Effect of Light Polarization on the Absorption Index of Alkali Metal Vapor in Optical Pumping Phenomenon

Samaneh Birzhandi[a], Malihe Ranjbaran[a], Seyed Mohammad Hosein Khalkhali[b], Seyedeh Mehri Hamidi[a,*], Mohammad Mehdi Tehranchi[a,b,*]

[a]Laser and Plasma Research Institute, Shahid Beheshti University,Tehran, Iran
[b]Physics Department, Shahid Beheshti University, Tehran, Iran.

Corresponding Authors Emails: Teranchi@sbu.ac.ir, m_hamidi@sbu.ac.ir

ABSTRACT— **Recently atomic magnetometers are one of the best tools in biomagnetic measurement such as magnetic field of brain and heart. In this paper, the technology of optically pumped atomic magnetometer based on circularly polarized light absorption pumping is described. We have been investigated a new method for measuring polarization effect in an alkali vapor based on polarized light transmission. In addition several magnetometers' response factors such as cell temperature, laser's intensity are introduced and reviewed. Our results show that the difference between absorption of circular and linear light not only depends on polarization, but also in number of polarized atoms.**

KEYWORDS: Atomic magnetometer, optical pumping, optically detected magnetic resonance.

I. INTRODUCTION

One of the most sensitive magnetic field probes is the electron spin magnetic momentum (MM) of paramagnetic atoms. MM of these atoms can produce a macroscopic magnetization which leads to various magnetic phenomena. One of the magnetic phenomena is enhancement of magnetization by orienting spins of the medium along a common axis. An effective method to produce the spin polarized media is optical pumping [1]. In this method circularly polarized light (in D1 transition line of Alkali metal) used to polarize atoms by transferring polarization of light to the atoms. Also linearly polarized light (in D2 transition line of Alkali metal) can be used for studying the changes of atomic polarization. Beside linear light detection, absorption of pumped light can be used as polarization probe. This technique is called optically detected magnetic resonance (ODMR) [2, 3].

The transmitted light intensity is a function of absorption caused by light-matter interaction. Absorption of media depends on many factors such as number of atoms, wavelength of absorption line and population distributions of atomic energy states. When light with near or on absorption resonance wavelength passes through the medium, it is partially or completely absorbed. Absorption of circularly polarized light in alkali vapor leads to redistribution of population in hyperfine states and induces polarization in the media. As a result, light with right and left circularly polarization will have different refraction index. In this situation polarization angle of linearly polarized light rotate with respect to magnetic field amount. This property has been used for measuring magnetic field as an atomic magnetometer. Nevertheless non-homogeneous polarization along cell can reduce magnetometer sensitivity. In addition, the magnetometer's band width, which means magnetometer's velocity in following magnetic changes, depends on polarization lifetime [3]. However, high polarization gradient in cell is one of the factors that affect relaxation rate and so increases bandwidth. Light intensity (pumping rate) is one of the effective parameters in creating homogenous polarization in the cell [4]. In this paper, effect of this parameter and temperature effect have been investigated.

II. OPTICAL PUMPING THEORY

If a right circularly polarized photon absorbed by an alkali vapor atom, the atom changes its magnetic quantum number by +1. The excited atom can decay to ground state via three possible channels 0, ±1. After several exciting and decaying process, atoms pump into level with maximum angular momentum (Dark state). In this state, atoms cannot absorb the incident light anymore and the vapor is called polarized. The whole process is shown in Fig. 1.

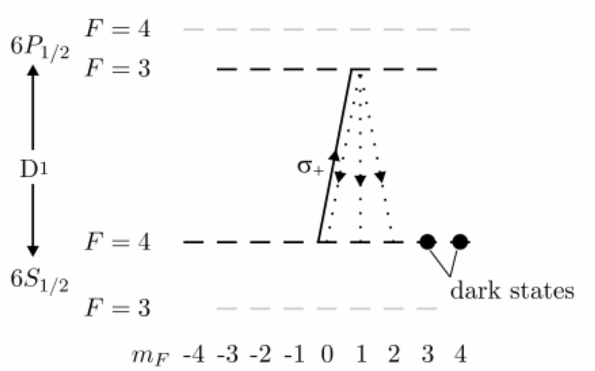

Fig. 1. The optical pumping process with circularly (σ+) polarized light [1].

