6. Operating Instructions

1) Controller description

a. Power supply

Power switch: for the auxiliary source and the main unit.

Horizontal magnetic field: turn “H-Field” knob to adjust the current of the horizontal field, displayed on the meter above the knob.

Vertical magnetic field: turn “V-Filed” knob to adjust the current of the vertical field, displayed on the meter above the knob.

b. Auxiliary source

Cell temperature switch: the ON/OFF switch for temperature control of the absorption cell.

Direction switch of Sweep Field: for changing the current direction of the sweep field (select the sweep field direction).

Direction switch of H-Field: for changing the current direction of the horizontal field (select the horizontal field direction).

Direction switch for V-Field: for changing the current direction of the vertical field (select the vertical field direction).

Selection switch of Sweep Wave: for selecting signal mode of the sweep field, i.e. square or triangle.

Selection switch of Int./Ext. (back panel): for selecting internal or external sweep field signal.

Indicators of Cell Temp. and Lamp Temp.: indicate the temperature status of the lamp and the absorption cell, respectively.

Sweep Field Amplitude: adjust the amplitude of the sweep field.

2) Experimental procedure and contents

a. Preparation

Prior to turning on power, configure and align the components of the main unit (see Section 5 “setup and adjustment”), orientate the rail parallel to the direction of the horizontal component of the earth’s magnetic field with the aid of the compass, check the correctness of all wirings, turn the knobs of “V-Field”, “H-Field” and “Sweep Field Amplitude” to minimum, and press down “Cell Temp.” switch.

Then connect the power cord and turn on the power switch. In approximate 30 minutes (note, the time may vary depending on the lab temperature), both the “Lamp Temp.” and “Cell Temp.” indicators are lit. The apparatus enters working state.

b. Observation of optical pumping signal

Do not apply RF signal and H-Field remains minimum. Place the compass on top of the absorption cell, preset the vertical field current at approximately 0.07 A to offset the vertical component of the earth’s magnetic field by setting the vertical field direction opposite to the direction of the vertical component of earth’s magnetic field (now, the tip of the compass will be lifted a little to be approximately leveled). Next, select “square wave” as the sweep field signal, and increase its amplitude. Alternate the direction of the sweep field to let the sweep field direction opposite to the direction of the horizontal component of earth’s magnetic field. Then remove the compass. Next rotate the polarizer, gradually adjust the amplitude of the sweep field, the amplitude of the vertical field, until a maximum optical pumping signal is observed as seen in Figure 7. Finally, finely adjust optical focusing and alignments to further maximize the optical pumping signal.

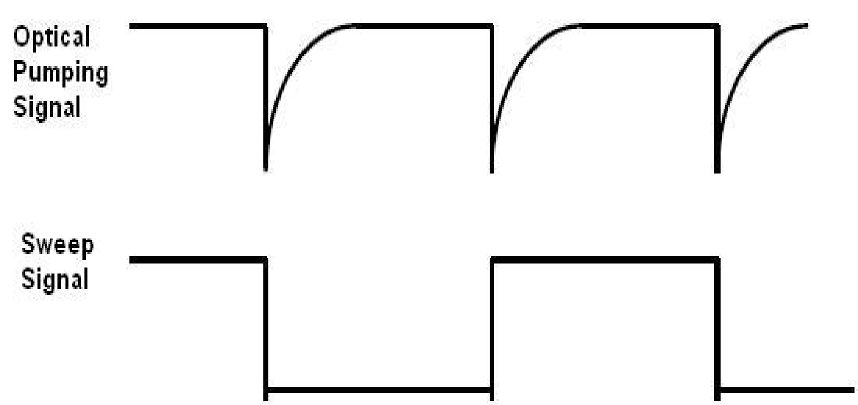

Figure 7 Optical pumping signal (upper trace) and sweep signal (lower trace)

c. Observation of optical magnetic resonance spectrum

(i) Measurement of *g*-factor

Select "triangle wave" as the sweep field signal. Preset the current for the horizontal field at 0.20 A, and orientate the horizontal field, the sweep field and the horizontal component of the earth's magnetic field in the same direction as determined by the compass. Remain the vertical field amplitude and the polarizer angle unchanged as in the previous experiment.

