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High Sample Rate Optically Pumped Helium Magnetometer

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Abstract: Optically pumped helium magnetometers are important instruments which have many applications in military, mass spectroscopy and space applications. In this paper, the working principles of helium magnetometers have been explained. There is also an introduction of a new method for finding the resonant frequency, which has advantages to the typical method such as more sample rate possibility and realizing with cheaper prices.

Keywords: Optically Pumped Magnetometer, Helium Magnetometer and Conic Method

1. INTRODUCTION

Optically pumped magnetometers are sensitive and accurate devices which can be applied for measuring small magnetic fields [1, 2]. These devices can be distinguished by the method which they use to monitor the magnetic field and the gas which is used for optical pumping process. For the first one, there are methods to monitor magnetic field changes such as sweeping the frequency of the radio frequency (R.F.) field to find resonant frequency [3], self-oscillating magnetometers [4-6] and Conic method which is introduced in this paper. For the second one, gases which commonly used as resonant element are rubidium (Rb) [7-9], cesium (Cs) [10-12] and helium (He) [13-15]. Among these resonant elements, He has advantages over the rest, like relatively high Larmor frequency ($\approx 28\frac{Hz}{nT}$) that allows to find the resonant frequency easier and more accurate than other. So, the magnetometers are the important one, which have many

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applications like military and space usage since 1960 [16, 17].

The optical pumping of He was reported experimentally by Colegrove and Franken in 1960 [18]. Helium magnetometers can be divided in two groups according to their optical pumping radiation source: lamp and laser pumped magnetometers. Most of helium magnetometers manufactured in 1960 to 1990 were lamp pumped magnetometers [14]. Developments in making single line sources resulted laser pumped magnetometers which are more sensitive, accurate and smaller than lamp pumped magnetometers [3, 17]. In the steady state, He atoms have two electrons in 1S level. In the first excited state, One electron presumed to be in the ground state (1S) and the other one is in upper state (2S), which can have either parallel (triplet state, orthohelium) or anti-parallel (singlet state, parahelium) spin to the ground state electron. In the magnetic field $\mathbf{B_0}$, Zeeman effect takes place and the 2^3S_1 sublevels separate into magnetic states m=-1,0,1 (Fig. 1). The separation energy between these sublevels is $\Delta E = h\upsilon_0$, where $\upsilon_0 = \gamma \mathbf{B_0}$ and $\gamma = 28.024 \frac{Hz}{nT}$ is the gyromagnetic ratio. In the absence of optical pumping these three sublevels are populated equally.

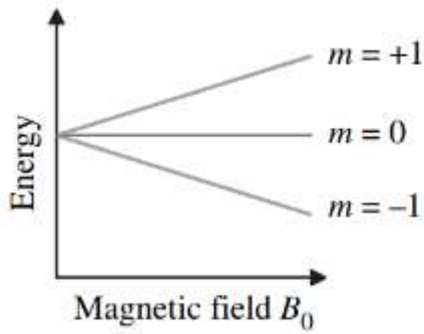

Fig. 1. Zeeman effect in 2^3S_1 level.

In Fig. 2(a) we can see the helium atom energy levels and their sublevels in the presence of an external magnetic field. As we can see in this figure, for producing 2^3S_1 atoms (metastable atoms) we need an ultra violet radiation, but electromagnetic transition between these two levels is forbidden. So, metastable atoms should be produced by electron collisions with ground state atoms in a weak high frequency (H.F.) electrodeless discharge. When a circularly 1082.9 nm beam is irradiated to metastable atoms, they excite from m=-1 to 2^3P_0 level, then decay back to 2^3S_1 sublevels with equal probability (Fig. 2(b)). So, optical pumping drives the metastable population to a nonequilibrium distribution over the magnetic sublevels. More details of optical pumping can be found in [19, 20].

The reminder of this paper planned as follows. In section 2, a block diagram of helium magnetometer is shown and its operating principles are described. Section 3 contains a full description of conic method for obtaining resonant frequency. At last summary and conclusion remarks are presented in section 4.