In alkali metal vapors, polarized Light-matter interaction, leads to polarization dependent intensity. As the intensity of light passing through the vapor varies as,

$$\frac{dI}{dz} = -n\sigma(\nu)I(1-2\mathrm{s}\langle S_z\rangle) , \tag{1}$$

where n is the density of the alkali vapor and $\sigma(\nu)$ is the photon absorption cross-section. In the case of linearly polarized light (s=0), the solution is an exponentially function of z,

$$I(z) = I(0)\exp(-n\sigma(\nu)z) \tag{2}$$

where z is the position in the cell and I (0) is the intensity of light entering the cell. The optical depth, OD, which is the total attenuation of light through the cell, is given by:

$$OD = n\sigma(\nu)l \tag{3}$$

where *l*, is the length that the light passes through the vapor. In addition to optical depth, the absorption of incident light depends on both the alkali and photon polarization. For example, at high spin polarization, the circularly polarized light passes through the alkali vapor with no attenuation, and the vapor becomes transparent to such light, while at low spin polarization, it is mostly absorbed. For the case of circularly polarized light (s=1), the answers obtained by solving an algebraic equation:

$$I(z)\exp\left(\frac{\sigma(\nu)I(z)}{R_{rel}}\right) = \mathrm{I}(0)\exp\left(\frac{\sigma(\nu)I(0)}{R_{rel}} - \mathrm{n}\,\sigma(\nu)\mathrm{z}\right), \tag{4}$$

That can be solved by using the Lambert W-function:

$$I(z) = \frac{R_{rel}}{\sigma(\nu)}W\left[\frac{\sigma(\nu)\mathrm{I}(0)}{R_{rel}}\exp\left(\frac{\sigma(\nu)I(0)}{R_{rel}} - \mathrm{n}\,\sigma(\nu)\mathrm{z}\right)\right], \tag{5}$$

$$P = \frac{1}{1+1/\mathrm{I(z)}},$$

where *P*, a dimensionless and z dependent parameter, is the polarization of vapor through the cell and R_{rel} is the relaxation rate of polarization in the vapor. The polarization of vapor and light attenuation through the cell are shown in Fig. 2 for a cell with nominal OD=5 and low $(R_{op} = R_{rel})$ and high pumping rates $(R_{OP} = 15R_{rel})$ at the front of the cell.

At low pumping rate, as the pumping is lower than the expected value, there is a large polarization gradient through-out the cell. However, at high pumping rate the vapors fully polarized and as a result the beam is rarely absorbed [4, 5].

Nevertheless in the above equation effect of pumping rate on polarization relaxation aren't taken into account. At high pumping rate, the probability of unwanted transitions increases due to factors such as pumping in wavelengths far from resonance that forces atoms to leave coherent state. This is the cause of decreasing differences between circular and linear light transmission [6, 7].

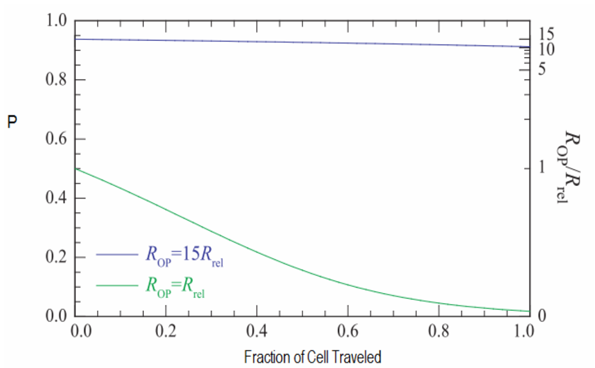

Fig. 2. Light intensity or atomic polarization through-out the cell with high optical depth (OD=5) for low pumping rate $\left(R_{op}=R_{rel}\right)$ and high pumping rate $\left(R_{OP}=15R_{rel}\right)$. Pumping rate was calculated from Eq 5. [2]

