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Multicore fiber for cold-atomic cloud monitoring

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Abstract: Thanks to an all solid core photonic crystal fiber (PCF) used as a multicore fiber, we propose and experimentally demonstrate what is to our knowledge a new optical detection scheme for the spontaneous emission collection of cold atoms. A Magneto-Optical Trap (MOT) is placed in front of a polished PCF end-face. As they display a higher optical index than the surrounding cladding silica, the 108 rods (equivalent to a 108 pixels camera) of this PCF are light guiding and behave like an array of detectors. Both global and local properties of the trapped atoms are probed. A MOT lifetime is reported. We also take advantage of the multi-core geometry for a real time detection of the center-of-mass motion of the atomic cloud.

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1. Introduction

Probing and manipulating matter with light play an essential role in cold-atom experiments. More and more experiments take advantage of the integration of different types of optical fibers with cold atoms systems. One-core optical fibers, i.e. standard single-mode fiber, have recently been integrated in the detection scheme of those apparatus [1–4]. Single fluorescent photon detection is thus achieved and allows studying small atomic ensembles. Trapping and manipulating cold atoms in an optical potential created by the evanescent light field surrounding a tapered fiber has been also demonstrated [5]. Nonlinear light-matter interactions at very low light levels are accessible by placing an atomic vapor in the vicinity of tapered fiber waist [5, 6] or by loading cold atoms into the hollow-core of a photonic-crystal fiber [7, 8].

All those previous works study collective properties of atomic cloud or low atomic signal in a limited volume. In this paper, we demonstrate a new approach based on the use of multicore fiber. This multicore fiber is a Photonic Crystal Fiber (PCF), see [9] for a review. This fiber is originally designed as an all solid-core photonic bandgap fiber [10]. A polished end-face of this fiber is located at one millimeter from the atomic cloud of a Magneto-Optical Trap (MOT) while the other end-face is imaged on a camera. The total fluorescence signal (related to the total atom number) can thus be detected by considering the collected light guided in the different cores (as in a detection scheme with a one-core fiber). At the same time, we can focus on a few cores to probe fluorescence signal imbalance and study motion of the atomic cloud in position-space.

In this paper, after describing the experimental setup [section 2], we report [section 3] a MOT lifetime measurement and the detection of the MOT global center of mass motion induced by a modulated magnetic field.

2. Experimental setup

Our experimental setup (Fig. 1a) consists of a laser system, a vacuum chamber and the multicore fiber detection stage. The vacuum system is a stainless steel octagonal vessel with attached viewports and a 25 l/s ion pump. To generate the MOT laser beams at 780 nm, we use a frequency-doubled 1560 nm laser system [11]. The starting point of this system is a low noise distributed feedback laser diode (DFB) emitting at ~ 1560 nm. This DFB is characterized with a Brillouin fiber laser spectral analysis tool [12] and displays a ~ 1 MHz full width at half maximum for 1 s. In addition to the cooling main atomic transition, sidebands for the repumper frequency are generated with a fibered intensity modulator driven at ~ 6 GHz (only the red-shifted sideband is resonant). The modulated source then seeds a cw 10 W Erbium Doped Fiber Amplifier (EDFA). The EDFA output beam is converted to a 780 nm beam by second-harmonic generation (SHG) into a nonlinear crystal in free space, with up to $\sim 10\%$ efficiency, which is far better than what is needed. Through the SHG system, the DFB is frequency-locked to the atomic cooling transition of ^{87}Rb with a standard saturated-absorption spectroscopy lock-in setup. The final 780 nm beam is finally split into three arms for the three, orthogonal, retro-reflected beams. Each beam uses 25 mW of power, and is about 10 mm in diameter.