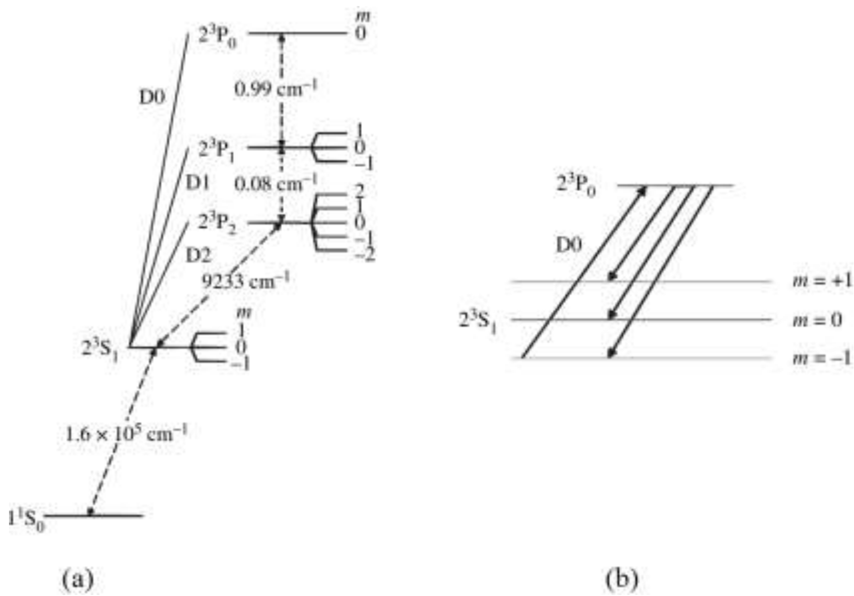

Fig. 2. a) Helium energy levels in an external magnetic field; b) Optical pumping of metastable atoms.

2. HELIUM MAGNETOMETER PRINCIPLES

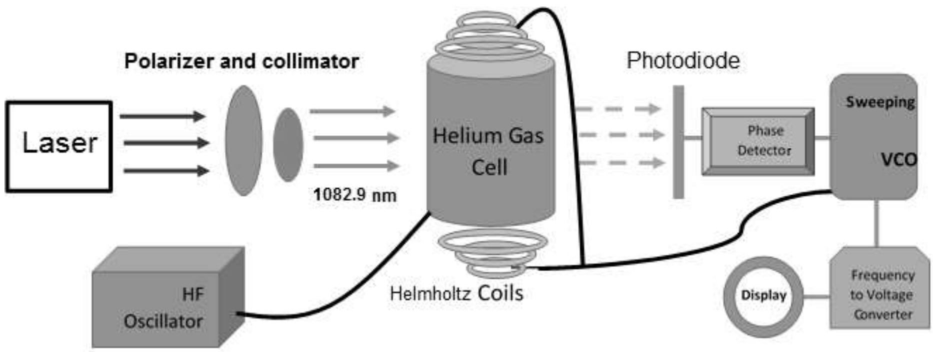

Fig. 3. A block diagram of a laser helium magnetometer.

Finding the resonant frequency is the magnetometer aim. As we mentioned before, optical pumping leads to light absorption and nonequilibrium distribution in magnetic sublevels. Equal population of sublevels can be obtained by applying the R.F. magnetic field. Depending on the frequency of this magnetic field, light absorption is different. If this frequency is equal to the resonant frequency, most light absorption occurs. So, we need to find a frequency which has the most light absorption. In this section, we explain general method to find the resonant frequency in a laser pumped magnetometer.

In Fig. 3, a block diagram of a laser pumped magnetometer is shown. Referring to this figure helium atoms in a cylindrical cell excite by H.F. oscillator. The laser radiates a beam at wavelength 1082.91 nm through the helium cell. This beam is collimated, expanded and circularly polarized before striking helium cell. A photodiode is placed after the helium cell and detects the 1082.91 nm beam. There are two Helmholtz coils around the cell which produce the R.F. magnetic field. In Fig. 4, we can see the photodiode signal as a function of R.F. magnetic field frequency.

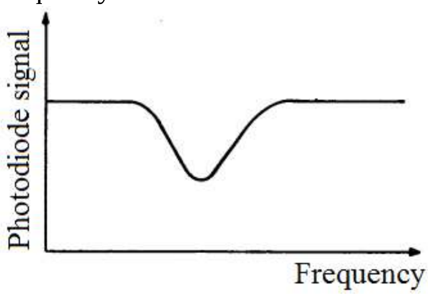

Fig. 4. Photodiode signal as a function of R.F. magnetic field frequency. The minimum point corresponds to the resonant frequency.

