Optical parametric oscillation with distributed feedback in cold atoms

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There is currently a strong interest in mirrorless lasing systems¹, in which the electromagnetic feedback is provided either by disorder (multiple scattering in the gain medium) or by order (multiple Bragg reflection). These mechanisms correspond, respectively, to random lasers² and photonic crystal lasers³. The crossover regime between order and disorder, or correlated disorder, has also been investigated with some success⁴–⁶. Here, we report one-dimensional photonic-crystal-lasing (that is, distributed feedback lasing⁷,⁸) with a cold atom cloud that simultaneously provides both gain and feedback. The atoms are trapped in a one-dimensional lattice, producing a density modulation that creates a strong Bragg reflection with a small angle of incidence. Pumping the atoms with auxiliary beams induces four-wave mixing, which provides parametric gain. The combination of both ingredients generates a mirrorless parametric oscillation with a conical output emission, the apex angle of which is tunable with the lattice periodicity.

Among the possible systems that can be used to produce and study mirrorless lasers, cold atoms are interesting because of some specific properties that differ from those of standard photonic materials. First, they are resonant point-like scatterers, producing extremely narrow spectral features (gain curves, scattering cross-section), which can provide flexibility⁹ or give new effects. Second, their temperature is low enough to make Doppler broadening negligible in most situations, but large enough to make them move substantially on a millisecond timescale, which makes disorder-configuration averaging or dynamic evolution from order to disorder very easy. Third, cold atoms are well isolated from the environment, which makes them good candidates in the search for quantum effects.

Conventional lasing has already been demonstrated when cold atoms are used as the gain medium⁰,¹¹, as has radiation trapping due to multiple scattering¹² and efforts are under way to combine both factors to obtain random lasing¹³,¹⁴. In the opposite regime, a one-dimensional photonic bandgap (PBG), yielding efficient Bragg reflection of light, has recently been demonstrated in a cold, ordered atomic vapour¹⁵. In this Letter, we demonstrate optical parametric oscillation (OPO) with distributed feedback (DFB) in cold atoms trapped in a one-dimensional optical lattice, by combining the PBG with four-wave mixing (FWM), which provides the gain mechanism¹⁰,¹⁶–¹⁸.

We trapped cold ⁸⁷Rb atoms in a one-dimensional lattice of tunable wavelength $\lambda_{\text{DFB}}$. The trapping beam was retroreflected to generate a potential of periodicity $\lambda_{\text{DFB}}/2$ (Fig. 1 and Methods). Typically, $N = 5 \times 10^7$ trapped atoms were distributed over a length $L \approx 3$ mm ($\sim 7,700$ atomic layers) at a temperature $T \approx 100 \mu$K, leading to a root-mean-square (r.m.s.) transverse radius of the cloud $\sigma_{r} \approx 60$ nm. Such an atomic pattern gives rise to a periodic modulation of the refractive index $n$ and we have shown recently¹⁵ that the very small modulation amplitude $\Delta n \approx 1 \times 10^{-3}$ inherent to dilute vapours (density $n \approx 1 \times 10^{12}$ cm$^{-3}$) could be balanced by the large number of layers, provided that the Bragg condition is fulfilled for a small angle of incidence and for a frequency slightly off the atomic resonance to avoid too much scattering losses. A Bragg reflection as efficient as 80% can be obtained.

In the present experiment, we investigated the situation when gain was added to the system. Cold atoms can amplify light when pumped by auxiliary near-resonant beams, and several gain mechanisms have already been demonstrated (see ref. 10 and references therein). The combination of enough gain and multiple Bragg reflection should lead to DFB lasing.

