Laser pumping Cs atom magnetometer of theory research based on gradient tensor measuring

Zhang Yang, Kang Chong, Qingtao Wang, Cheng Lei and Caiping Zheng
College of Science, Harbin Engineering University, Harbin 150001, China
E-mail: zhangyang@hrbeu.edu.cn

Abstract. At present, due to space exploration, military technology, geological exploration, magnetic navigation, medical diagnosis and biological magnetic fields study of the needs of research and development, the magnetometer is given strong driving force. In this paper, it will discuss the theoretical analysis and system design of laser pumping cesium magnetometer, cesium atomic energy level formed hyperfine structure with the I-J coupling, the hyperfine structure has been further split into Zeeman sublevels for the effects of magnetic field. To use laser pump and RF magnetic field make electrons transition in the hyperfine structure to produce the results of magneto-optical double resonance, and ultimately through the resonant frequency will be able to achieve accurate value of the external magnetic field. On this basis, we further have a discussion about magnetic gradient tensor measuring method. To a large extent, it increases the magnetic field measurement of information.

1. Introduction
Magnetometer is an instrument used to measure the magnetic field, mainly in the air, land, and marine, biomedical and other fields to detect magnetic field. As the important role of the magnetometer in the national economy, space exploration, military technology and navigation field, it has been a hot issue in all countries. From the Development of magnetometer, could be divided into three stages [1], the first stage, adopt flux-gate magnetometer, proton magnetometer and optical pumping magnetometer of helium to measure total magnetic field intensity; the second stage, in addition to measurement of the total magnetic field intensity, but also make use of alkali metals (cesium, potassium, rubidium) laser optical pumping magnetometer measuring the horizontal and vertical magnetic field gradient which be paid more and more attention; the third stage, is just started, atomic magnetometer and superconducting magnetometer with very high resolution and sensitivity. From the magnetic detection technology perspective, now China is still in the first stage, with a big gap between the world advanced level, and high-performance magnetometer is under an embargo, included in the export control list of goods, thus developing laser optical pumping magnetometer of alkali metal is of great significance.

2. Theoretical analysis of Cesium (Cs) laser pumping magnetometer
Cesium laser optical pumping magnetometer is based on the Zeeman effect generated by energy levels of cesium atoms in a magnetic field, be made by the principle of magneto-optical double resonance caused by laser pump and RF magnetic field.
2.1. Cs atomic energy levels

Cesium is monobasic alkali metal, atomic number is 55, valence electrons are in the 6th shell, the main quantum number $n = 6$, the same principal quantum number $n$ there

$$l = 0,1,\cdots,(n-1)$$

$l$ is electron orbital angular momentum quantum number, in addition to orbital motion, the electron also do spin motion, the electron spin angular momentum quantum number $s = 1/2$, the interaction between spin and orbital motion of the electron (LS coupling) would produce energy levels splitting, known as the fine structure [2]. Therefore electronic orbital angular momentum and spin angular momentum composition of electronic total angular momentum, electronic total angular momentum quantum number is $j$, there

$$j = l + s, l + s - 1,\cdots, |l - s|$$

Since $s = 1/2$, so the value of a set $l$,

$$j = l + 1/2, |l - 1/2|$$

Similar with electron, the atomic nucleus also has angular momentum, commonly called nuclear spin angular momentum, represent by $I$. The interaction between nuclear spin angular momentum and electronic total angular momentum ($I$ - $J$ coupling), producing hyperfine structure [3], using $F$ to represent, $F$ is the atomic total angular momentum quantum number, there

![Figure 1. Cesium atomic energy level diagram with quantum number $n = 6$](image-url)
\[ F = I + j, I + j - 1, \ldots |I - j| \]  

(4)

For the cesium atom, atomic nucleus spin angular momentum \( I = \frac{7}{2} \), when \( j = \frac{1}{2} \), with \( F = 4 \) and \( F = 3 \) two states; When \( j = \frac{3}{2} \), with \( F = 5 \), \( F = 4 \), \( F = 3 \) and \( F = 2 \) four states. When external magnetic field exists, the interaction between atomic total angular momentum and external magnetic field, hyperfine structure could produce Zeeman splitting further and form Zeeman sub-level, with the magnetic quantum number \( m_F \) to indicate that

\[ m_F = F, F - 1, \ldots, -F \]  

(5)

That is, split into \( 2F + 1 \) Zeeman sub-levels which are equal level spacing. Cesium atomic-level structure talked above is shown in Figure 1. The condition of electronic transitions between energy levels [4] is shown

\[ \Delta L = \pm 1, \Delta J = 0, \pm 1, \Delta F = \pm 1, \Delta m_F = 0(\pi) \]

or

\[ \Delta L = \pm 1, \Delta J = 0, \pm 1, \Delta F = 0, \pm 1, \Delta m_F = \pm 1(\sigma) \]  