The photodiode signal is multiplied in voltage control oscillator (V.C.O.) signal by phase detector. If V.C.O.'s frequency be less than resonant frequency, phase detector observes a phase difference which states the V.C.O.'s frequency should be increased (Fig. 5(a)). On the other hand, if V.C.O.'s frequency be more than resonant frequency, detector observes a phase difference which states the V.C.O.'s frequency should be decreased (Fig. 5(c)). Finally, if the resonant frequency is equal to V.C.O.'s frequency, the signal shape becomes like Fig. 5(b) and the phase detector looks for this. The proper frequency of V.C.O. depends to amount of the magnetic field. For example, if the magnetic field is 50000 nT, the resonant frequency will be 1.4 MHz. The V.C.O.'s low end is about 0.6 MHz and its high end is about 2.2 MHz, which correspond to earth magnetic field range 20000-75000 nT. For finding the resonant frequency, V.C.O. should sweep among its frequency range and it causes a lot of sweeps in this range, which takes much time. Also, such a V.C.O is complicated and expensive. So finding a simple and cheap method could be useful to realize the magnetometer. Conic method is a possible method which can be realized cheaper and more simple than sweeping whole of the frequency range. This method is described in the next section.

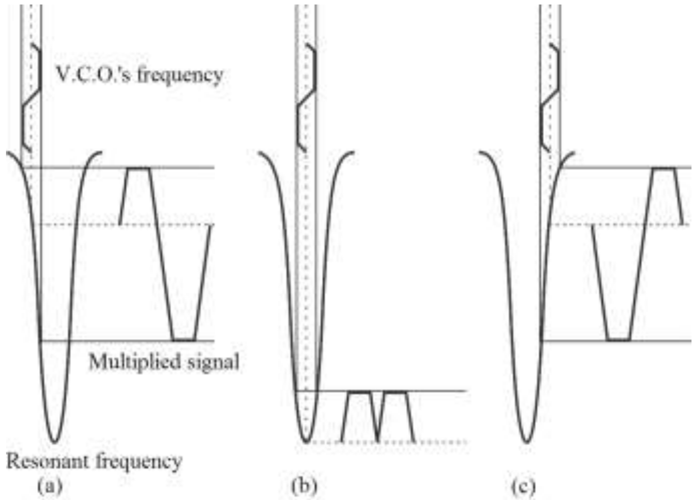

Fig. 5. The resonant and V.C.O.'s frequencies and their multiplied signal shape in different situations.

3. CONIC METHOD IN A MAGNETOMETER

As we said before, the typical method for finding resonant frequency in magnetometers is sweeping the V.C.O.'s frequency among its frequency range. In this method we need a lot of sweeps to find resonant frequency. For example, if V.C.O.'s frequency increased in 500 Hz steps (0.6, 0.6+0.0005, 0.6+0.001, …), 3200 sweeps are needed.

Here we will introduce an effective and fast method which we named it as *Conic method*. In the conic method, the V.C.O. sweeps among its frequency range in large steps (50 KHz), then the point which has the minimum light intensity is determined by microcontroller after detecting by photodiode. In the next level, V.C.O.'s frequency range is decreased around this minimum point and V.C.O. sweeps in this decreased range in smaller steps (5 KHz). The minimum point is determined in this new range and finally, V.C.O.'s frequency range is decreased around this new minimum point. Which is swept by V.C.O. in smaller steps (500 Hz). The minimum point is determined and this point is obtained with less sweeps in comparison to sweeping whole frequency range. We used an algorithm, which is shown in Fig. 6 to find the minimum point. Just 114 sweeps are needed by using this algorithm which is approximately 28 times less than 3200 sweeps. Since, both time complexities of finding the minimum

