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► **To cite this version:**

Alexander Schilke, Claus Zimmermann, Philippe W. Courteille, William Guerin. Distributed Feedback Lasing with Cold Atoms. 2011. hal-00626835v1

**HAL Id: hal-00626835**

**<https://hal.science/hal-00626835v1>**

Preprint submitted on 27 Sep 2011 (v1), last revised 1 Feb 2012 (v2)

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# Distributed Feedback Lasing with Cold Atoms

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There is currently a strong interest in mirrorless lasing [1]. In these systems, the electromagnetic feedback is provided either by disorder, i.e., multiple scattering in the gain medium itself, or by order, i.e., multiple Bragg reflection. This corresponds, respectively, to “random lasers” [2] and “photonic crystal lasers” [3]. The crossover regime, between order and disorder, or correlated disorder, starts also to be fruitfully investigated [4–7]. Here, we report one-dimensional photonic crystal lasing, i.e., distributed feedback lasing [8, 9], with a cold atom cloud that provides simultaneously both gain and feedback. The atoms are trapped in a 1D lattice, giving a density modulation that creates a strong Bragg reflection under a small angle of incidence. Pumping the atoms with auxiliary beams induces four wave mixing that provides gain. The combination of both ingredients generates a mirrorless laser with a conical output emission, whose apex angle is tunable with the lattice periodicity through the Bragg condition.

Among the efforts to produce and understand mirrorless lasers, cold atoms are interesting systems because of their specific properties in comparison with standard photonic materials. First, they are resonant point-like scatterers, which leads to extremely narrow spectral features (gain curves, scattering cross-section), which can provide flexibility [10] 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 at the ms 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 to search for quantum effects.

Conventional lasing has already been demonstrated with cold atoms as the gain medium [11] as well as radiation trapping due to multiple scattering [12] so that there is a current effort to combine both ingredients together to obtain random lasing [13, 14]. In the opposite regime, a 1D photonic band gap (PBG), yielding efficient Bragg reflection of light, has been recently evidenced in a cold, ordered atomic vapour [15]. In this letter we demonstrate DFB lasing with cold atoms trapped in a 1D optical lattice, by combining the PBG with four-wave mixing (FWM), which provides the gain mechanism [11, 16–18].

We trap cold  $^{87}\text{Rb}$  atoms in a 1D lattice of tunable wavelength  $\lambda_{\text{dip}}$  (see Methods). The beam has a waist  $w_{\text{dip}} = 220 \mu\text{m}$  and is retroreflected, thus generating a potential whose periodicity is  $\lambda_{\text{dip}}/2$  (Fig. 1). Typical numbers for the trapped atoms are  $N = 5 \times 10^7$  atoms distributed over a length  $L \sim 3 \text{ mm}$  ( $\sim 7700$  layers) and the temperature  $T \sim 100 \mu\text{K}$ , leading to a rms transverse radius of the cloud  $\sigma_{\perp} \simeq 60 \mu\text{m}$ .

Such an atomic pattern gives rise to a periodic modulation of the refractive index  $n$  and we have shown recently that the very small modulation amplitude  $\Delta n \sim 10^{-3}$  inherent to dilute vapours (density  $\rho \sim 10^{12} \text{ cm}^{-3}$ ) could be balanced by a relatively 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% has been observed [15].

In the present experiment, we investigate the situation when *gain* is added to this system. Cold atoms can amplify light when pumped by auxiliary near-resonant beams, and several gain mechanisms have already been demonstrated (see [11] 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. To trap the atoms by the dipole force, the lattice beam must be red-detuned from the atomic transition (D2 line of  $^{87}\text{Rb}$ , wavelength  $\lambda_0 = 780.24 \text{ nm}$  in vacuum), so that the Bragg condition can only be fulfilled for a non-zero propagation angle  $\theta$ ,

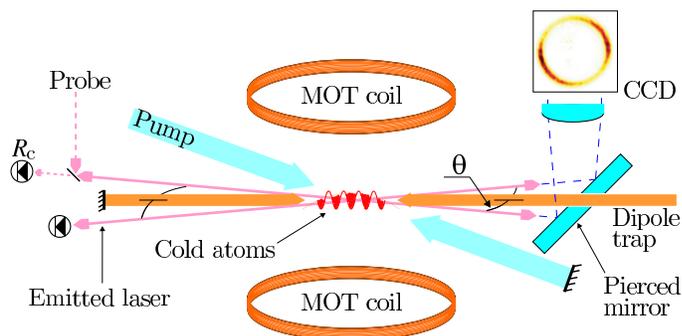


Fig. 1. **Setup.** Schematics of the experimental arrangement.

