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Multiple Cold-Atom Lasers

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We realize a laser with a cloud of cold rubidium atoms as gain medium, placed in a low-finesse cavity. Three different regimes of laser emission are observed corresponding respectively to Mollow, Raman and Four Wave Mixing mechanisms. We measure output power of up to 300 μW and present threshold and gain spectra in each regime.

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Since the Letokhov's seminal paper [1], random lasers have received increasing interest in the past decade. Random lasing occurs when the optical feedback due to multiple scattering in the gain medium itself is sufficiently strong to reach the lasing threshold. So far, it has been observed in a variety of systems (see [2] for a review) but many open questions remain to be investigated, for which better characterized samples would be highly valuable. A sample of cold atoms could provide a promising alternative medium to study random lasing, allowing for a detailed understanding of the microscopic phenomena and a precise control on essential parameters such as particle density and scattering cross section. These properties have been exploited for radiation trapping [3] and coherent backscattering of light [4] in large clouds of cold atoms. As many different gain mechanisms have been observed with cold atoms, combining multiple scattering and gain in cold atomic clouds seems a promising path towards the realization of a new random laser. Besides the realization of a random laser, cold atoms might allow to study additional features, such as the transition from superfluorescence to amplified spontaneous emission [5] in a multiple scattering regime. One preliminary step along this research lines is to build a (cavity-)laser. An efficient laser built on cold atoms as gain medium is also an interesting tool for quantum optics, as one can take advantage of the non linear response of the atoms to explore non classical correlations or squeezing [6]. Interesting dynamics can also appear when the decay rates of optical coherences, populations and laser intensity [7] become comparable to those of position and momentum of the atoms [8, 9].

In this letter, we present the realization of a cold-atom laser, that can rely on three different gain mechanisms, depending on the pumping scheme. By pumping near resonance, Mollow gain [10, 11] is the dominant process and gives rise to a laser oscillation, whose spectrum is large (of the order of the atomic spectral width Γ), whereas by pumping further from resonance, Raman gain between Zeeman sublevels [12] gives rise to a weaker, spectrally sharper laser, as already demonstrated in [13]. At last, by using two counter-propagating pump beams, degenerate four-wave mixing (FWM) [14, 15] produces a

laser with a power up to 300 μW . By adjusting the detuning with respect to atomic resonance or the imbalance between the two pump beams, we can continuously tune the laser from one regime to another.

Our experiment uses a cloud of cold ^{85}Rb atoms confined in a vapor-loaded Magneto-Optical Trap (MOT) produced by six large independent trapping beams, allowing the trapping of up to 10^{10} atoms at a density of 10^{10} at/cm^3 , corresponding to an on-resonance optical thickness of about 10. A linear cavity, formed by two mirrors (a coupling-mirror with curvature $RC1 = 1$ m, reflection coefficient $R1 = 0.95$ and plane end-mirror with reflection coefficient $R2 \approx 0.995$) separated by a distance $L = 0.8$ m is placed outside the UHV vacuum chamber, yielding a large round trip loss $\mathcal{L} = 32\%$ with a correspondingly low finesse $\mathcal{F} = 16$. The waist of the fundamental mode of the cavity at the MOT location is $w_{\text{cav}} \approx 500$ μm . To add gain to our system, we use either one or two counter-propagating pump beams, denoted F (forward) and B (backward), produced from a same laser with a waist $w_{\text{pump}} = 2.6$ mm, with linear parallel polarizations and a total available power of $P = 80$ mW, corresponding to a maximum pump intensity of $I = 2P/(\pi w_{\text{pump}}^2) \approx 750$ mW/cm^2 . The pump is tuned near the $F = 3 \rightarrow F' = 4$ cycling transition of the $D2$ line of ^{85}Rb (frequency ω_A), with an adjustable detuning $\Delta = \omega_{F,B} - \omega_A$ and has an incident angle of $\approx 20^\circ$ in respect to the cavity axis. An additional beam P can be used as a probe to measure single-pass gain or as a local oscillator to measure the spectrum of the laser. Its frequency ω_P can be swept around the pump frequency with a detuning $\delta = \omega_P - \omega_{F,B}$. Both lasers, pump and probe, are obtained by injection-locking of semiconductor laser from a common master laser, which allows to resolve narrow spectral features. All our experiments are time-pulsed with a cycling time of 30 ms. The trapping period lasts 29 ms, followed by a dark period of 1 ms, when the MOT trapping beams and magnetic field are switched off. In order to avoid optical pumping into the dark hyperfine $F = 2$ ground state, a repumper laser is kept on all time. Lasing or pump-probe spectroscopy are performed during the dark phase, short enough to avoid expansion of the atomic cloud. Data acquisitions are the

