and the mean index of the atomic cloud. The researchers directly imaged the conical output beams after stable oscillation was established and measured the opening angle as a function of lattice periodicity. As the lattice laser is shifted to longer wavelengths, the angle of the output cones increases as expected from the Bragg condition. As a final measurement, the researchers measure the emitted intensity as a function of the pump power and observe a clear threshold behaviour. Although the output power saturates due to limitations of the FWM process as well as heating of atoms at high pump powers, a maximum output power of 3 μW from each side of the apparatus was measured. The maximum sustained oscillation time is reported to be 0.5 ms.

Despite being a highly controllable and tunable approach, lasers and oscillators made out of trapped atoms probably won't likely replace semiconductor lasers as a commercial light source, but they could help provide insights into optical transport[5] and light-matter coupling. Of particular interest to Schilke *et al.* is the study of lasing as the optical feedback goes from being periodic and ordered to disordered. Clearly ordered structures such as 1-D Bragg mirrors and higher dimensional photonic crystals can support lasing, but lasing is also found in disordered structures, a phenomenon known as random lasing[6,7]. An intriguing question is what happens in intermediate regimes. Cold atoms in optical lattices are a nearly ideal platform for such an investigation. As a gain medium, they support narrow spectral features and are well-isolated from the environment. As a feedback element, the initial configuration of the atomic sites is set by the lattice lasers, with the atoms' non-zero temperature giving rise to atomic motion that introduces disorder over a timescale that can allow the crossover between order and disorder to be explored. Just recently[8], a group from the University of Illinois in the US demonstrated 3D Anderson localization of atomic matter waves in an ultracold atomic gas. The current work of Schilke *et al.* helps set the stage in which such techniques can be extended from particle transport to photonic transport in these ultracold atomic systems. While it remains to be seen if ultracold atomic systems can impact photonics in the way that they have already done so for condensed matter physics, there is certainly reason to be hopeful.

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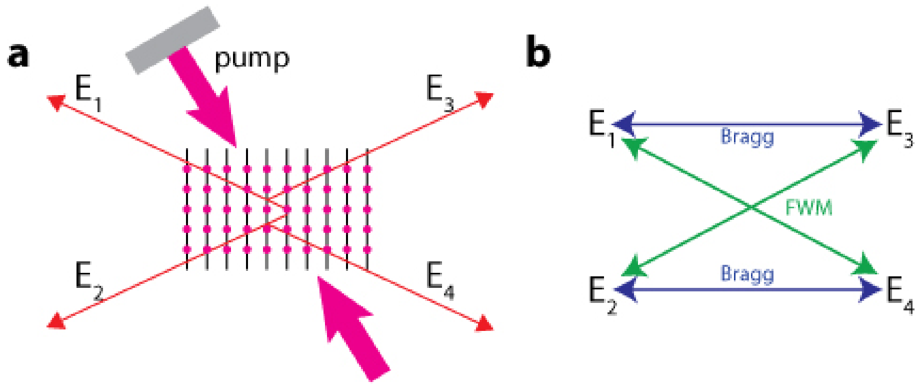

Figure Caption: Optical parametric oscillation with distributed feedback in cold atoms. a) Atoms are cooled and trapped in a 1-D optical lattice where they provide resonant optical feedback (Bragg scattering) for light traveling at a specific angle with respect to the lattice axis. Light is generated along these directions by the atomic cloud through four-wave mixing (FWM) of two counter-propagating pump beams. b) A feedback diagram showing how Bragg scattering and FWM couple the four output fields. Provided the gain from FWM is sufficient, the output fields can reach stable oscillation.