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We have observed Hanle signals and $n = 0$, $p = 1$ parametric resonances of 2^3S_1 metastable helium atoms in a discharge cell by optically pumping the helium atoms with a tunable Nd:LNA laser. These resonances were used to construct a sensitive magnetometer for the measurement of very small magnetic fields. Since magnetometer sensitivity is proportional to the slope of the parametric resonance signal (signal amplitude divided by linewidth), the slopes for single-line laser pumping were compared with similar quantities obtained from conventional helium lamp pumping. Laser pumping yielded 45 times greater slopes with comparable power requirements, thus establishing the potential for developing ultrasensitive resonance magnetometers using single-line laser pumping.

I. INTRODUCTION

Optically pumped helium magnetometers have been used since the early 1960s to measure interplanetary, planetary, and cometary magnetic fields.[1-3] These instruments use 1083-nm radiation from an rf electrodeless discharge helium lamp to optically pump a sample of 2^3S metastable helium atoms. The pumping radiation consists of the three spectral lines D_0, D_1, and D_2 around 1083 nm corresponding to the 2^3S-$2^3P_{0,1,2}$ transitions. The pumping beam both optically polarizes the sample and monitors the ensemble polarization.[4]

A rate equation analysis of the optical pumping process predicts the inefficiencies resulting when the ensemble is pumped by the natural output from a helium discharge lamp. The optical pumping signal, defined as the change in the transmitted light that occurs when the sample goes from the pumped to the unpumped condition, consists of the contributions from each of the three spectral components present in the lamp, D_0, D_1, and D_2. The D_1 and D_2 components produce signals of opposite polarity and nearly equal intensity so that their contribution to the total signal is negligible.[5] Thus, the fractional change in the transmitted light signal as the sample is pumped by a discharge lamp is typically 0.1%.

An obvious solution is to use a tunable emission-line source to avoid this cancellation. However, until recently there were no lasers available that matched the helium absorption lines at 1083 nm and could be used to test this solution. We have used the recently developed Nd-doped, $La_{1-x}Nd_xMgAl_{11}O_{19}$ crystals pumped by a high-power, cw diode laser to produce tunable emission at 1083 nm[6] in order to evaluate single-line optical pumping for use in high-sensitivity helium magnetometers. Zero-field parametric resonance techniques[7] were used to observe single-line laser pumping and compare the resonance signals with those obtained using conventional helium lamps.

We report here the initial results obtained from laser pumping in a helium magnetometer sensor using the Nd:LNA laser pumped with a high-power diode laser.

II. EXPERIMENT DESCRIPTION

It is more convenient to use parametric resonances rather than paramagnetic resonances to compare resonance signals generated by optical pumping since no rf fields perturb the optically pumped sample.[8] It does, however, require that the experiment be conducted in a region of low magnetic fields. The low-field region found inside a μ-metal room at the magnetic Test Facility at the Jet Propulsion Laboratory was used for our experiments. The shield eliminated the major part of the earth's field and residual fields can be controlled or eliminated using Helmholtz coils within the shield.

The optical pumping apparatus is shown in Fig. 1 and has been described in detail in Ref. 8. The amplitude of the resonance signal for the optically pumped metastable level was measured using the Hanle effect. With the optical pumping apparatus loctated in zero field inside the JPL Magnetic Shield a field H_0 is applied perpendicular to the beam direction. The signal along the pumping beam direction is proportional to M_x, where

$$M_x = M_0/[1 + (\omega_0\tau)^2], \quad (1)$$

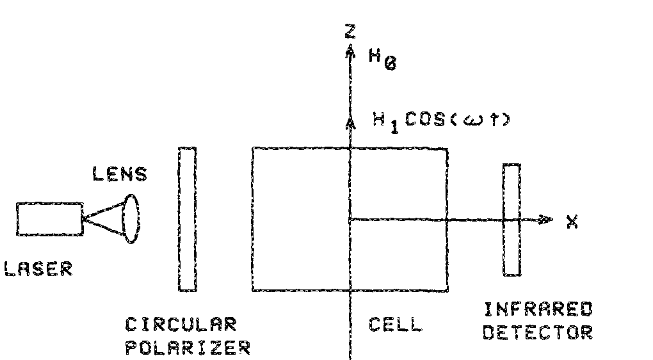

FIG. 1. Schematic representation of the helium magnetometer. The cell containing the helium gas is placed in a nominally zero magnetic field. H_0 and $H_1 \cos \omega t$ are fixed and oscillating magnetic bias fields produced by Helmholtz coils.

and M_0 is the optically induced magnetic moment in the gas, τ is the decay time of M_x, and ω_0 is the Larmor precession frequency.