result of an average of typically 1000 cycles.

As in a conventional laser, if gain exceeds losses in the cavity, lasing occurs, which can be observed as strong directional light emission from the cavity. As we will discuss in detail below, we are able to produce lasing with cold atoms as the gain medium using three different gain mechanisms : Mollow gain, Raman gain and Four Wave Mixing (FWM). We can control the different mechanisms by the pump geometry and the pump detuning Δ (see Table I). Mollow and Raman gain mechanisms only require a single pump beam (F), whereas FWM only occurs when both pump beams F and B are present and carefully aligned. With a single pump beam, we find Mollow gain to be dominating close to the atomic resonance, whereas Raman gain is more important for detuning larger than $|\Delta| \approx 4\Gamma$. The polarization of the laser also changes with the gain mechanism : Mollow gain yields a lasing mode with a polarization parallel to the pump polarization, whereas the Raman and FWM lasers produce orthogonal output polarizations, except for the blue-detuned FWM. The polarization features of the Mollow and Raman lasers are explained by the larger single pass gain for the corresponding gain mechanisms. The red-blue asymmetry for the FWM laser is more difficult to understand. We have checked that for any pump detuning or probe power, the FWM signal is stronger for orthogonal probe polarization. We speculate that pump-induced mechanical effects [16] or more complex collective coupling between the atoms and the cavity [9] might be at the origin of this polarization feature.

In Fig. 1 we show spatial (transverse) patterns of these lasers, observed by imaging the output of our laser onto a CCD camera. By inserting a small diaphragm inside the laser cavity, we can force the cavity to operate on its fundamental TEM₀₀ mode [Fig. 1(a)]. Without additional spatial filtering the different lasers (Mollow, Raman and FWM) yield distinct transverse pattern. In Fig. 1(b) (resp. 1(c)) we show the transverse pattern obtained with a Mollow (resp. Raman) laser. We note that our Mollow laser typically produces transverse pattern with radial symmetries well described by Laguerre-Gauss modes, whereas the modes of the Raman laser are rather Hermite-Gauss modes. The origin of such radial vs cartesian symmetry might arise from the different polarization of those two lasers. As we can continuously tune our laser from a Mollow to a Raman laser, we could thus study the transverse pattern which are neither pure Laguerre-

pump beam(s)	$\Delta < -4\Gamma$	$-4\Gamma < \Delta < +4\Gamma$	$\Delta > +4\Gamma$
F	Raman (\perp)	Mollow (//)	Raman (\perp)
F+B	FWM (\perp)	Mollow (//)	FWM (//)

TABLE I: Different regimes of cold-atoms laser versus pump detuning. The polarization of the lasers are either parallel (//) or orthogonal (\perp) to the polarization of the pump beams.