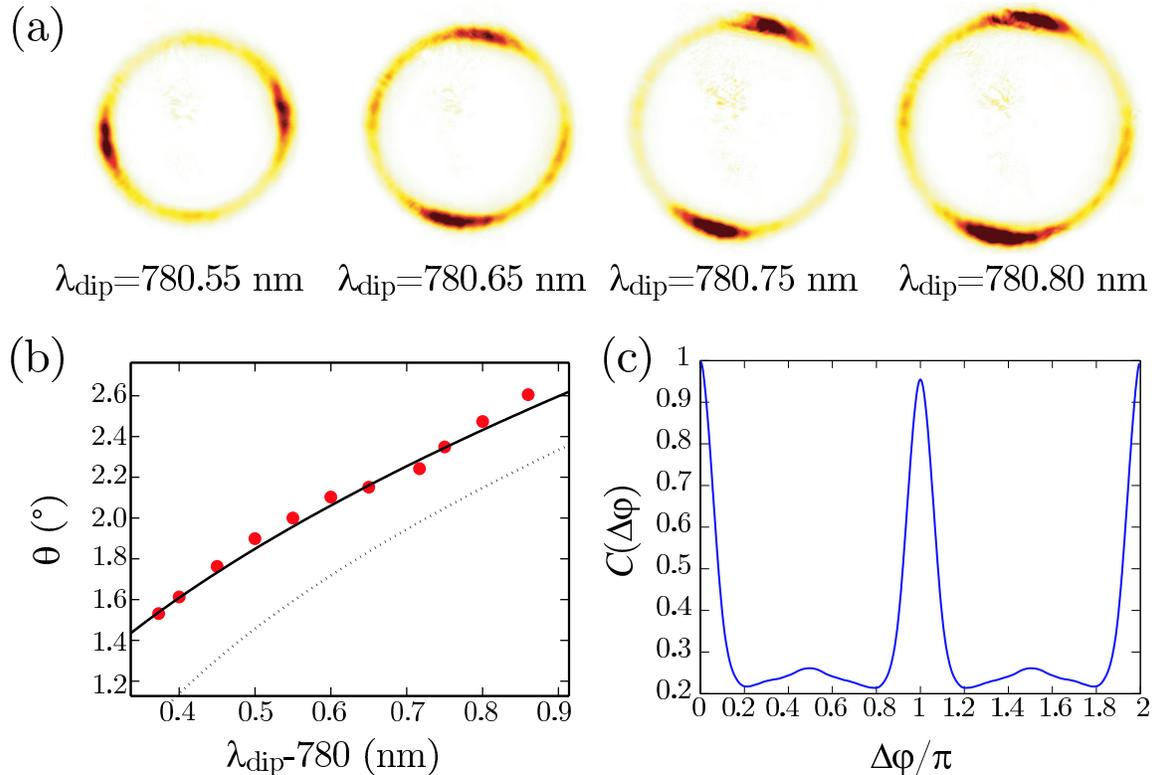


Fig. 2. **Transverse mode of the emitted beam.** **a**, Cross section of the beam for different  $\lambda_{\text{dip}}$ . Each image is the result of an average of about 100 pictures of integration time  $200 \mu\text{s}$ . **b**, Measured emission angle  $\theta$  as a function of  $\lambda_{\text{dip}}$  (red dots). The dashed line is the Bragg condition (1) with  $\bar{n} = 1$  and the solid line is a fit with  $\bar{n}$  as a free parameter. **c**, Averaged angular correlation function  $\mathcal{C}(\Delta\varphi)$  measured for the  $\lambda_{\text{dip}} = 780.75 \text{ nm}$  data.

relatively to the lattice axis, given by

$$\lambda_{\text{dip}} \cos(\theta) = \lambda_0 / \bar{n}, \quad (1)$$

where  $\bar{n}$  is the averaged refractive index of the atomic medium. Because of this angle, typically  $\theta \sim 2^\circ$  for  $\lambda_{\text{dip}} = 780.6 \text{ nm}$ , the Bragg reflection does not lead *a priori* to a stable feedback mechanism: after a few reflections, the wave would escape on the sides of the atom cloud.