The fiber integration inside the vacuum chamber is technically demanding as it simultaneously has to keep low optical loss properties suitable with light collection and Ultra-High Vacuum requirements (baking out, low outgasing, leak-free and sufficient final pressure for typical cold-atom experiments). We have designed and tested an inexpensive and reliable optical fiber feedthrough for UHV systems [13]. The fiber is embedded with an UV curing adhesive in a drilled vacuum flange. This method minimizes the mechanical constraints on the fiber. It does not require any precision mechanics while being insensitive to non-standard cladding diameter. Another difficulty is to perform an accurate and stable fiber positioning inside the vacuum chamber. Large diameter PCFs are also sometimes hard to cleave. To solve

these problems, we insert the PCF in a silica capillary. The capillary is then filled with the same UV curing adhesive, and polished to obtain an optical grade quality end-face [14]. As previously mentioned, the PCF we are using here as a multicore fiber is originally designed to realize an all solid-photonic bandgap fiber [10]. The transversal structure of this fiber (Fig. 1b) is made of 5 rings of high index rods embedded in a pure silica background. Each of these 108 rods surrounded by silica acts as an optical waveguide. Thus this fiber can be used as a multicore fiber, each core having a diameter of $7.7 \mu\text{m}$, with a distance between them (corresponding to the pitch of the periodic cladding of the all solid photonic bandgap fiber) of $10.8 \mu\text{m}$.

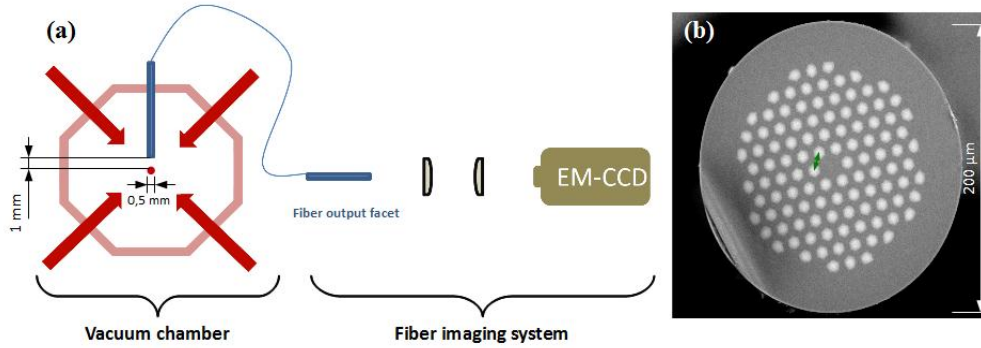


Fig. 1. (a) Schematic view of the experimental setup. Red arrows are two pairs of MOT beams, the third one is orthogonal to the others. (b) Scanning electron micrograph of the imaging PCF fiber. The outer diameter of the PCF is about 200 microns. At 780 nm, the fiber is slightly multi-mode (6 modes) for each core, but the fundamental mode is mainly excited, as shown by the image of Fig. 4. The coupling between these cores is thus negligible. The green arrow shows the PCF pitch ($10.8 \mu\text{m}$).

The fiber is sealed in its glass capillary and placed in the vacuum chamber at about 1 mm of the cold Rb cloud. The atomic spontaneous emission compatible with the cores capture cones is guided throughout the PCF which acts as an effective array of detectors. With solid angle consideration, we estimate the fraction of light collected from the MOT by all the cores. For a 1 millimeter distance between the MOT and the fiber facet, this fraction is around 0.03%. It should increase quadratically with the distance inverse. For a distance of 100 microns, it is for instance estimated to be around 3%. The other fiber end is imaged by a telescope on an EM-CCD camera (Hamamatsu Orca R-2), see Fig. 2.

3. Experimental procedure and results

The Rb vapour in the MOT cell is produced by a dispenser. Once the cold MOT cloud is obtained (about 10^6 atoms), the dispenser heating supply is switched off to stop the atomic flux. We then observe the decay of the atomic population trapped in the MOT by monitoring the fluorescence signal transmitted by the PCF. A signal proportional to the remaining trapped atom number is then recovered by integrating the whole fiber output facet imaged on the EM-CCD. Figure 3 shows a typical exponential decay of MOT population after dispenser current being switched off. The $1/e$ lifetime of the trapped atoms is about 10 seconds, in good agreement with our estimated residual vacuum. After a few tens of seconds, only the fluorescence signal from the background Rb atoms and the MOT beams light injected in the fiber is detected. By considering the dynamic range of our lifetime measurement (with a computation of its standard deviation noise), we estimate that the minimum currently detectable number of atoms is about 5000. An animation showing this decay is shown in [Media 1](#).