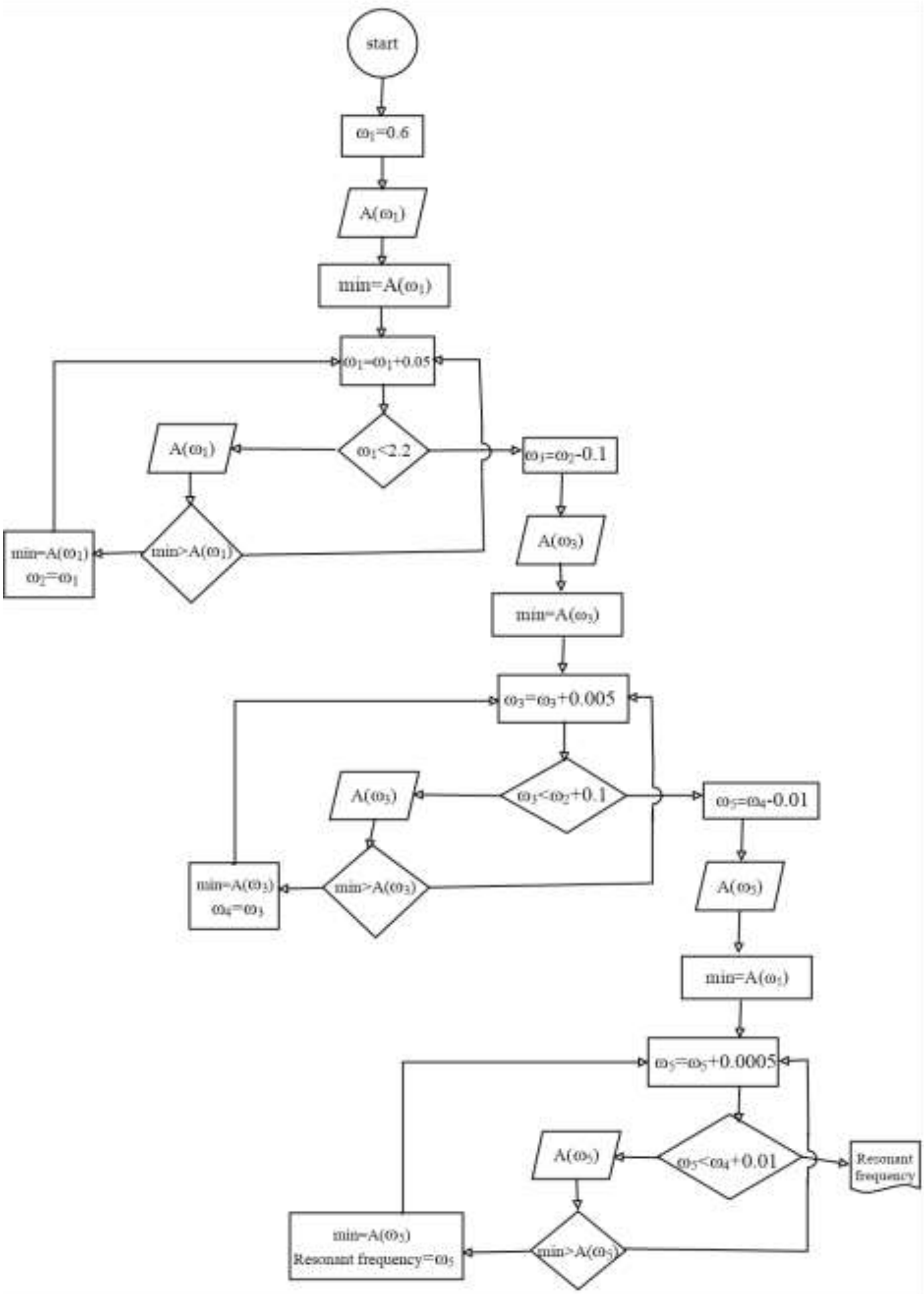

Fig. 6. The algorithm that is used in our calculation for conic method.

point and sweeping whole frequency range are linear [21, 22], so the conic method is a better method to find resonant frequency. Also in this method we don't need to the expensive phase detector. This process can be done by a good microcontroller.

4. CONCLUSION

In this paper we reviewed optically pumped magnetometers operating principles and introduced a new method for finding the resonant frequency, which is named conic method. In the conic method the number of sweeps were approximately 28 times less than the general method, which allows to have more sample rates. Also, realizing a magnetometer by this method is cheaper than the typical one, because you don't need the phase detector in the conic method.