However, in this system, the stability of the feedback mechanism is a critical issue. We trap the atoms using a lattice beam that is far red-detuned from the atomic transition (D2 line of ⁸⁷Rb, wavelength $\lambda_0 = 780.24$ nm in vacuum, linewidth $\Gamma/2\pi = 6.07$ MHz), so that the Bragg condition can only be fulfilled for a non-zero propagation angle $\theta$, relatively to the lattice axis, given by

$$\lambda_{\text{DFB}} \cos \theta = \lambda_0/n$$

Figure 1 | Schematics of the set-up. Cold atoms are trapped in the lattice formed by a retroreflected dipole trap. The pump beam is also retroreflected and has an incident angle of $\sim 8^\circ$. Above threshold, the system emits light with an angle $\theta$ around the lattice: in any given plane including the lattice, four waves are coupled. $E_1$ and $E_4$ as well as $E_2$ and $E_3$ are coupled by the phase-conjugation process; $E_1$ and $E_2$ as well as $E_3$ and $E_4$ are coupled by the Bragg reflection. The emitted light is detected by avalanche photodiodes (APDs) and the beam cross-section is observed by a charge-coupled device (CCD) camera. Additionally, a probe beam (incident power $P_0$) can be used to measure the phase-conjugate reflectivity $R_{pc} = P_{pc}/P_0$, where $P_{pc}$ is the reflected power. Inset: scheme of the four-photon transition corresponding to FWM. Upward (downward) arrows represent pump (probe and conjugate) photons. MOT, magneto-optical trap.
where \( n \) is the averaged refractive index of the atomic medium. Because of this angle, typically \( \theta \approx 2^\circ \) for \( \lambda_{\text{dip}} = 780.6 \text{ nm} \), the light beam is not perfectly reflected onto itself such that it transversely walks off and leaves the interaction volume after a certain number of Bragg reflections.

Because this walk-off effect plays an important role, we must consider, for each plane containing the lattice, four different waves having a propagation angle \( \theta \) relatively to the lattice axis (Fig. 1). In this case, a ‘standard’ gain amplifies one wave \( \left(E_i\right) \) with a walk-off. This problem can be overcome by producing gain with a phase-conjugation mechanism such as degenerate or nearly degenerate FWM. Then, each wave generates a backward phase-conjugated wave. Combined with the Bragg reflection, this leads to a global, walk-off free coupling between all four waves (Fig. 1), which favours an oscillatory behaviour.

Experimentally, inducing FWM in a phase-conjugation configuration is done by simply retroreflecting a near-resonant, linearly polarized pump beam (Fig. 1). Its typical detuning from the \( F = 2 \rightarrow F' = 3 \) closed transition is \( \Delta = -5 \Gamma \), it makes an incident angle with the lattice of \( \sim 8^\circ \), and it is collimated with a waist \( w \approx 2.4 \text{ mm} \), thus ensuring a nearly homogeneous pumping of the whole lattice. To avoid optical pumping into the dark hyperfine \( F = 1 \) ground state, a repumping laser is kept on all the time. In addition, a weak probe beam, phase-locked with the pump, can be used for pump–probe experiments or as a local oscillator.

When the pump power \( P \) overcomes a certain threshold, namely \( P_{\text{th}} \approx 1 \text{ mW} \) for \( \Delta = -5 \Gamma \) (Fig. 3), we observe a strong, directional light emission that can be recorded either with avalanche photodiodes (APDs) or with a charge-coupled device (CCD) camera (Fig. 1). This radiation is due to OPO with DFB in the cold atom sample, with FWM as the gain mechanism. This interpretation is supported by many observations, as discussed in the following.

First, this radiation is obtained only with a retroreflected pump beam, the alignment of which is critical, which is a strong indication that FWM is at work (with only one pump beam, we observe a strong Raman gain in pump–probe experiments but no laser). Second, the polarization of the emitted radiation is linear and orthogonal to that of the pump beam. This is also consistent with the properties of FWM, which is much more efficient for orthogonal pump and probe polarizations. Third, we measured the frequency of the emitted light with a beat note experiment (see Supplementary Information). The emitted light is just a few kilohertz detuned from the pump frequency, which is consistent with nearly degenerate FWM and inconsistent with Raman gain, for which the amplification line was detuned by \( \sim 200 \text{ kHz} \) with similar parameters.