This problem can be overcome by producing gain with a phase-conjugation mechanism such as degenerate or nearly-degenerate FWM [11, 16–18]. In this case, a wave propagating off axis still generates a backward conjugated wave, which returns into the medium. This process should improve the stability of the system, exactly as phase-conjugate mirrors make any resonator stable [9].

Experimentally, inducing FWM in a phase-conjugation configuration is done by simply retro-reflecting a near-resonant pump beam (Fig. 1). Its typical detuning from the  $F = 2 \rightarrow F' = 3$  closed transition is  $\Delta = -5\Gamma$ , it is collimated with a waist  $w \simeq 2.4 \text{ mm}$  and makes an incident angle with the lattice of about  $8^\circ$ . Its polarization is linear. In order 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  $P_{\text{th}} \sim 1 \text{ mW}$  for  $\Delta = -5\Gamma$  (Fig. 3), we observe a strong, directional light emission, that can be recorded either with avalanche photodiodes or with a CCD camera (Fig. 1). This radiation is due to DFB lasing in the cold atom sample, with FWM as the gain mechanism. This interpretation is supported by many observations, as discussed in the following.

Firstly, this laser emission is obtained only with a retroreflected pump beam, whose alignment is critical, which is a strong indication that FWM is at work (with only one pump beam, we observe a strong Raman gain [11] in pump-probe experiments but no laser). Secondly, the polarization of the emitted radiation is linear and orthogonal to the one of the pump beam. This is also consistent with the properties of FWM, which is much more efficient for orthogonal pump and probe polarizations [19]. Thirdly, we measured the frequency of the emitted light by a beat note experiment. The emitted light is just a few kHz detuned from the pump frequency, which is consistent with nearly-degenerate FWM [20] and inconsistent with Raman gain, whose amplification line was detuned from  $\sim 200 \text{ kHz}$  with similar parameters.

The role of the Bragg reflection as the feedback mechanism is evidenced by the beam shape, which we

record using a pierced mirror (to let the lattice beam go through) and a CCD camera (Fig. 1). The emission occurs with a given angle  $\theta$  from the lattice axis and, because of the cylindrical 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  $\bar{n}$  as a free parameter is fully consistent with the Bragg condition (1) and gives  $\bar{n} - 1 = (2.0 \pm 0.2) \times 10^{-4}$  (Fig. 2b), which is the expected order of magnitude given the atomic density. We observe also that, even if the number and the positions of local azimuthal maxima within the intensity profile  $I(\varphi)$  strongly vary from shot to shot, there is always a symmetry, i.e.,  $I(\varphi) \simeq I(\varphi + \pi)$ . This can be more precisely quantified by computing from the images the angular correlation function  $\mathcal{C}(\Delta\varphi) = \langle I(\varphi)I(\varphi + \Delta\varphi) \rangle / \langle I(\varphi)^2 \rangle$ , which exhibits indeed a very strong correlation  $\mathcal{C}(\pi) \simeq 0.96$  (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.

Finally, we have measured the emitted intensity as a function of the pump parameters. We observed that the laser is not very sensitive to the precise value of the pump detuning  $\Delta$ , provided it is negative (red-detuned) and not too close to resonance: we did not observe any significant change between  $\Delta = -4\Gamma$  and  $\Delta = -10\Gamma$ . Closer to resonance or with a positive detuning, the pump-induced heating destroys the lattice and the laser emission is inhibited or much weaker. The dependance with the pump power is much more important. Above the threshold, the emitted power increases with the pump power up to an optimum at  $P \sim 5$  mW above which a saturation, and then a decrease, are observed (Fig. 3). We estimate the maximum emitted power to be  $\sim 3 \mu\text{W}$  on each side. The decrease of the reflectivity past an optimum pump intensity is a known behaviour of FWM [16]. In our case, we also suspect a detrimental mechanical effect (heating or residual radiation pressure) which destroys the lattice. We indeed observed, in the temporal behaviour of the laser emission, that the laser works for a longer time for lower pump intensities, the longest duration being  $\sim 0.5$  ms.

We also measured the FWM phase-conjugate reflectivity  $R_c$  as a function of the pump power (Fig. 3). Below the lasing threshold, we compare the case of an ordered atomic structure and of a disordered one of the same optical thickness, by suddenly switching off the lattice just before the measurement (to compensate the lattice-induced light-shift, we increased the pump detuning accordingly). It shows that the lattice increases the FWM reflectivity when approaching the threshold, which demonstrates a positive-feedback effect. The threshold is reached when the phase-conjugate reflectivity without lattice is  $R_c \sim 0.5$ .