Since our primary interest in the tunable solid-state laser is a radiation source for single-line optical pumping, a direct comparison of laser-pumped resonance signals and resonance signals produced by radiation from a typical rf electrodeless helium lamp of the type commonly used in helium magnetometers is desirable. The key parameter is the slope of the resonance curve at the inflection points which is proportional to the resonance amplitude divided by the linewidth. This quantity has been shown[8] to be proportional to the slope of the dispersion-shaped curve at zero field for the $n = 0$, $p = 1$ parametric resonance that is observed on the transmitted light beam as a signal proportional to

$$M_x = M_0 J_0\left(\frac{\gamma H_1}{\omega}\right) Jp\left(\frac{\gamma H_1}{\omega}\right) \frac{\omega_0 \tau}{1 + (\omega_0 \tau)^2} \sin p\omega t. \quad (2)$$

The term H_1 is the parametric drive field, which in the present H_1 experiment is a 30-kHz field, was applied perpendicular to the direction of the optical pumping beam. The resonance signal described by Eq. (2) is monitored by the infrared detector with its output directed to a lock-in amplifier tuned to 30 kHz. The lock-in output is displayed on an X-Y recorder. We have demonstrated in an earlier paper that the slope of the dispersion signal is proportional to the minimum detectable signal for a magnetometer operating on this resonance.[7,8] Maximum signal size can be obtained when the amplitude of the 30-kHz drive field is adjusted to the optimum value as determined by the Bessel function solutions to the phenomenological Block-type equation describing the $n = 0, p = 1$ parametric resonance [Eq. (2)].

III. TUNABLE SOLID-STATE LNA LASER

The essential features of the diode-pumped LNA laser are described in Ref. 9. The principal changes in the laser cavity described there and the device used in this experiment are the use of a single 1-W GaAlAs diode, model 304W from SONY Corp., a special coating on the output coupler, which obviated the need for the Lyot filter, and the use of a 50%, 0.25-mm-thick etalon for tuning. With the diode providing a pump power of about 550 mW (1.6 V, 890 mA) the LNA laser output at 1083 nm is typically several mW. The scattered light from a helium cell registered as the laser wavelength is tuned through the resonance lines as shown in Fig. 2. The resolution of the D_1 and D_2 lines shown suggests that the laser linewidth is less than the Doppler width (1.8 GHz).

The laser is easily tuned to each of the three desired transitions and is stable for long periods of time without operator intervention. With the SONY diode operating at maximum output, the laser power at the helium transition exceeded 10 mW. For the experiments described below, the diode was operated with a power input of approximately 1.5 W.

IV. EXPERIMENTAL RESULTS

We were able to observe both the Hanle signals and the $n = 0, p = 1$ parametric resonance by monitoring the pumping radiation passing through the cell. Distinct resonance curves were observed for each of the three lines D_0, D_1, and D_2 even though the D_1 and D_2 absorption line is barely resolved spectroscopically. For comparison of the laser curves with the resonance curves produced by a standard rf electrodeless discharge helium lamp used in space magnetometers, the sample of helium atoms in the standard helium cell was further restricted to a column 42 mm long and 16 mm in diameter. The sample length was set by the cell length and the sample diameter was set by the diameter of the infrared detector.

When the pumping light intensity increases, the resonance line is slightly broadened. It is therefore important to measure not only the amplitude of the resonance of the parametric resonance signal but also the slope at zero field that is effectively the resonance line amplitude divided by the linewidth.