(6)

2.2. **System design and principles analysis**

Cesium (Cs) laser optical pumping magnetometer system [5] is shown in Figure 2, the work process: the laser emit light of 894nm wavelength (D1 line), the light goes through the lens into parallel light, after a polarizer and 1/4 wave plate into laevogyrate circularly polarized light \( \sigma^+ \), Irradiate cesium absorption chamber (absorption chamber is made of the airtight glass, cesium elements of absorption chamber is gaseous), while adding a RF magnetic field in the vertical direction of the external magnetic field. When it produces magneto-optical double resonance, light through the absorption chamber is weakest, the moment could be detected by the optical detector, and moreover the value of the external magnetic field can be obtained through the resonance frequency.

![Figure 2. Cesium optical pumping magnetometer system diagram](image)

Work principle: Laser emits wavelength of 894nm light(D1 line), known as the Figure 1, the electron can transit between the \( 6^3S_{1/2} \) state and \( 6^3P_{1/2} \) state, the formula (6) gives the transition of energy level conditions, according to Zeeman effect theory[6], \( \Delta m_F = +1 \) is laevogyrate circularly polarized light \( \sigma^+ \), \( \Delta m_F = -1 \) is dextrogyrate circularly polarized light \( \sigma^- \), we adopt laevogyrate circularly polarized light \( \sigma^+ \) here, then only produce transition of \( \Delta m_F = +1 \), for example, the electron of
ground state $^6S_{1/2}$ with $m_F = +3$ energy level can transit to $^6P_{1/2}$ with $m_F = +4$ energy level. From figure 1 we can find that $^6P_{1/2}$ state does not exist $m_F = +5$ energy level, so the electron transition probabilities of ground state $^6S_{1/2}$ with $m_F = +4$ energy level is zero, that is, laevozygate circularly polarized light could excited each level on the ground state except $m_F = +4$ of electron to the states of $^6P_{1/2}$. At the same time, electrons which transit to the $^6P_{1/2}$ states after about $10^{-8}$ seconds return to the ground through state spontaneous transition, as the probability of return to the ground state of each level is basic equal, as a result electrons of $m_F = +4$ energy level will continue to increase. When the light irradiates continuously, it will reach dynamic equilibrium, and electrons of $m_F = +4$ energy level will greatly increase, that means electrons of ground state except $m_F = +4$ will be pumped empty. The optical pumping cause the uneven distribution of electrons of Zeeman energy levels of ground state, do not obey the Boltzmann distribution, that is, polarization [7]. The process can be seen from detect signal of the light detector, the moment when the light irradiation, equivalent of the total number of 7/8 of the electrons absorb $\sigma^+$ light, light through the absorption chamber is weak, as electronic continuous transition, light absorption decreased continuously, light through absorption chamber gradually increase, to the dynamic equilibrium, light intensity through the absorption chamber reach maximum and no longer changes. Now add a RF magnetic field in the vertical direction of the external magnetic field, when the RF magnetic field frequency $f_0$ is equal to adjacent Zeeman sub-level transition frequency, will produce magnetic resonance, resulting to the orientation effect, thus the electrons of Zeeman sub-level produce stimulated transition. As Figure 1, electrons of ground state with $m_F = +4$ energy level stimulated transition to $m_F = +3$ energy level, electrons of ground state with $m_F = +3$ energy level stimulated transition to $m_F = +2$ energy level, transition by order, So that the distribution of atoms obey the Boltzmann distribution law, then the orientation of atomic magnetic moment has been disrupted, meanwhile optical pumping goes simultaneously, electrons of ground state except $m_F = +4$ will be pumped to $m_F = +4$ once again, stimulated transition and optical pumping will reach a new dynamic equilibrium, at this time maximum absorption of light, the light intensity that light detector detects is weakest. The adjacent Zeeman sub-level transitions frequency is directly proportional to the measured external magnetic field, the Formula is:

$$f_0 = \frac{\Delta E}{\hbar} = \frac{g_F \mu_B}{\hbar} B = \frac{\gamma_p B}{2\pi}$$

(7)

$g_F$ is Legendre factor, $\mu_B$ is Bohr magneton, $\gamma_p$ is magnetogyric ratio, B is external magnetic field.

From (7), we know, as long as measure the frequency of the RF magnetic field when the light detector detects the weakest light intensity, the value of the external magnetic field can be obtained.