III. Experimental Procedure

In this study a spherical cell used for optical pumping experiment containing a mixture of isotope 85 of Rubidium atoms and Neon as buffer gas. Vapor cell surrounded by four heaters each placed in four sides of the cell to ensure uniform atomic gas distribution. A DFB diode laser was used as pump source with internal wavelength stabilization at 795nm. The transmitted light intensity measured by photo detector in combination with a lock in amplifier to ensure high signal to noise ratio.

As the photo detector voltage is proportional to the incident light intensity, the light intensity can be read in unit of voltage from lock-in amplifier and transfer to intensity unit (W/cm^2) with constant factor.

Firstly, to measure the difference between circularly and linearly polarized light versus input intensity at different temperature, two polarizer placed before a quarter-wave plate to control the input intensity. Then modulated light was used for observing cell's circular and linear light transmissions due to the laser intensity changes with high signal to noise ratio.

IV. Results and Discussion

To investigate the creation of spin polarization in Rb vapor, the transmission of circularly and linearly polarized light through the medium as a function of input intensity is depicted in Fig. 3. In this figure, the excess in intensity of transmitted circularly polarized light with respect to linearly one, shows the amount of created spin polarization in the atomic vapor at a constant temperature (density). In addition, growth of the number of alkali atoms participating in optical pumping process, leads to enhancement of difference between circularly and linearly polarized light transmission.

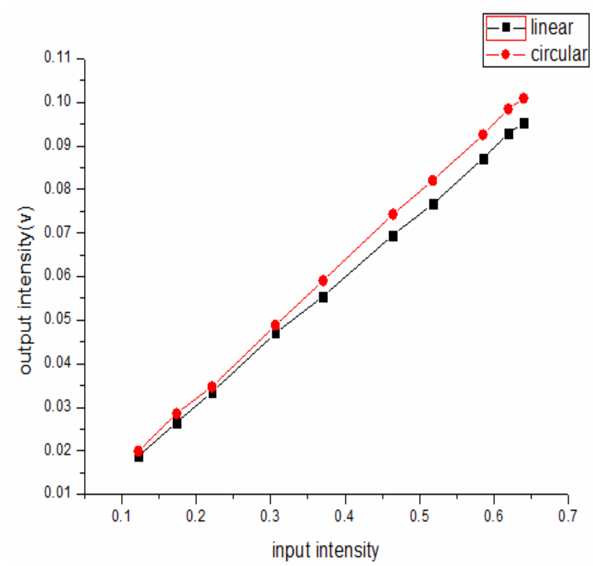

Fig. 3. Output light intensity versus input light for circularly and linearly polarized light. Difference between circular and linear light transmission levels fall below a certain threshold.

However, at low input intensity, the transmission rate of the two kinds of polarized light shows that for polarization creation, the input intensity should exceed a certain threshold. The threshold input intensity to have a significant pumping rate with respect to relaxation rate is shown in Fig. 3.

The fitting curve results from Lambert W-function and experimental data of the circularly polarized light transmission with OD=2.7 is evaluated in Fig. 4. As can be seen, the dashed line of lambert model overlaid with the experimental data (blue solid line) which shows the goodness of fitting.

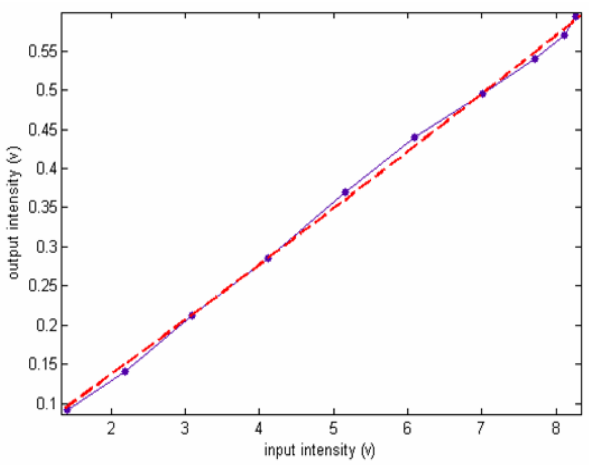

Fig. 4. Output intensity of circularly polarized light (solid curve) and theoretical fit with lambert function (Dashed line).

