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Optically Pumped Potassium M_x-Magnetometer of Highest Performance

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Abstract:

The most precise measurement of total magnetic field strength is provided nowadays by quantum magnetometers based on the Zeeman effect in radio-spectra of nuclei and atoms. The optically pumped potassium magnetometer based on a single resolved magnetic resonance line is considered to be the most advanced one when the highest base line stability or/and short-term sensitivity are required. The ultimate potential resolution of potassium magnetic resonance line has been found better than 10 fT/Hz$^{1/2}$ under expected base-line stability not worse than 10 pT. This highest performance can be reached using paraffin coated cells of about 1litre volume under very low pumping light intensity and potassium vapour density providing the resonance line width of about 1Hz. The base line stability can be further 10 times improved at the expense of short-term sensitivity. Both lamp pumping and laser pumping regimes have been studied. The laser pumping further improves 2-3 times both leading characteristics.

Keywords: Quantum magnetometer, Optical pumping, Magnetic resonance.

1. INTRODUCTION

Measurements of magnetic fields with highest resolution become of great interest for many branches of basic and applied research. One of the most serious problem of magnetic prospecting is the problem of Earth's magnetic field variations. These variations can be effectively suppressed in the gradiometric mode of measurement, when at least two magnetometers are used separated by a fixed base. However, to meet the requirements of modern practice the resolution of the sensors should be better than 100 fT.

This order of sensitivity and even higher (better than 10 fT/Hz$^{1/2}$ r.m.s.) can be achieved with the use of modern optically pumped magnetometers (OPM) which are the subject of this paper.

2. BASIC PRINCIPLES OF THE OPTICALLY PUMPED MAGNETOMETERS (OPM)

Below we give only a brief description of basic principles of the OPM operation. For more details see for example reviews [1] and references therein.

The atomic resonance magnetometers belong to the family of instruments based on Zeeman effect, the most known of them being proton precession magnetometer. Usually OPM measures the frequency of an induced magnetic-dipole transition between magnetic sub-levels of the ground or a metastable state of some polarized paramagnetic particles. The values of this frequency is related to scalar value of magnetic field via a relationship of intrinsically absolute nature, being dependent only on atomic and fundamental constants.

The atomic systems became competitive with condensed paramagnets after invention of Optical Pumping - Double Resonance method [2] which made it possible to achieve highest polarisation of the vapour by means of optical pumping and to monitor with ultimate efficiency the RF-induced transitions via optical channel.

Speaking of OPM, we will characterize it by resolution $\Delta H_{min}(t)$ defined as the smallest distinguishable magnetic field excursion equal to root-mean-square random deviation of the instrument readings normalized to the pass-band of 1 Hz and averaged over the time interval t. There are several sources of noise limiting the OPM sensitivity. The influence of disturbing factors can be restricted to some extent by proper choice of measuring mode or of the measuring time. To begin with, each magnetometer reveals spurious variation of reading being rotated even in perfectly uniform magnetic field. These tilt-errors are of crucial importance for on-board applications of magnetometer.

Other sources of OPM errors can be divided into two groups. The first one contains only one fundamental source of noise - the shot-noise of a primary photo-detector. This noise limits the accuracy of localizing the resonance curve center. This noise is characterized by "white" spectrum, having equal spectral density at each frequency. This noise source produces no systematic errors.

The second group includes many different sources of systematic errors. Their nature is partly connected with parametric shifts of the resonance line under the influence of a number of factors. Spectral density of the corresponding random processes decreases rapidly with frequency and becomes smaller than that of the shot noise at frequencies higher than ~ 0.001 Hz. In other words, the parametric shifts are as a rule perfectly stable within the time intervals shorter than several minutes. So, it makes sense to introduce the ultimate "short-term resolution" (or "short-term sensitivity") ΔH_{min} revealed for