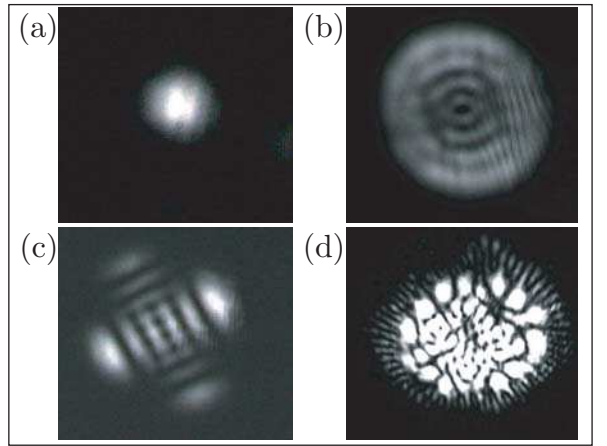


FIG. 1: Transverse modes of the different cold-atom lasers. (a) Gaussian profile, obtained by inserting a small diaphragm near the waist of the cavity. Typical modes of: (b) the Mollow laser, (c) the Raman laser, and (d) the four-wave mixing laser respectively.

Gauss nor pure Hermite-Gauss modes [17]. Fig. 1(d) shows the transverse pattern of our laser in the FWM regime. As phase conjugation mechanisms are at work in such a laser, any transverse mode can easily cross the lasing threshold and complex lasing pattern are produced. This property could induce quantum spatial correlations inside the beam, that might be useful for quantum imaging [18, 19].

We now turn to a more detailed description of the gain mechanisms of our different lasers. The quantitative understanding of their behavior needs to take into account effects such as pump geometry and parameters (intensity, detuning), gain spectra, gain saturation, gain asymmetry for both propagation directions in the cavity, mechanical effects induced by the pump beam(s).

Let us first discuss our Mollow laser. Amplification of a weak probe beam can happen when a two-level atom is excited by one strong pump beam. Mollow Gain [10, 11] of a weak probe crossing the atomic cloud in single pass can be written as

$$g_M = e^{-b_0 f_M(\Omega, \Delta, \delta)}, \quad (1)$$

where b_0 is the on-resonance optical thickness (without pump) of the cold-atom cloud. The expression of $f_M(\Omega, \Delta, \delta)$ can be obtained from Optical Bloch Equations [10]:

$$f_M(\Omega, \Delta, \delta) = \frac{\Gamma}{2} \frac{|z|^2}{|z|^2 + \Omega^2/2} \times \Re \left[\frac{(\Gamma + i\delta)(z + i\delta) - i\Omega^2\delta/(2z)}{(\Gamma + i\delta)(z + i\delta)(z^* + i\delta) + \Omega^2(\Gamma/2 + i\delta)} \right], \quad (2)$$

where $z = \Gamma/2 - i\Delta$ and Ω is the Rabi frequency of the pump laser, related to the pump intensity I by $\Omega^2 = \Gamma^2 I / (2I_{\text{sat}})$ ($I_{\text{sat}} = 1.6 \text{ mW/cm}^2$ is the saturation

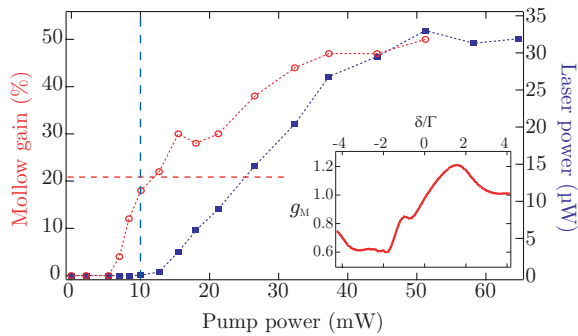


FIG. 2: Laser power (squares) and Mollow gain (open circles) versus pump power, with $b_0 = 11$ and $\Delta = +\Gamma$. Lasing threshold (vertical dashed line) is expected to appear with a gain of about 21% (horizontal dashed line), in good agreement with the experimental data. Inset: typical transmission spectrum.

