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Laser frequency locking with low pump field saturated absorption spectroscopy*

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In recent years, many systems based on quantum effects have been applied to precision measurement. A laser pumped helium 4 absolute scalar atomic magnetometer which is carried by the Swarm satellite is used to measure the earth magnetic field intensity (Fratter et al., 2016). China launched the first cold atomic clock in 2016, in which frequency stabilized laser systems were very important (Li et al., 2016). A compact cold atom gravimeter was developed for field application (Bidel et al., 2013). Most of these systems, which require frequency stabilized laser systems, are placed on moving platforms. The vibration of these platforms is an important noise source to the laser frequency because the long-term changes of adjustable parts may occur under the vibration condition (Liu et al., 2013).

There are many laser spectroscopy schemes that can be used as a reference for frequency locking (Debs et al., 2008; Martins et al., 2010; Yang et al., 2010; Biesheuvel et al., 2013; Wan et al., 2016). Saturated absorption spectroscopy is one of these convenient schemes used as reference for laser frequency locking in precision measurement experiments (Debs et al., 2008). In this scheme, reflecting mirrors are adjusted for the coincidence of the pump field and probe field. Therefore, long-term drift of the pump light direction may occur from the change in mirrors in a vibration environment. The long-term drift causes a negative effect on laser frequency locking. To avoid the vibration noise from separated reflecting mirrors, we present a low pump field saturated absorption spectroscopy without additional reflecting mirrors. The reflected light of the probe beam from the inner surface of the vapor cell is applied as the pump field.

The diagram of the low pump field saturated absorption spectroscopy is shown in Fig. 1. The material of the vapor cell is K9 glass with no coating on the surfaces. The reflectivity of the glass is about 10% and the length of the cell is about 7 cm.

The experiment is shown in Fig. 2. A 50 mW 795 nm laser of 4 mm diameter which is tuned to the transitions F_g=3 to F_e of ^{85}Rb atoms is generated by a commercial semiconductor diode laser Toptica DL 100. The light passes through an optical isolator and is then reflected by a wedge prism. The prism is coated with anti-reflective films and the reflectivity of each surface is 1%. The laser beam reflected from the first surface is normal to the vapor cell surface and acts as the probe field. The angle between the direction of the other reflected beam and that of the probe field is 20°. Therefore, the saturated absorption spectroscopy only exists in the signal of the probe field. The other reflected field acts as the reference field for eliminating the Doppler absorption background. The signals are detected with the differential mode and amplified by a pre-amplifier with a factor of 10^4 V/A. The amplified signal is sent to a lock-in amplifier SR 830. The

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reference signal of the lock-in amplifier is produced by an arbitrary waveform generator RIGOL DG 4162, which modulates the current of DL 100 via the current modulation input interface (MOD). It is a sine signal with a frequency of 2 kHz. The depth of modulation of laser frequency is several MHz. The input and the output of the lock-in amplifier are monitored with an oscilloscope Tektronix TDS 2014C (not drawn in Fig. 2). The output signal is used as the error signal of the laser frequency and sent to the commercial Toptica proportional-integral-differential regulator (PID 110). The output of PID 110 is then sent to the scan control module (SC 110), which controls the laser frequency by controlling the voltage of the piezoelectric ceramic (PZT). With different lengths of the PZT, the length of the external cavity of DL 100 is modified.

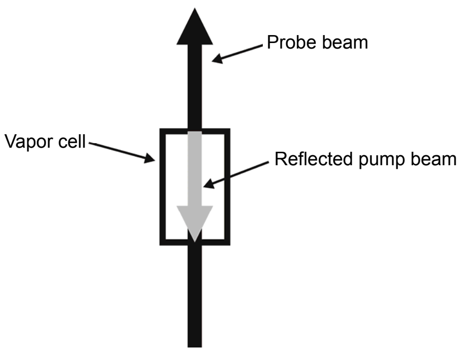

Fig. 1 Low pump field saturated absorption spectroscopy scheme
The probe beam travels through the vapor cell and the reflected light from the inner surface is the pump field