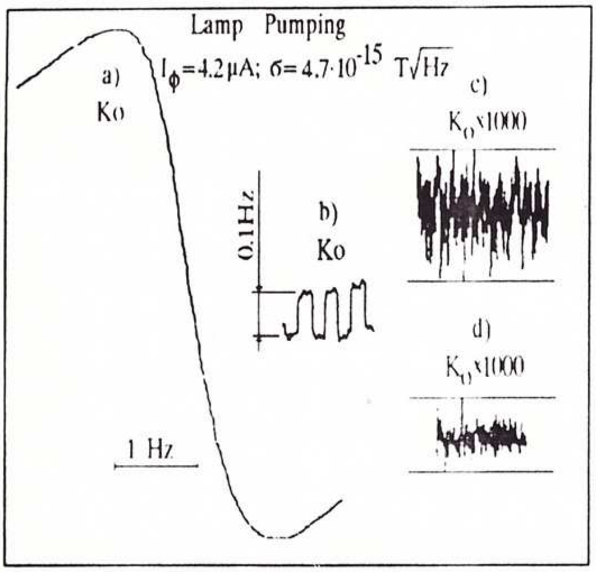

Fig. 4 The procedure of the ultimate resolution evaluation.

Hz. To estimate the intrinsic noise of this magnetometer model the RF field was switched off and amplification of the signal channel was 1000 times increased. The trace *c* gives an example of ~ 1 minute noise record. Peak-to-peak amplitude of noise is about 43 fT at integration time of 0.1s. It corresponds to the r.m.s. value of about 5.7 $fT/(Hz)^{1/2}$. The lowest noise trace *d* was recorded when the light was switched off. This record demonstrates the contribution of an excess noise from electronic equipment which is low enough, decreasing the final resolution only by the factor of 1.2 as compared with the intrinsic resolution of the resonance (4.7 $fT/Hz)^{1/2}$.

This experiment demonstrates the potential ability of atomic frequency discriminator. The practical realization of this ability is not an easy technical problem. One of the most obvious difficulties is connected with necessity to measure frequency with highest accuracy. The field resolution 10 fT corresponds to $0.7\cdot10^{-4}$ Hz frequency resolution. For Earth magnetic field it corresponds to the reference oscillator stability of around 10^{-10}. It is very high though technically reasonable stability. In any case, this problem requires a careful attention. As it is shown below, it is not fully solved yet: the highest realised resolution is about 30 fT.

The instrument realisation of commercial potassium magnetometer is made by **GEM Systems, Inc.** [1].

Fig.5 shows an example of short-term sensitivity test of a "super-gradiometer" (1997). The trace displays the difference of readings of two independent magnetometers in the natural Earth magnetic field, their sensors being separated by 2.5 m. One can see that the random magnetic field variations (with magnitude of the order of 1 nT) turned out to be highly correlated at these two points, the difference being stable within 250 fT. It means that root-mean-square deviation estimated for one instrument does not exceed 30 fT. The nature of the remaining noise is not fully clear. It may include the magnetic gradient noise as well as the counting system noise.

4. ON LASER PUMPING OF POTASSIUM

Laser pumping is widely considered as an obvious step towards more advanced OPM. These expectations are fully motivated relative to helium OPM, because only laser permits to excite selectively the single D_0 line of the triplet 2^3S_1 - $2^3P_{0,1,2}$ with a great gain in pumping efficiency [8, 9], but they are justified only partly with respect to potassium which can be perfectly pumped by single D_1 line. Computer simulation [10] predicted only a modest (not more than twice) increase of resolution due to laser pumping. But laser promises other pure technical advantage: the usage of laser allows light to be sent to and from the sensor by means of fibre light-guides of almost unlimited length with obvious merit of reducing of the equipment magnetic influence. It also opens the prospects of gradiometer network development with many sensors pumped by a single laser source.

Two main problems should be solved to provide effective laser pumping: the frequency stabilisation of laser light at the center of potassium D_1 line (769.9 nm) and suppression of the excess amplitude noise typical for laser sources.

We succeeded in solving these problems using an extended cavity diode laser with external cavity. To stabilise the laser frequency we used a narrow Doppler-free resonance of saturated absorption in an additional uncoated vapor cell ^{39}K [11, 12].