Adjust the frequency of the RF signal generator as well as the amplitude of the sweep field while monitoring the resonance signal as seen in Figure 8 (a). Record frequency ν_1 with corresponding horizontal field current *I*.

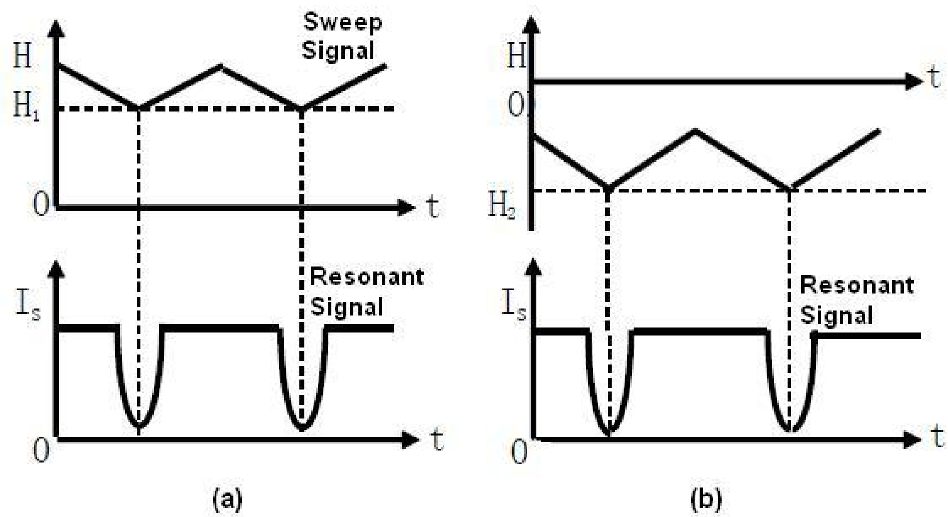

Figure 8 Resonant signal and sweep signal

Reverse the direction of the horizontal field to let it opposite to the horizontal component of the earth's magnetic field and the sweep field, and remain the amplitude of sweep field unchanged. Similarly, adjust the frequency of the RF signal generator, resonant frequency ν_2 can be achieved as shown in Figure 8 (b).

Thus, the corresponding frequency of the horizontal magnetic field is $\nu=(\nu_1+\nu_2)/2$, which excludes the influences of the horizontal component of the earth's magnetic field and the DC component of the sweep field. The value of the horizontal magnetic field can be calculated from the current of the horizontal field and the parameters of the horizontal Helmholtz coil (see Appendix).

The *g*-factor can be calculated from the formula below:

$$h\nu = \mu_0 g_F H \tag{1}$$

$$g_F = h\nu / \mu_0 H \tag{2}$$

where μ_0 is Bohr magneton, h is Planck's constant, H is the horizontal DC magnetic field, and ν is the resonance frequency.

Note: (1) to improve measurement accuracy, please repeat the above experiment by setting the current of horizontal field at different values, (2) always record resonant frequencies ν_1 and ν_2 of resonance occurring at the same point of sweep signal, i.e. at either peak or valley point.

(ii) Measurement of the earth's magnetic field

Similarly, first set the horizontal field, the sweep field and the horizontal component of the earth's magnetic field in the same direction, and measure frequency ν_1. Then press the direction switches of the sweep field and the horizontal field to let them opposite to the direction of the horizontal component of the earth's magnetic field, and measure frequency ν_2, so the frequency corresponding to the horizontal component of the earth's magnetic field is $\nu=(\nu_1-\nu_2)/2$, which excludes the effects of the sweep field and the horizontal magnetic field. From (1), we get the horizontal component of the earth's magnetic field as:

$$H_H = h\nu / \mu_0 g_F \tag{3}$$

As the vertical magnetic field offsets the vertical component of the earth's magnetic field, the value of the vertical component of the earth's magnetic field can be calculated from the current of the vertical field (this current value was obtained in **Experiment b** when a maximum optical pumping signal was observed by the adjustment of vertical field) and the parameters of the Helmholtz coil.

Finally, the earth's magnetic field can be acquired from its horizontal and vertical components.