As shown in this figure, dashed line is a fit to a model that includes the effects of input intensity and relaxation rate in light transmutation as described in the text.

Transmitted rate of circular and linear light for different temperature is shown in Fig. 5 while the maximum error is in the order of several tenth of millivolt.

As mentioned above, the difference between transmissions of circular and linear light not only depends on polarization but also in number of polarized atoms. So the temperature increasing results in enhancement of the difference output intensity value. Moreover, temperature growth leads to increasing the threshold of input intensity.

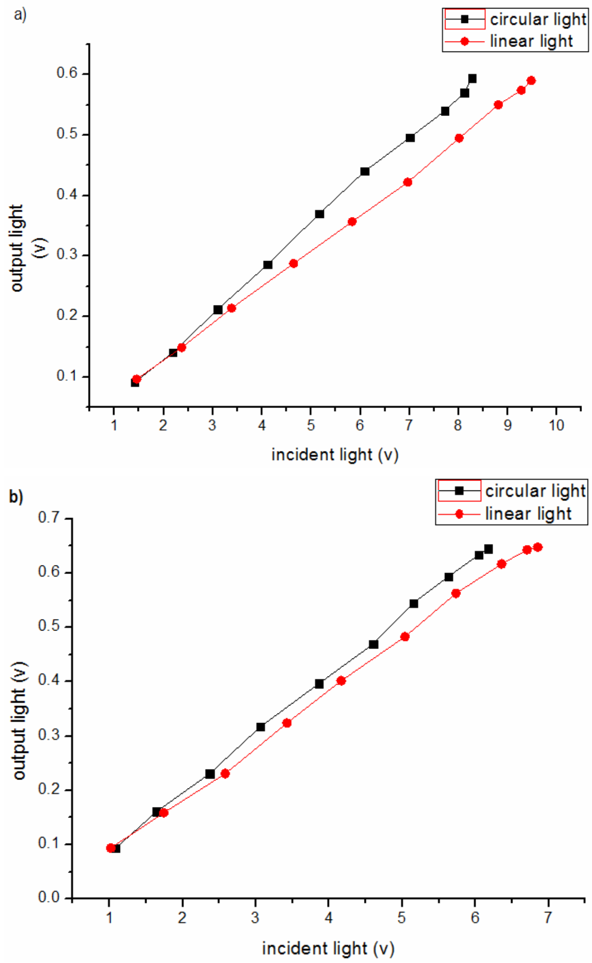

Fig. 5. Output versus input light for circularly and linearly polarized light in a) 100˚C b) 92˚C. Difference in threshold intensity for two temperature and increasing polarization with intensity is specified in this figure.

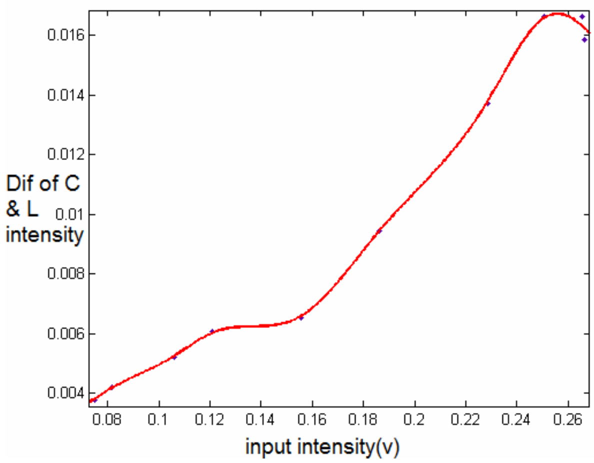

Fig. 6. Variation of the difference of transmitted circularly and linearly polarized light versus input intensity that shows the input intensity in which the relaxation rate dominates the pumping rate.