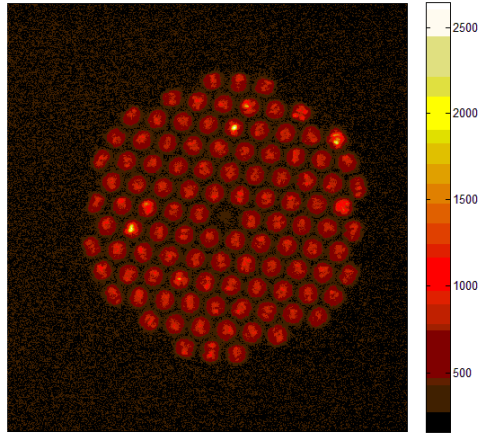


Fig. 2. EM-CCD false-color image of the fiber end during atomic fluorescence detection. The corresponding movie of the MOT lifetime can be seen from [Media 1](#).

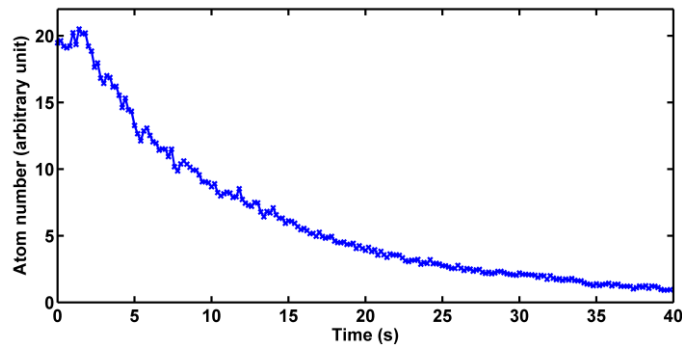


Fig. 3. Time evolution of the fluorescence signal detected by the multi-core fiber.

One should notice that the decay experiment gives only global information on the MOT, which could also be obtained by a single-mode fiber or a free space photo-detector. Our long-term aim is to achieve a near-field camera. This camera would have a working principle close to a standard near-field microscope, except that it is made of several tips (as many as the cores) working simultaneously. As there are no lenses in front of the fiber end, this camera is not strictly speaking an imaging system. The potential spatial resolution of the PCF camera is directly given by the core distance, i.e. the fiber pitch. This is especially true if one assume that each atom is close enough to the fiber end to mainly irradiate a single core at the same moment. Increasing the resolution requires a smaller pitch. However, reducing the pitch below a few micrometers is quite difficult. To solve this problem we plan to taper the fiber end. The pitch could then be reduced to value below half the optical wavelength thus realizing a “near-field camera tip”. The image reconstructed at the other end of the fiber would then give sub-wavelength informations. This is potentially useful to probe the atoms dynamics inside a periodic dipole trap. This is also potentially a breakthrough and the main interest of our system because this purpose cannot be achieved with a conventional optical imaging system. Another difficulty is to bring the atomic cloud closer to the fiber end. For that, one might think of loading the atomic cloud into a few micrometers large waist of a far detuned laser beam. After the loading stage, the laser focused point could then be moved towards the PCF on a micrometer scale (or even a nanometer scale) by simply displacing the lens used to focus the beam. Before that, to show that the PCF can give spatial, and even dynamical, information, we perform a second experimental sequence to extract information on the atomic cloud center of mass motion. After producing a MOT (without switching the dispenser off this

time), we apply a time-modulated spatially homogeneous magnetic field to the cold-atom cloud which modulates the zero magnetic field position point of the trap gradient. The frequency modulation is $F_B = 200$ mHz. The choice of F_B is low enough to ensure that the trapped cloud center of mass will adiabatically follow the 0 magnetic field point. We estimate that the modulated magnetic field induced a ~ 115 μm atomic spatial amplitude motion, to be compared to the ~ 170 μm distance separating two opposite cores of the fiber. As previously mentioned, the camera global fluorescence oscillation signal does not give relevant information about the atomic motion because there is no indication concerning the motion direction (it could also be atomic loss). However, a detection of the motion can be performed by computing separately the light transmitted by the different rods. If an atomic motion occurs in front of the fiber face, it means that two cores, ideally located on the oscillation direction, will not see the same fluorescence signal at a given time. We consider henceforth difference between the fluorescence signal of pairs of cores (see Fig. 4), diametrically opposed, to extract possible evidence of atomic motion. Two pairs of cores are chosen (corresponding to the signals S_1, S_2 , and S_3, S_4 , see Fig. 4) and monitored on the EM-CCD camera (see detail in [Media 2](#)). We then calculate the visibility factors V and V' which have the following expressions:

$$V = \frac{S_2 - S_1}{S_2 + S_1} \text{ and } V' = \frac{S_4 - S_3}{S_4 + S_3}$$