3) Precautions

a. During experiment, the resonance spectral lines of Rb^{87} and Rb^{85} should be distinguished. When the horizontal magnetic field is unchanged, the frequency of the resonance spectral line of Rb^{87} is higher than that of the resonance spectral line of Rb^{85}. If the RF frequency is fixed, the resonance spectral line of Rb^{85}corresponds to a larger horizontal magnetic field while the resonance spectral line of Rb^{87}corresponds to a smaller horizontal field.

b. For more accurate measurement, the power of the temperature control for the absorption cell can be turned off for a short period of time to remove the influence of the residual magnetic field from the heating wire of the absorption cell.

c. To avoid the effect of ambient light and the electric-magnetic interference of fluorescent lamps on the amplitude and waveform of the signal, the main unit should be covered with the cloth cover if necessary, and it is preferred to turn off ambient light.

d. Place the compass on the top of the absorption cell, the needle tip of the compass will be a little downward to the ground when there is no vertical field since the vertical component of the earth's magnetic field is downward. After applying the vertical field, if the needle tip downwards further to the ground, it means the vertical field is in the same direction of the earth's magnetic field, if the needle tip turns to upward, it means the vertical field is in opposite direction now.

e. During experiment, the main unit must be isolated from other ferromagnetic objects, strong electromagnetic fields, and high power supply cords.

7. An example for data recording and processing

Note: data only for reference purpose, not the criteria for apparatus performance。

a. Observation of optical pumping signal

By adjusting the amplitudes of sweep field and vertical field, and rotating the polarizer, a maximum optical pumping signal is observed as shown in Figure 9, where the current of vertical field is 0.057 A which remains unchanged for following experiments and is used for calculating the vertical component of earth's magnetic field.

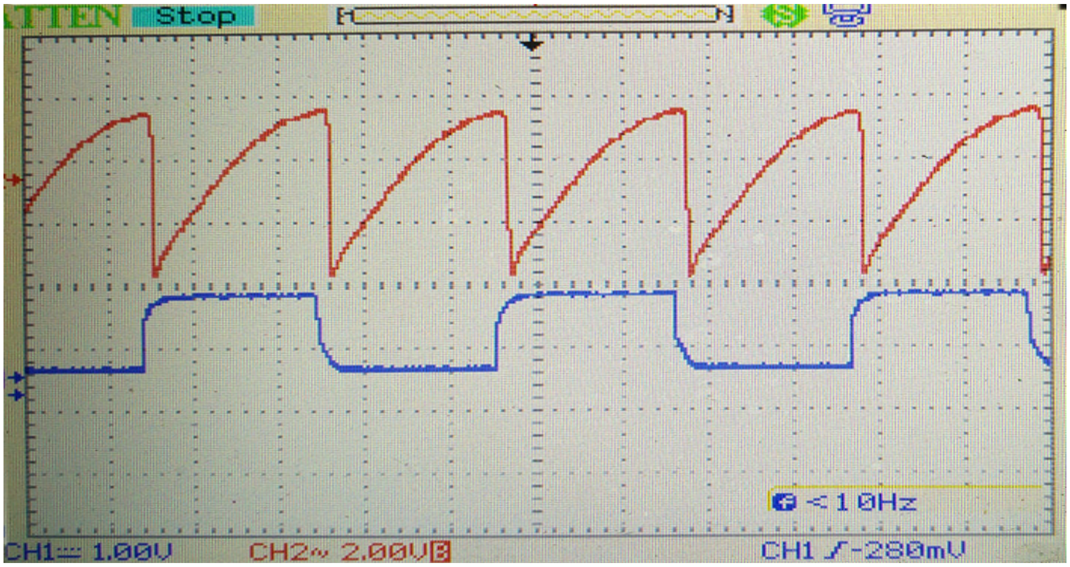

Figure 9 Observed optical pumping signal on oscilloscope

(blue trace: square-wave sweep signal; red trace: optical pumping signal)

b. Observation of optical magnetic resonance spectrum

An example of observed resonant signal on oscilloscope is shown in Figure 10.