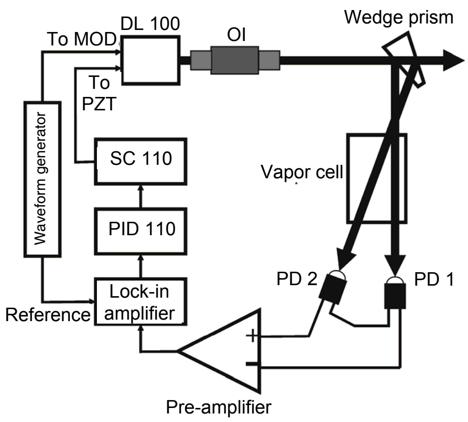

Fig. 2 Experimental apparatus
OI: optical isolator; PD: photodiode detector; MOD: current modulation input interface; PZT: piezoelectric ceramic

The low pump field saturated absorption spectroscopy is shown in Fig. 3. The deep curve background shows that the probe field is strongly absorbed by the atoms when the laser is near resonance. The peak 3 to 2 corresponds to the transition F_g=3 to F_e=2 and the peak 3 to 3 corresponds to the transition F_g=3 to F_e=3. The peak Co (2, 3) is the crossover peak. It is clear that the amplitude of the signal in our scheme is smaller than that in typical saturated absorption spectroscopy. The signal contrast can reach 2% when the probe beam is normal to the surface of the vapor cell. It is large enough for frequency locking.

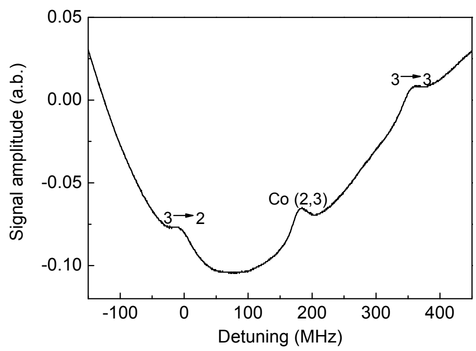

Fig. 3 Low pump field saturated absorption spectroscopy
The horizontal coordinate represents laser frequency detuning from the transition F_g=3 to F_e=2. The vertical coordinate represents the signal amplitude

To evaluate the influence of the motion of the vapor cell in our scheme, we measure the relative intensity of the signal with different incident angles of the probe beam (Fig. 4).

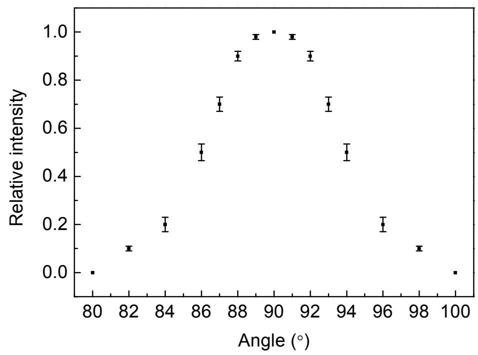

Fig. 4 Relationship between incident angle of the probe beam and the relative intensity of the signal

It is clear that the change rate of the relative intensity is very small when the incident angle is 90°±1°. This means that the signal remains well within an angular tolerance of 2°. In a traditional saturated absorption spectroscopy scheme, several separated reflecting mirrors are used to adjust the pump field direction in order to ensure that the pump field and probe field coincide as much as possible. However, there are springs in the holders of the mirrors, which may lead to long-term drift of the mirrors' reflecting angle under vibration. These changes result in the long-term drift of the direction of the pump field. It is known that the coincidence degree of the pump field and probe field is an important factor in the effect of laser frequency locking. Thus, the long-term drift of the direction of the pump field will cause a long-term negative effect. Compared with the traditional scheme, the low pump field scheme has no additional reflecting mirrors. The long-term drift of the mirror's angle can be eliminated. In addition, it is easier to control the motion of the vapor cell to within 2° than to suppress the long-term drift of the mirror's angle. Therefore, the low pump field scheme is less sensitive to vibration than the traditional one.