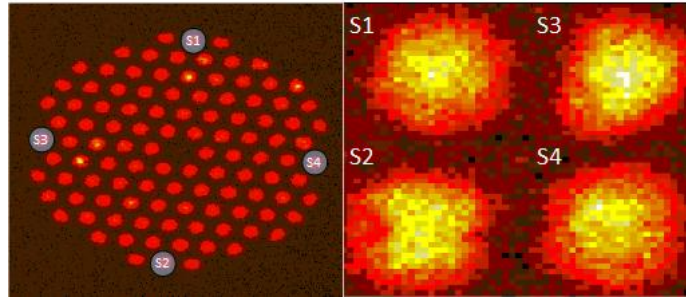


Fig. 4. (Left) EM-CCD image of the fiber output facet. Grey circles indicate the four cores involved in data processing. (Right) Zoom on those cores. Related animation can be found in [Media 2](#).

Figure 5. shows the visibility V with S_1 and S_2 along roughly the figure vertical axis (respectively V' with S_3 and S_4 with a $\sim 90^\circ$ angle with respect to the previous direction). We found the maximum visibility ($\sim 2\%$) for the first direction (S_1, S_2) which oscillates at F_B . Conversely, a noisy signal without any noticeable oscillation at F_B is found for the second direction (S_3, S_4), which confirms that the oscillation well occurs along (S_1, S_2). We tried other directions by choosing different pairs of cores diametrically opposed, but no pair of cores with a better contrast was found.

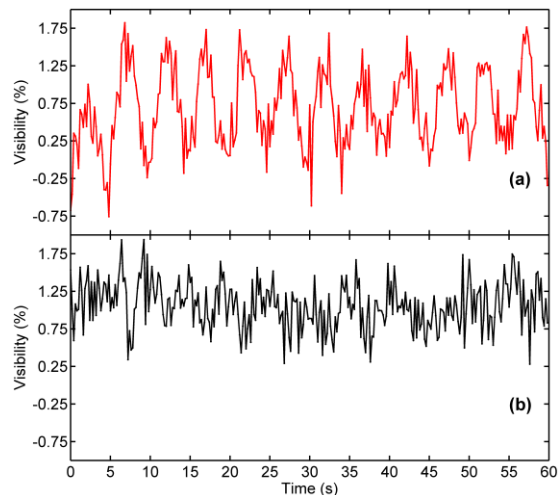


Fig. 5. Atomic motion evidence with the multi-core fiber detection scheme. Visibilities (multiplied by 100 to be expressed in percentage) corresponding to orthogonal directions in the microstructured array of cores are plotted as a function of time. (a) Red line: V . (b) Black line: V' .

4. Conclusion

An original detection scheme based on a microstructured optical fiber compatible with cold-atom experiments is demonstrated. We achieve a lifetime measurement of the atomic population of a MOT by monitoring and integrating the fluorescence signal injected in the PCF. We also take advantage of the multicore feature of this PCF. A method to obtain qualitative and quantitative information on the atomic center of mass global motion is implemented, while trapped atoms driven by a time-modulated magnetic field are oscillating. This system demonstrates possibilities of microstructured optical fibers for studying cold-atom dynamics. Reducing the distance between the fiber input facet and the cold atoms cloud (down to a few tens of microns) or adding micro-lenses on the fiber input surface [15] may greatly improve the signal to noise ratio, as well as the spatial resolution. In a near future, this setup could be useful for recovering spatial information of experiments that usually take place in the momentum space. This is notably the case for Anderson localization experiments performed with a kicked rotor [16, 17]. The atoms undergo the kicks of a laser pulsed standing wave. The spatial period of the dipole potential is half the optical wavelength, out of reach of conventional imaging systems. One could also simultaneously think to reverse the process. By injecting light inside the cores from outside the vacuum cell, it is possible to generate a new kind of far-detuned dipole trap with a sub-wavelength structuration following the cores pattern. Such a dipole trap is hard to build with an optical imaging system. The PCF could then be both a near field detecting and a multipurpose tool for cold atom manipulation.

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