As the input intensity increases, decaying rate surpasses the pumping rate and so the difference value will decrease (Figure 4). It should be noticed that reduction of input intensity in Fig. 4 with respect to previous figures is due to the using of one filter for preventing saturation of photo detector.

Comparing the temperature dependent curves in Fig. 7 shows the fact that temperature growth not only results in increasing the difference of two kinds of polarized light output intensity but also in decreasing slope of the curves. Further reduction at higher input intensity is a direct result of more relaxation at higher temperature due to more collisions.

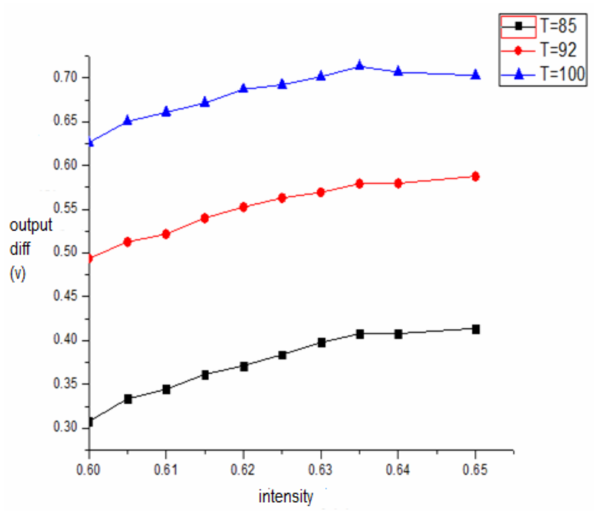

Fig. 7. Difference between circularly and linearly polarized light at different temperature.

V. Conclusion

Systematic studies on the optical pumping phenomena in alkali metals have been done. In this purpose, the effect of light polarization, pumping rate and the temperature has been investigated. Our results show that the decaying rate exceeded from the pumping rate with enhancement of the pumping intensity. Also we have difference in threshold intensity for two temperature and increasing polarization with intensity in our alkali metal's vapor. Moreover, dominance of relaxation rate due to high pumping rate because of unwanted transition has been reported.

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Samaneh Birzhandi received her Master's degree in photonics in 2014 at Shahid Beheshti University, Tehran. She worked on the project titled with 'Resonance Frequency Measurement of Rb alkali vapor in atomic

magnetometer' whose research is focused on the development of the atomic magnetometer.

Malihe Ranjbaran, received her B.Sc. in physics from Iran University of Science and Technology in 2005 and M.S. in photonics from Shahid Beheshti University in 2010. She is currently a photonics doctoral student in Shahid Beheshti University. Her research interest includes magnetic sensors and their applications.

Seyed Mohammad Hosein Khalkhali, received the Ph. D. degree in physics from physics department of Shahid Beheshti University, Iran, in 2014. He has worked on the ferroelectric and photovoltaic composite thin films.

Seyedeh Mehri Hamidi received the Ph.D. degree in photonics from Laser and Plasma Research institute, Shahid Beheshti University, Iran, in 2009. She is currently the director of magneto-plasmonic lab of Laser and Plasma research institute. She has worked on the research fields of magneto-plasmonic, nanophotonics, photonic and magneto-photonic crystals, Surface Plasmon Resonance, dielectric and magnetic waveguides and Pulsed laser deposition technique.

Mohammad Mehdi Tehranchi, received the Ph.D. degree in physics from Prokhorov General Physics Institute of the Russian Academy of Sciences (GPI RAS) in 1997. He is currently a professor of Physics and the director of magneto-photonic lab of Laser and Plasma research institute and Physics department of Shahid Beheshti University. He has worked on the research fields of magnetic materials (such as amorphous materials, multiferroic materials and magnetophotonic crystals) and magnetic effects (such as linear and nonlinear magneto-optical effects and Giant magnetoimpedance effects) which are utilized in magnetic sensors and nondestructive testing technology.