3. Gradient measurement theory based on cesium optical pumping magnetometer

In order to understand the distribution characteristics and rules of the magnetic field better, in addition to measuring the magnetic field modulus and vectors, also need to measure space rate of change of the three components modulus and vectors, that is, gradient measurement[8]. The advantage of gradient measurement can eliminate the effects of regional magnetic field and time-varying magnetic field. Gradient measurement is different from total magnetic field measurement, to obtain the gradient value of some direction at a point, requires cesium pumping vector magnetometer loaded with two three-axis coils measuring simultaneity. Set down the distance between the two magnetometer is $\Delta Z$, the measurement value of magnetic above is $B_1$, the measurement value of magnetic below is $B_2$, the vertical gradient
By (8), can be seen that the two magnetometers closer, the higher resolution of gradient values, while the closer requires higher precision magnetometer, so system design should take overall consideration, not only consider the precision of magnetometer, but also consider the resolution of gradient. Similarly longitudinal horizontal gradient and lateral horizontal gradient. According to the three components of the space rate of change above, could get magnetic gradient tensor [9], the complete magnetic field gradient tensor can be expressed as:

$$\nabla \cdot B = \frac{\partial B_x}{\partial x} + \frac{\partial B_y}{\partial y} + \frac{\partial B_z}{\partial z} = 0$$

$$\nabla \times B = \left[ \begin{array}{c} i \\ j \\ k \end{array} \right] = 0$$

$$B_{xx} + B_{yy} + B_{zz} = 0, B_{xy} - B_{yx} = 0, B_{xz} - B_{zx} = 0, B_{yz} - B_{zy} = 0.$$ Therefore, only five elements are independent in nine elements. And the magnetic gradient tensor is a real symmetric matrix, can be carried out real eigenvalue diagonalization, define eigenvalue of the magnetic gradient tensor as $\lambda_1, \lambda_2, \lambda_3$, the magnetic gradient tensor eigenvalue equation can be expressed as:

$$\lambda^3 - I_0 \lambda^2 + I_1 \lambda - I_2 = 0$$

The coefficient $I_0, I_1, I_2$ are magnetic gradient tensor invariants, are respectively expressed as:

$$I_0 = g_{xx} + g_{yy} + g_{zz} = 0$$

$$I_1 = g_{xx}g_{yy}g_{zz} + g_{xy}g_{xz}g_{yz} + g_{xz}g_{yz}g_{zx} - g_{xx}^2 - g_{yy}^2 - g_{zz}^2$$

$$I_2 = g_{xx}(g_{yy}g_{zz} - g_{yz}^2) + g_{xy}(g_{yx}g_{zx} - g_{xx}g_{yz}) + g_{xz}(g_{xy}g_{yz} - g_{xx}g_{yy})$$

Magnetic gradient tensor invariant itself has many nice properties [9], invariant contour map not affected by the direction of magnetic field, can draw a good field source boundary. When there are several field sources closely, the magnetic gradient tensor invariant can better distinguish field source
compared to the total magnetic field. As the magnetic gradient measurement system’s measurement object is the gradient of magnetic field vector component, unlimited by total field measurement, the measurement results can reflect information on vector magnetic moment of the objective body, geomagnetic field’s obliquity and declination have a small effect on tensor elements, the calculated tensor invariants do not require additional processing can be a good description of the magnetic field source [10], and the magnetic gradient tensor inversion can accurately describe the field source body’s magnetization direction and geometry, improving resolution of the magnetic source body.

4. Conclusions
This paper presents theoretical analysis and laser cesium optical pumping magnetometer and system design, explains the magneto-optical double resonance theory and the work process of cesium optical pumping magnetometer through cesium atomic hyperfine level structure diagram. On this basis, we discuss on the measuring method of the magnetic gradient tensor, which increase information of magnetic field measurement to a large extent. At present, our country’s magnetic measurement technology is still at the first stage, with the great gap between the world advanced level, and the important role of the magnetometer in many key areas, research of laser optical alkali metal pumping magnetometer will have a very bright future.

Acknowledgements
The authors would like to acknowledge the support of International Science and Technology Cooperation Funds (2008DFR20420) and Fundamental Research Funds for the Central Universities (HEUCFL20101110).

References
[1] Weis A and R. Wynands 2005 J. Optics and Lasers in Engineering. 43 387
[2] Groeger S and Bison G 2006 J. Sensors and Actuators A. 129 15
[3] Groeger S, Pazgalev A and Weis A 2005 J. Applied Physics B. 80 645
[4] Chung-Hoon Lee, Hang Guo and Shankar Radhakrishnan 2004 J. Solid-State Sensor, Actuator and Mi-crosystems. 20 23
[5] Chen Jing-biao, Wang Feng-zhi, Wang Yi-dao and Yang Dong-hai 2005 J. Optoelectronics laser. 11 563
[6] Harris M, Adams C and Cornish S 2006 J. Physical Review A. 24 64
[7] Smith D and Hughes I 2004 J. Am. J. Phys. 35 631
[8] Harris M, Adams C and Cornish S 2006 J. Physical Review A. 17 112
[9] Luo Yao and Changli Yao 2007 J. Journal of China University of Geosciences. 11 431