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A compact laser system for the cold atom gravimeter

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ABSTRACT

With the rapid development of the technologies in the field of laser cooling atoms, a portable and stable laser system is urgently required for the wide applications based on the cold atoms. In this paper, we report a modular laser system for a gravimeter based on atom interferometry, which enable us to realize high-precision gravity measurements outside of laboratory. The system is based on two distributed feedback (DFB) laser diodes of 1560 nm, which are used as the master laser and the reference laser respectively. The frequency of the reference laser is locked on a rubidium transition, the master laser is frequency locked on the reference one by the method of beat locking. The master laser is power amplified firstly by the erbium-doped fiber amplifier (EDFA), and then frequency doubled by using a periodically poled lithium niobate (PPLN) crystal to obtain 1 W laser output at 780 nm. The repumping and Raman lasers are generated by adding an electro-optic modulation on the master laser, featuring extremely low phase noise. With this laser system, we obtain a cloud of ^{87}Rb atoms with a temperature of 5 μKin a magneto-optical trapping. And a gravity resolution of $1.0 \times 10^{-8}g$ within 200 s integration time is reached.

1. Introduction

Since the invention of laser cooling of neutral atoms [1–3], this technology has attracted wide interests. Many important applications are developed, such as inertial acceleration measurement [4,5], atomic clock [6–9], the gravitational constant *G* measurement [10], the validation of the weak equivalence principle [11] etc. But most of the applications are still confined to the laboratory environment. One of the main reasons is the complexity of the laser system for cooling and controlling the atoms. In order to move the experimental system out of the lab and achieve dynamic measurement under different complex environments, a small size, high stability and movable laser system is urgently required.

The present optical system using the traditional external cavity semiconductor lasers (ECDL) is sensitive to the temperature and the vibration of the environment. Furthermore, the ECDL beam propagates freely in the air by using the discrete optical device in the experimental optical platform, so that the whole laser system has a large volume. Recently, the development of portable laser system [12–15] shrinks the volume of laser system and improves the system stability, but the external cavity semiconductor laser is still used, and the complexity remains.

The development of the optical fiber makes it possible to simplify and stabilize the laser system for atom cooling [16–18]. Compared with the traditional optical components, the optical fiber has smaller volume and is less sensitive to the temperature and the vibration of the environment, so it has higher stability for the beam propagation, and is widely used in the optical communication system. At present, the wavelength used for the optical fiber communication is about 1550 nm. In order to obtain the laser beam with wavelength of 780 nm used for the laser cooling, we can adopt the second harmonic generation technology by means of the PPLN crystal [19–21].

In this paper, we utilize two 1560 nm DFB lasers instead of the traditional ECDL lasers to realize an atom gravimeter with a high precision. A laser is first frequency doubled by the PPLN waveguide, then locked on the ^{87}Rb transition of D2 line used as a reference laser. The other laser is frequency locked by means of beat signal with the reference laser. This laser is first power amplified by the EDFA, then frequency doubled by the PPLN crystal, used for the atom cooling. We obtain the repumping beam and Raman beams by an electro-optic modulator, through which we can get two sidebands at several gigahertz apart from the frequency of the master laser. Due to the development of the fiber technology, the laser and the fiber optical components are integrated together in a standard 19-inch cabinet. The modular laser system is not only in small size but also with high stability. Based on this technology, the atom gravimeter based on cold atoms is closer to practical applications.

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2. Principle

The first step of an atom gravimeter is to obtain the cold atoms. The magnet-optical trapping (MOT) is a standard system for the atom cooling. In our experiment, in order to load atoms more effectively in the three-dimensional (3D) MOT, a two-dimensional (2D) MOT is applied to pre-cooling atoms, as shown in Fig. 1. One push beam in the horizontal direction pushes the pre-cooled atoms from 2D-MOT to 3D-MOT. The 2D-MOT contains two pairs of orthogonal laser beams in opposite propagation directions and two orthogonal anti-Helmholtz coils, which is used for pre-preparation of the cold atoms beam. The 3D-MOT contains three pairs of orthogonal laser beams and an anti-Helmholtz coil, which is used for trapping 3D atoms cloud.

For ^{87}Rb atoms, the realization of the laser cooling and trapping requires two kinds of laser beams, which are called as the cooling beam and the repumping beam respectively. The difference of frequency between the two beams equals to the difference of the two lower states of the atoms, which is about several gigahertz for ^{87}Rb atoms. In our experiment, the distributions of the atom hyperfine states and the laser frequencies are shown in Fig. 2(a). The frequency of the cooling beam is locked to 2Γ~6Γ($\Gamma \sim 6$ MHz) detuning below the $5\,^2S_{1/2}$, $F = 2 \rightarrow 5\,^2P_{3/2}$, $F' = 3$ resonance transition of the ^{87}Rb D2 line. The frequency of the repumping beam is locked to the $5\,^2S_{1/2}$, $F = 1 \rightarrow 5\,^2P_{3/2}$, $F' = 2$ resonance transition line, which differs from the frequency of the cooling beam to 6.58 GHz. The repumping beam is mainly used to repump the atoms that inevitably fall into the $5\,^2S_{1/2}$, $F = 1$ dark state of the cooling transition. The power of the 2D and 3D cooling laser beams requires 200 mw, and for the repumping beam, it is 5 mw.