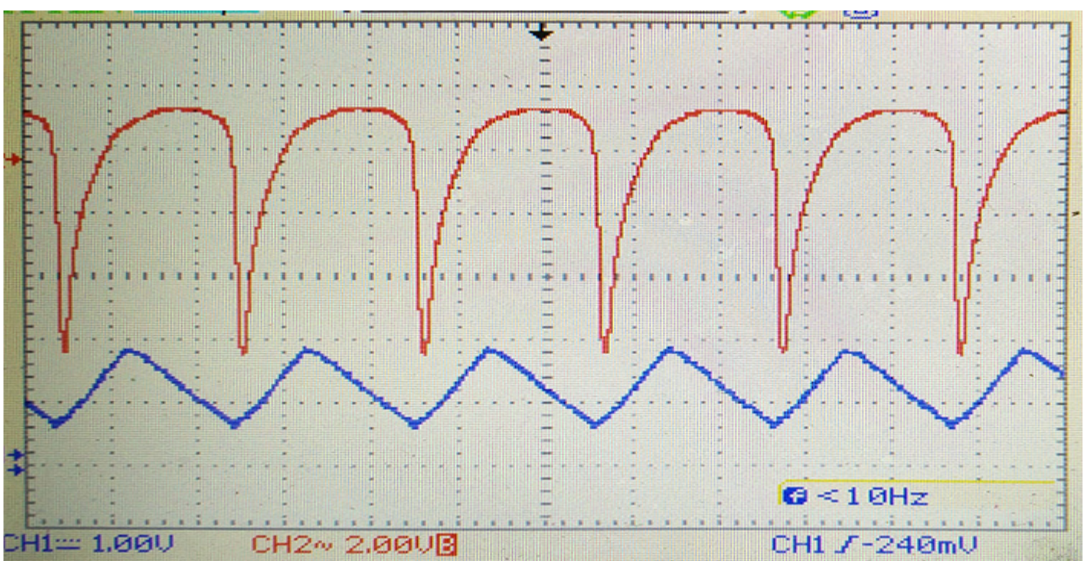

Figure 10 Sweep signal (blue) and observed resonant signal (red) observed on oscilloscope

1) Data for measuring g-factor

By setting the direction of horizontal field along with and to the opposite direction of the sweep field and the horizontal component of earth's magnetic field, respectively, the resonant frequencies are obtained as shown in Table 1.

Table 1 Data of horizontal field current and resonant frequency

Current of H- field (A)	Frequency of same direction ν_1 (kHz)		Frequency of opposite direction ν_2 (kHz)	
	^{87}R	^{85}R	^{87}R	^{85}R
0.20	1065	706	239.5	142.1

The value of horizontal magnetic field is calculated from the current of the horizontal field and the parameters of the horizontal Helmholtz coil (see Appendix), and g-factor is calculated by using formula (2). Results are given in Table 2.

Table 2 Calculated results of g-factor

H- field Current (A)	ν_1 (kHz)		ν_2 (kHz)		H-field H (T×10^{-4})	$g_F = h(\nu_1+\nu_2)/2\mu_0 H$	
	^{87}R	^{85}R	^{87}R	^{85}R		^{87}R	^{85}R
0.20	1065	706	239.5	142.1	0.9285	0.502	0.308

where $\mu_0 = 9.274\times10^{-24}\, J/T$, $h = 6.626\times10^{-34}\, J\cdot s$. The theoretical values of g-factor for ^{87}R and ^{85}R are 0.500 (or ½) and 0.333 (or 1/3), respectively.

2) Data for measuring horizontal component of earth's magnetic field

By setting the directions of horizontal field and sweep field along with and to the opposite direction of the horizontal component of earth's magnetic field, respectively, the resonant frequencies are obtained as shown in Table 3.

Table 3 Data for measuring horizontal component of earth's magnetic field

Current of H- field (A)	Frequency of same direction ν_1 (kHz)		Frequency of opposite direction ν_2 (kHz)	
	^{87}R	^{85}R	^{87}R	^{85}R
0.20	1065	706	475	352

From formula (1), we have $H = h(\nu_1 - \nu_2)/2\mu_0 g_F$. The values of horizontal component of earth's magnetic field are calculated as 0.421×10^{-4} T (using data of ^{87}R) and 0.379×10^{-4} T (using data of ^{85}R), respectively, so the average value of horizontal component of earth's magnetic field is 0.400×10^{-4} T.

The current of vertical field is 0.057 A. It is used to compensate the vertical component of earth's magnetic field. So, the vertical component of earth's magnetic field is calculated as 0.335×10^{-4} T.

Thus, the earth's magnetic field onsite is 0.522×10^{-4} T ($=\sqrt{0.4^2+0.335^2}\times10^{-4}T.$) and pitch angle 39.95° ($=\tan^{-1}(0.335/0.4)$).