intensity). In our setup we observe single pass gain higher than 20% in the spectrum of the transmitted probe (inset of Fig. 2), with a large gain curve (width $> \Gamma$). These features are consistent with Eqs. (1-2). From Eq. (2) we can also predict the maximum gain in respect to the pump parameters Ω , Δ . We observe good agreement between the behavior of the laser power and of the function f_M when varying Δ : the maximum gain and laser power are achieved for $|\Delta| \sim 2\Gamma$ (the exact value depends of Ω) and $\Delta = 0$ is a local minimum. However, due to absorption by the atom cloud, more pump power is needed in the experiment than expected from Eqs. (1-2) to achieve the same gain. As shown in Fig. 2 (squares), we observe a Mollow laser emission with an output intensity reaching $35 \mu\text{W}$. Taking into account the round-trip losses \mathcal{L} in our setup, the condition for laser oscillation is $g_M^2(1-\mathcal{L}) > 1$. This corresponds to a gain at threshold of $g_M = 1.21$ (horizontal line in Fig. 2), in good agreement with the observation. We note that this Mollow gain might be of particular interest for a possible random laser, as it can lase with the pump tuned on the atomic resonance, which might allow to combine multiple scattering and gain.

When we detune the pump frequency farther away from the atomic resonance, a different gain mechanism becomes dominant and the resulting polarization of the laser is orthogonal to the pump polarization. In this regime, Raman gain is at the origin of our laser. Raman gain makes use of a population inversion among different light-shifted Zeeman sublevels of the $F = 3$ hyperfine level of ^{85}Rb , and single-pass Raman gain of a weak probe can be written as:

$$g_R = e^{-b_0 f_R(\Omega, \Delta, \delta)}, \quad (3)$$

with the function f_R is given by

$$f_R = -\frac{\Omega^2}{\Delta^2} \left(\frac{A_1}{(\delta + \delta_R)^2 + \gamma^2/4} - \frac{A_2}{(\delta - \delta_R)^2 + \gamma^2/4} \right), \quad (4)$$

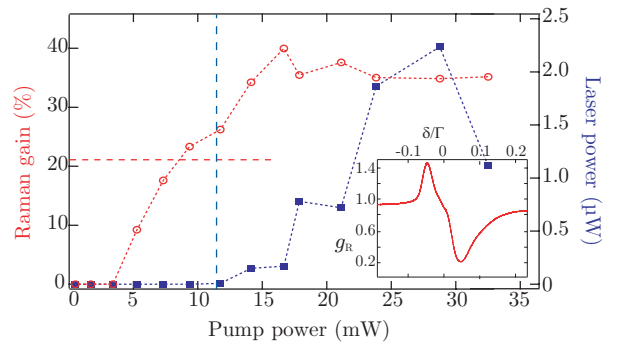


FIG. 3: Laser power (squares) and Raman gain (open circles) versus pump power, with $b_0 = 10$ and $\Delta = -7\Gamma$. Lasing threshold (vertical dashed line) is expected to appear with a gain of about 21% (horizontal dashed line), in good agreement with the experimental data. Inset: typical transmission spectrum.

where δ_R is the detuning between the involved Zeeman sublevels, γ is the width of the Raman resonance, and $A_{1,2}$ are the respective weights of the amplification and absorption [20]. The width of the Raman resonance γ is related to the elastic scattering rate of the pump photons and is much lower than Γ , due to the strong detuning Δ . The result is thus a much narrower gain spectrum as in the previous case (inset of Fig. 3). This leads to an important practical limitation of our single pump Raman laser: atoms are pushed by the pump beam and the Doppler shift becomes quickly larger than the gain spectrum width. As a consequence, the gain in the cold-atom cloud is no longer the same for a wave copropagating with the pump beam (F) and the wave running in the counter-propagating direction. For the copropagating direction, the relative Doppler shift is negligible, whereas for the counterpropagating wave, a Doppler shift of $2kv$ larger than the width of the gain spectrum leads to a suppression of corresponding gain. As a consequence, emission of our Raman laser stops after $\approx 20 \mu\text{s}$ [21].