REFERENCES

[1] E. Labyt, M.-C. Corsi, W. Fourcault, A. P. Laloy, F. Bertrand, F. Lenouvel, G. Cauffet, M. Le Prado, F. Berger and S. Morales, *Magnetoencephalography With Optically Pumped ^{4}He Magnetometers at Ambient Temperature*, IEEE Trans. Med. Imag. 38 (2019) 90.

[2] O. Baffa, R. H. Matsuda, S, Arsalani, J. R. A. Miranda and R. T. Wakai, *Development of an optical pumped gradiometric system to detect magnetic relaxation of magnetic nanoparticles*, J. Magn. Magn. Mater. 475 (2019) 533.

[3] D. D. McGregor, *Laser driven helium magnetometers,* U.S. Patent 4 780 672, (1988) Oct. 25.

[4] R. E. Slocum, P. C. Cabiness Jr. and S. L. Blevins, *Self-oscillating Magnetometer utilizing optically pumped $^4He^*$*, Rev. Sci. Instrum. 42 (1971) 763.

[5] M. J. Usher, W. F. Stuart and S. H. Hall, *A self-oscillating rubidium vapour magnetometer for geomagnetic measurements*, J. Sci. Instrum. 41 (1964) 544.

[6] Q. Zhao, B. L. Fan, S. G. Wang and L. J. Wang, *A vector atomic magnetometer based on the spin self-sustaining Larmor method*, J. Magn. Magn. Mater. 481 (2019) 257.

[7] A. J. Fairweather and M. J. Usher, *A vector rubidium magnetometer*, J. Phys. E: Sci. Instrum. 5 (1972) 986.

[8] A. L. Bloom, *Principles of operation of the rubidium vapor magnetometer*, Appl. Opt. 1 (1962) 61.

[9] D. Arnold, S. Siegel, E. Griasanti, J. Wrachtrup and I. Gerhardt, *A rubidium M_x-magnetometer for measurements on solid state spins*, Rev. Sci. Instrum. 88 (2017) 023103.

[10] H. Kai-Kai, L. Nan and L. Xuan-Hui, *A high sensitivity laser-pumped cesium magnetometer*, Chin. Phys. Lett. 29 (2012) 1007011.

[11] S. Groeger, G. Bison, P. E. Knowles, R. Wynands and A. Weis, *Laser-pumped cesium magnetometers for high-resolution medical and fundamental research*, Sens. Actuator. A: Phys. 129 (2006) 1.

[12] W.-M. Sun, Q. Huang, Z.-J. Huang, P. W. Wang and J.-H. Zhang, *All-Optical Vector Cesium Magnetometer*, Chin. Phys. Lett. 34 (2017) 058501.

[13] H. Gilles, J. Hamel and B. Chéron, *Laser-pumped ^{4}He Magnetometer*, Rev. Sci. Instrum. 72 (2001) 2253.

[14] D. D. McGregor, *High-sensitivity helium resonance magnetometers*, Rev. Sci. Instrum. 58 (1987) 1067.

[15] F. Beato, E. Belorizky, E. Labyt, M. Le Prado and A. Palacios-Laloy, *Theory of a ^{4}He parametric-resonance magnetometer based on atomic alignment*, Phys. Rev. A 98 (2018) 053431.

[16] M. H. Acuna, *Space-based Magnetometers*, Rev. Sci. Instrum. 73 (2002) 3717.

[17] R. E. Slocum, L. D. Schearer, P. Tin and R. Marquedant, *Nd:LNA laser optical pumping of ^{4}He: Application to space magnetometers*, J. Appl. Phys. 64 (1988) 6615.

[18] F. D. Colegrove and P. A. Franken, *Optical pumping of helium in the $^3S_1$ metastable state*, Phys. Rev. 119 (1960) 680.

[19] D. Budker and D. F. J. Kimball, *Optical magnetometry*, Cambridge University Press, 2013.

[20] W. Happer, Y. –Y. Jau and T. Walker, *Optically pumped atoms*, John Wiley and sons, 2010.

[21] A. Shamir, *A linear time algorithm for finding minimum cutsets in reducible graphs*, SIAM J. Comput. 8 (1979) 645.

[22] Th. H. Cormen, Ch. E. Leiserson, R. L. Rivest and C. Stein, *Introduction to algorithms*, MIT press, 2009.