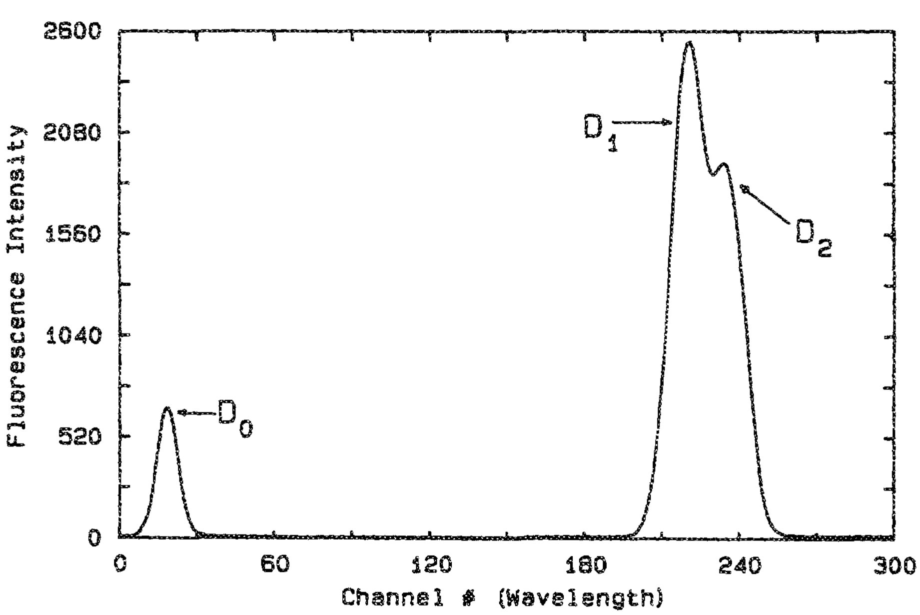

FIG. 2. Shown is the fluorescence spectrum from the He^4 metastable atoms as the laser is scanned through the 2^3S-2^3P transitions. The D_0 to D_1 separation is about 1 Å. The laser frequency is changed by tilt tuning the etalon.

A. Single-line pumping resonance signal amplitude

The amplitude of the resonance signal for the optically pumped metastable level was measured using the Hanle effect. With the optical pumping apparatus located in zero field inside the JPL Magnetic Shield, a field H_0 was applied perpendicular to the beam direction. The oscillating field at 400 Hz has a period greater than the relaxation time of the optically pumped helium. Maximum amplitude must be greater than the half-width of the resonance curve, which is 150 nT. As the field sweeps through zero field, a signal is produced at 800 Hz, which is proportional to the amplitude of the resonance curve. The optical resonance signal was detected by monitoring both the intensity of the pumping beam transmitted through the cell and by monitoring light scattered from the absorption cell in a direction parallel to the direction of the applied magnetic field.

The resonance signal was examined for each of the three helium lines generated by $2P$-$2S$ transition by etalon tuning the laser through lines at 1082.908 nm (D_0), 1083.025 nm (D_1), and 1083.034 nm (D_2). Lines D_1 and D_2 are barely resolved in the absorption cell; however, two separate resonance signals clearly separated by a null were observed. The laser linewidth is estimated to be less than 100 MHz.

For a laser power level of 1.39 mW the relative amplitudes of the Hanle signal measured in the transmission mode are: $D_0 = 0.71$, $D_1 = 1.00$, and $D_2 = 0.16$.

The same resonance was observed by monitoring resonance radiation scattered from the cell normal to the pumping beam direction along the direction of the sweep field. The resonance signal amplitudes have the following ratios: $D_0 = 0.41$, $D_1 = 1.00$, and $D_2 = 0.06$.

The D_1 line is clearly the choice for producing optical pumping signals. In this initial evaluation the D_1 signal for scattered light detection was a factor of 2.3 times larger than the signal for transmitted light detection.

B. Relative resonance slope for magnetic-field measurements

Using the parametric resonance method with a 30-KHz drive field swept about zero field, the slope for a helium lamp pumped signal was compared with the slope for the D_1 laser line, which generated the largest resonance signal. The comparison was made for a volume of the cell defined by the cell length (42 mm) and the diameter of the large-area silicon infrared detector (16 mm), which is approximately 15% of the 32-mm-diam cell's volume. The laser pumped resonance exhibited an observable light broadening; however, the signal amplitude resulted in a slope increase of 45.

V. CONCLUSIONS

We were able to experimentally demonstrate single-line pumping in the 2^3S level of helium 4 and obtain resonance signals more than an order of magnitude greater in strength than those produced by conventional helium discharge lamps. As the diode laser-pumped Nd:LNA laser was tuned through the D_0, D_1, and D_2 transitions, three distinct resonance signals were produced.

Optical broadening of the resonance line as well as the resonance signal amplitude must be taken into account in predicting potential improvements in magnetometers using laser pumping. A direct comparison of the slope of lamp-pumped signals and laser-pumped D_1 signals was made using the $n = 1, p = 1$ parametric resonance. Under otherwise identical conditions, we found the slope of the D_1 laser signal to be 45 times greater than the lamp-pumped signal.

No attempt was made to minimize the noise contributed by the solid-state laser. It can be concluded, however, that for the case of laser noise that is equal to that of current rf discharge helium lamps, laser-pumped magnetometers can be built that have sensitivities at least two orders of magnitude greater than the current instruments. Since the present day helium space magnetometers have a sensitivity of 0.01 nT, our current effort will proceed toward achieving sensitivities of 0.1 pT.

ACKNOWLEDGMENTS

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