The role of Bragg reflection as the feedback mechanism is demonstrated by the beam shape. Emission occurs with angle \( \theta \) from the lattice axis and, because of axial symmetry, forms two cone-shaped beams on each side of the lattice. From images of the beam cross-section (Fig. 2a), we extract the emission angle \( \theta \) as a function of \( \lambda_{\text{dip}} \). A fit with \( n \) as a free parameter is fully consistent with the Bragg condition (equation 1) and gives \( n - 1 = (2.2 \pm 0.5) \times 10^{-4} \) (Fig. 2b), which is the expected order of magnitude given the atomic density (the refractive index depends also on the pump power).

The intensity profile \( I(\psi) \), where \( \psi \) is the in-plane angle, exhibits strong shot-to-shot fluctuations. However, there is always a symmetry, that is, \( I(\psi) \approx I(\psi + \pi) \). This can be more precisely quantified by computing from the images the angular correlation function \( C(\Delta \psi) = \langle I(\psi) I(\psi + \Delta \psi) \rangle / \langle I(\psi) \rangle^2 \), which shows indeed a very strong correlation \( C(\pi) \approx 0.96 \) (Fig. 2c). This correlation comes from the couplings, namely the Bragg reflection and the phase conjugation, that exist in any given plane between the four directions of emission (Fig. 1). In contrast, the shot-to-shot fluctuations can be understood by the random direction of the initial spontaneous emission event that triggers the laser oscillation and by the absence of coupling between waves in different planes. In addition, we note that even after averaging, the intensity is not uniformly distributed along the ring (Fig. 2a), indicating that some effects break the axial symmetry (the incident angle of the pump beam and possibly some residual astigmatism in the lattice beam).
We indeed observed, in the temporal behaviour of the doped sample (Fig. 3) and Fig. 2), we used a CCD camera. The beam was first reflected off a mirror, which was retroreflecting the beam. After loading the optical lattice, the molasses beams were switched off and a waiting time of 20 ms allowed the trapped atoms to escape. Then, we could either characterize the trapped sample by absorption imaging, perform pump–probe spectroscopy to measure transmission, Bragg reflection and phase-conjugate reflection spectra, or shine only the pump beams to observe the emitted light. When the phase-conjugate reflectivity was measured without lattice (Fig. 3), the lattice was switched off with a mechanical shutter in 130 μs and the atoms freely expanded for 1 ms before measurements. This time of flight was large enough to completely smooth out the ordered structure and small enough to keep the optical thickness constant. All the stages following the initial MOT loading lasted only a few milliseconds, so the total cycle duration was not much longer than 1 s. The repetition rate was thus ~1 Hz, which allowed quick averaging over many realizations.

### Detection tools
To measure the phase-conjugate reflectivity, we used APDs and obtained spectra by sweeping the probe frequency with an acousto-optic modulator in double-pass configuration. Because the probe power fluctuated during the sweep, the recorded reflected intensity was divided by a reference intensity recorded simultaneously with another APD illuminated by part of the probe beam. The relative sensitivity of both APDs was calibrated with a 10% uncertainty due to thermal drifts.

To observe the transverse mode of the OPO (cross-section images shown in Fig. 2), we used a CCD camera. The beam was first reflected off a mirror, which was pierced to allow the lattice beam to go through (Fig. 1), and then collimated and focused 50 cm later on the camera. This allowed us to image the whole beam, and also to use several small black masks mounted on thin glass plates to get rid of stray reflections of the lattice beam on the vacuum chamber windows, which focused at intermediate distances. The angle calibration used the probe beam, which could also be imaged on the camera, as a reference. The incident angle of the probe beam was precisely determined using a series of Bragg reflection spectra off the passive lattice. When the spectra were symmetric, the probe angle fulfilled cos θ = λ/λ_{dp} (ref. 15).

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A.S. and W.G. performed the experiment and analysed the data, W.G. supervised the project and wrote the paper. All authors discussed the results and commented on the manuscript.

Additional information
The authors declare no competing financial interests. Supplementary information accompanies this paper at www.nature.com/naturephotonics. Reprints and permission information is available online at http://www.nature.com/reprints. Correspondence and requests for materials should be addressed to W.G.