To conclude, let us discuss the possible applications of this DFB FWM laser. Firstly, we stress that the idea of combining FWM with a red-detuned DFB grating, in

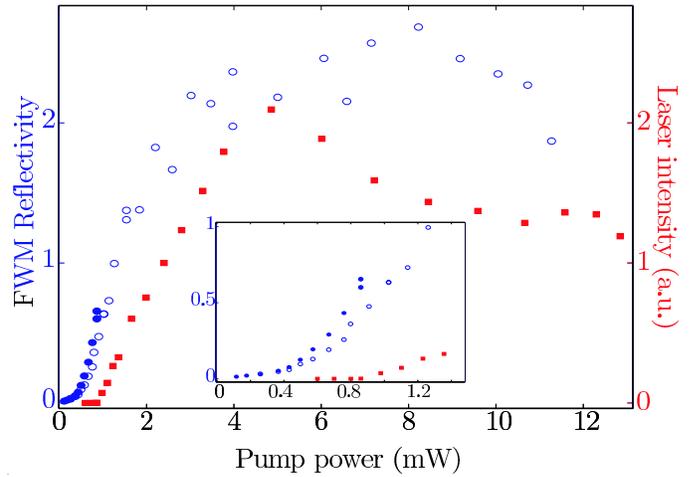


Fig. 3. **Emitted laser power and FWM reflectivity as a function of the pump power.** Red filled squares: Laser intensity. Filled blue circle: FWM reflectivity below the threshold (with lattice). The pump detuning is  $\Delta = -5\Gamma$ . Open blue circle: FWM reflectivity without lattice and with  $\Delta = -7\Gamma$ . Inset: zoom for low pump power.

order to generate conical laser beams, could also be applied in other systems, e.g., semiconductors [21, 22]. Secondly, the Bragg condition defines an angle between the longitudinal and the transverse wavevector of the emitted wave, which is also what defines a Bessel beam [23]. A complete analysis of the transverse modes of such DFB FWM lasers is beyond the scope of this work, but we speculate that they could be useful for producing Bessel beams, which are very interesting for their propagation properties, especially their robustness to diffraction [23, 24]. On the contrary, on-axis feedback could be obtained by using higher order Bragg reflection, e.g., with  $\lambda_{\text{dip}} = 2\lambda_0/\bar{n}$ . Combining this idea with frequency up-conversion schemes [25–28], one may be able to produce lasing at  $\lambda_0$  with pumps at longer wavelengths. In principle,  $\lambda_0$  can be any atomic transition, possibly in the UV range. Another possible application is the generation of “twin beams”, i.e., pairs of beams whose relative intensity noise is below the standard quantum limit. It is indeed well known that FWM induces quantum correlations and it has been shown that FWM oscillators above threshold could create twin beams [20]. We have already demonstrated strong angular classical correlations and, here again, more work is needed to investigate, theoretically and experimentally, the question of the possible quantum correlations in such systems. Here, the correlations might be shared among the four directions of emission in each plane. Finally, the extension to a 3D geometry, using the band gap predicted in [29], is an exciting open question.

## Methods

**Atomic sample preparation and experimental cycle.** The atoms are trapped and cooled in a magneto-optical trap (MOT) loaded from a background vapour during 1s. Then, stages of compression and molasses are used to increase the density and decrease the temperature, before loading the atoms in the dipole trap, which is generated by a home-made CW titanium-sapphire laser, following the design of [30]. The maximum available power is 1.3 W and its wavelength  $\lambda_{\text{dip}}$  is tunable. The beam is focussed with a waist ( $1/e^2$  radius)  $w_{\text{dip}} = 220 \mu\text{m}$  at the MOT position (Rayleigh length  $z_R \simeq 0.2 \text{ mm}$ ). The lattice is then formed by retroreflecting the beam. After loading the optical lattice, the molasses beams are switched off and a waiting time of 20 ms allows the untrapped atoms to escape. Then, we can 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 laser emission. All the stages following the initial MOT loading last only a few ms so that the total cycle duration is not much longer than 1s, which allows quick averaging.

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## Acknowledgments

We acknowledge support from the Alexander von Humboldt foundation, the Deutsche Forschungsgemeinschaft (DFG) and the Research Executive Agency (program COSCALI, No. PIRSES-GA-2010-268717).

## Author contributions

A.S. and W.G. performed the experiment and analyzed 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. Correspondence and requests for materials should be addressed to W.G.