After the acquisition of the cold atoms, an optical Raman transition is induced by a pair of lasers with a frequency difference of 6.834 GHz, as seen in Fig. 2(a). The black dash line is a virtual energy level which has a 1.5 GHz detuning with the upper energy level. During the falling of cold atoms, a pulse sequence ($\pi/2 - \pi - \pi/2$) of Raman lasers acts on the atoms, which constitutes the Mach–Zehnder atom interferometer. The detail process was demonstrated in our paper [22].

3. Experimental scheme

To achieve a compact and reliable laser system for the portable gravimeter, we use two DFB lasers with a wavelength of 1560 nm, which have been widely adopted in the telecommunication. The two DFB lasers we used were manufactured by Toptica with a model number of DL DFB BFY. The DFB laser was driving by matching DC 110 (diode laser supply and control rack), which served as a general basis for all plug-in modules of DCC 110 (current control), DTC 110 (temperature control) and DigiLock 110 (digital locking).

The DFB diode offers the tunability of an external cavity system without its mechanical complexity. The frequency selective element – a Bragg grating – is integrated into the active section of the semiconductor and ensures continuous single-frequency

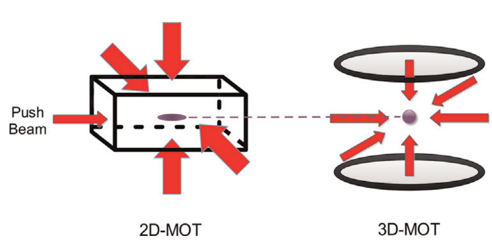

Fig. 1. The schematic diagram of the MOT setup.

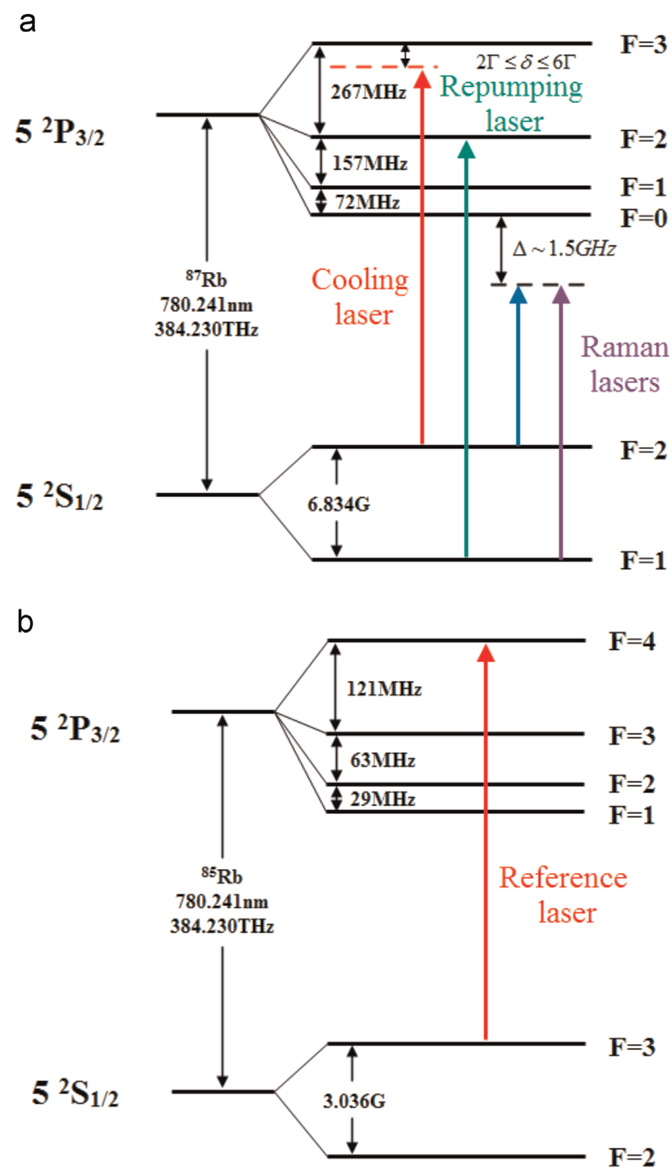

Fig. 2. The hyperfine structure of rubidium atom. (a) ^{87}Rb D2 transition; (b) ^{85}Rb D2 transition. The laser frequency required for atom gravimeter and the frequency locking are shown in the figure.

operation. The DFB laser has a 14-pin butterfly package and optical fiber output interface. The DFB laser frequency adjustment can be achieved by either changing the temperature or the operating current, among which the temperature regulating rate is 10～15 GHz/K, and the current rate is 0.3～1 GHz/mA. The DFB laser used in our experiment has a maximum output power of 100 mW. Compared with the ECDL, DFB laser has a higher noise immunity of the external environment and higher stability.

The schematic diagram of the laser system is shown in Fig. 3. One of the DFB lasers, used as a reference laser, is locked by the saturated absorption spectroscopy method to one transition line of rubidium. The other one, used as a master laser, is frequency locked by a method of DFHL. The beam output from the master laser is frequency modulated by an EOM (CONQUER), then power amplified by the EDFA (Manlight model No. ML10-EYFA-CW-SLM-P-TKS) and frequency doubled by the PPLN Crystal (HC Photonics). Finally, the laser beam is applied for the ^{87}Rb atom gravimeter.

In addition to the frequency doubled module and the spectrum module for frequency locking, the rest components of the whole laser system are optical fiber components, so that they can be