In Fig. 3 we plot the output power of our Raman laser as a function of pump power. A comparison with the single pass gain g_R is again in good agreement for the threshold condition $g_R^2(1-\mathcal{L}) > 1$: for Raman gain above 21% laser emission occurs. As shown in Fig. 3 (squares), the output power of our Raman laser emission ($\approx 2 \mu\text{W}$) is much lower than our Mollow laser. This lower output power might arise from a lower saturation intensity for Raman gain [22]. The interest of a Raman laser resides in the possibility of strong gain (it can exceed $g_R = 2$ [22]) and its narrow gain spectrum, which can also be controlled by an external magnetic field.

We have observed a further, more subtle, lasing when a balanced pumping scheme using two counterpropagating pump beams F and B is used. In this configuration FWM mechanisms appear [14, 15]. The creation of photons in the conjugated, reflected wave, resulting from a

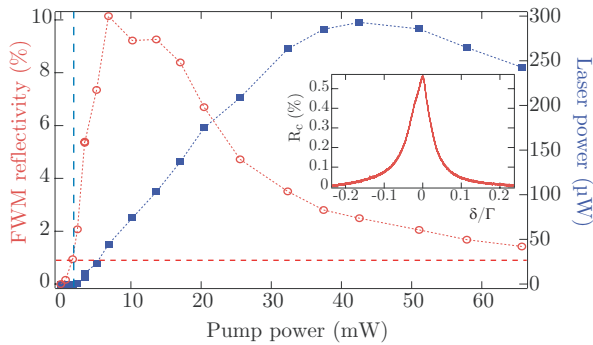


FIG. 4: Laser power (squares) and phase-conjugate reflectivity due to four-wave mixing (open circles) versus pump power, with $b_0 = 10$ and $\Delta = -8\Gamma$. Lasing threshold (vertical dashed line) is expected for a reflectivity around 1% (Eq. 5, horizontal dashed line), in good agreement with the experimental data. Inset: example of a reflectivity spectrum.

phase conjugation process, can be viewed as a gain mechanism. In the inset of Fig. 4 we show the FWM signal R_c (expressed as the reflection normalized to the incident probe power) illustrating the narrow spectrum of this phase conjugation signal. Thanks to constructive interference between transmitted and reflected waves, this mechanism is known to produce huge double pass gain with cold atoms [22] and it is thus a priori a very promising mechanism to trigger laser oscillation [23]. Due to these interference effects, the threshold for laser oscillation with such a mechanism is very different from the previous cases [22, 23], and is given by

$$R_c > \left(\frac{1 - \sqrt{\tilde{R}}}{1 + \sqrt{\tilde{R}}} \right)^2 = 0.9\%, \quad (5)$$

where $\tilde{R} = 1 - \mathcal{L}$. In Fig. 4, we see that this criterium (indicated by the horizontal line) is well respected for the threshold of our laser. The output power of this laser is quite strong ($300 \mu\text{W}$), with an energy conversion efficiency of 0.75% in this case. We note that as two pump beams are used in this situation, the mechanical effects based on radiation pressure will be negligible and lasing can be sustained for long periods of time. However atomic bunching, due to dipole force, can occur [16]. We think that with such a large output power, it will be possible to study the noise spectrum down to the shot noise level, and that such a cold-atom laser seems a good candidate to explore non classical features of light [24, 25].

In conclusion, we presented in this letter three types of laser using a sample of cold atoms as the gain medium. Three different gain mechanisms were demonstrated as being efficient enough to allow lasing, even with a low finesse cavity. Comparison between Mollow and Raman laser shows that the latter has a significantly lower power, although their gain are of the same order of magnitude.

These two gain mechanisms are good candidates for the search of random lasing in cold atoms, and the combination of these gains with multiple scattering will be the subject of further investigations. The FWM laser is by far the most efficient in term of power and could find applications in other fields, such as quantum optics, by using for instance the strong correlation between the transmitted and conjugated waves for the production of twin photons [24, 25].

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