Before locking the laser, we regulate the experimental apparatus by monitoring the input and output of the lock-in amplifier. The signals of a well-adjusted system are shown in Fig. 5. The input signal (Fig. 5a) is the low pump field saturated absorption spectroscopy after eliminating the Doppler absorption background. The output signal (Fig. 5b) is the error signal for frequency locking.

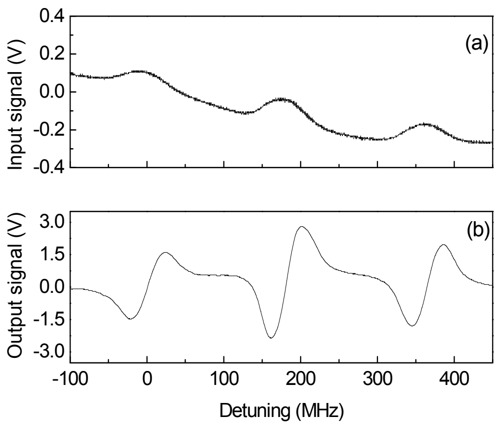

Fig. 5 Signals of a well-adjusted system
(a) Input of the lock-in amplifier; (b) Output of the lock-in amplifier

To evaluate the performance, we lock the laser to the transition F_g=3 to F_e=3 and record the error signal for several hours. In order to achieve a clear comparison, only one hour of data is shown in Fig. 6. The frequency of the laser varies in a wide range when it is free-running. After the frequency is locked, the relative frequency fluctuation is about 2 MHz and the performance is acceptable in most precision measurement experiments.

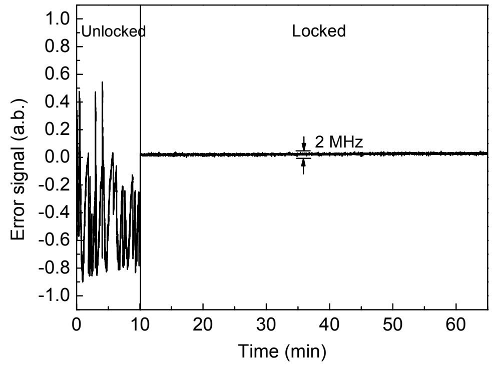

Fig. 6 Error signals before and after the frequency of the laser is locked

In conclusion, we put forward and demonstrate experimentally a laser frequency locking method using low pump field saturated absorption spectroscopy. Compared with the traditional high pump-low probe configuration, our low pump-high probe configuration is much simpler. There is no additional reflecting mirror in the scheme, and so it is less sensitive to vibration than the traditional scheme. It is a technique that can find application in precision measurement systems on moving platforms.

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中文概要

题　目： 用于激光锁频的低泵浦场饱和吸收光谱

目　的： 利用激光透过原子气室时的端面反射产生泵浦光，实现低泵浦场的饱和吸收光谱，提高饱和吸收光谱锁频方法对运动平台的适应性。

创新点： 1. 在饱和吸收光谱中实现无需额外反射镜调节的泵浦光与探测光的重合方法；2. 在饱和吸收光谱中实现强探测-弱泵浦的实验方式。

方　法： 1. 利用原子气室端面反射光作为泵浦光，实现低泵浦场的饱和吸收光谱装置（图 1 和 2）；2. 研究实现低泵浦场的饱和吸收光谱所需的角度控制精度（图 4）；3. 研究采用此方法的激光频率锁定效果（图 5 和 6）。

结　论： 1. 低泵浦场的饱和吸收光谱方法可以满足激光频率锁定的要求；2. 低泵浦场的饱和吸收光谱装置相比传统装置，没有多余的可调节的反射镜，装置更加简洁，锁频效果受环境影响更小，对运动平台的适应性更强。

关键词： 饱和吸收光谱；低泵浦场；长漂；运动平台