The ultimate resolution under laser pumping has been measured using the same procedure as before and was found to be about 2 $fT/Hz^{1/2}$.

In spite of this successful demonstration of Potassium laser pumping, we cannot at the moment recommend to include a laser as the regular part of Potassium OPM. The diode laser with external cavity is still rather capricious laboratory device. Though, one can soon expect appearance of much more stable laser diodes with an internal resonator like DBR-laser specially designed for Optical pumping of Helium [9][2].

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[2] We tried also a laser diode with an inner Fabry-Perot resonator and found it more stable than that with external resonator but still not enough for routine application.

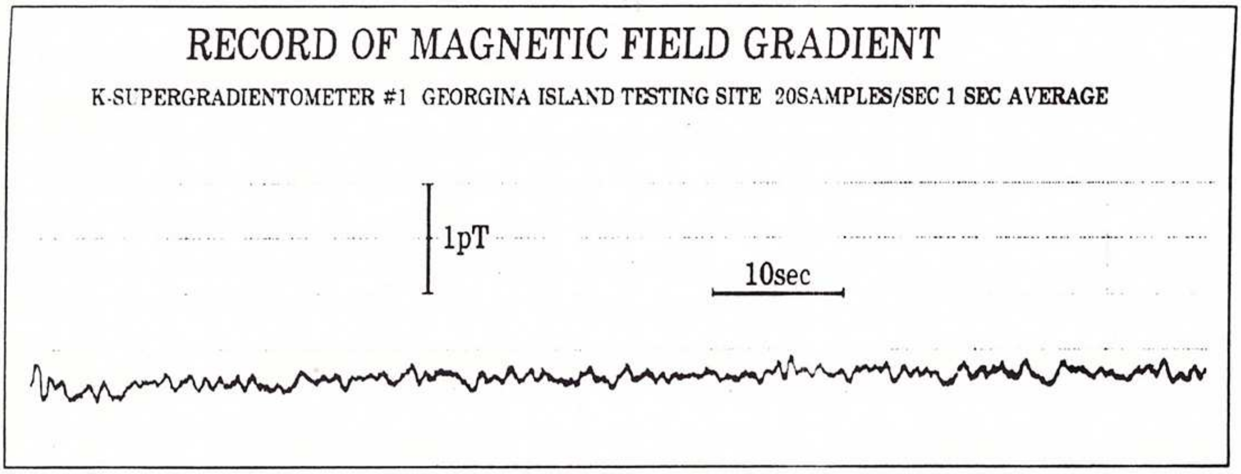

Fig. 5 An example of short-term sensitivity test made using commercial potassium "super-gradiometer" by GEM-Systems.

5. ON SYSTEMATIC ERRORS OF A „SUPER-MAGNETOMETER"

The measured ultimate short-term resolution of potassium OPM must be realised in stationary measurement mode. Any on-board application immediately meets the tilt errors problem. In fact, all systematic errors of OPM are tilt-dependent. A direct experimental investigation of the problem is very difficult at sub-picaTesla level of sensitivity, requiring extremely uniform magnetic field. But almost all constituents of the combined tilt error can be evaluated without real instrument rotation. A preliminary analysis shows that among all sources of systematic errors of Potassium OPM predominate the light induced shifts.

Pump light shifts resonance line due to two different effects [2]. The first one is the so-called optical AC Stark effect [13] proportional to the light intensity. Its frequency dependence is an odd function of the optical resonance detuning, so that pumping by a symmetrical spectral line centred at the absorption line do not produce any Stark shift. But in practice there is always some asymmetry of excitation, producing a residual shift. The sign and value of the shift depends on many factors (like a cell optical density, an operation regime of a gas discharge lamp, the pumping light direction relative to the magnetic field), being as a rule not more than ~10% of light induced contribution to the line width Γ_{light}. For the full line width ~1Hz it attains not more than 10pT.

The second contribution to the light shift is connected with so-called "coherency transfer effect" [14]. This part of the light shift is also linear to the light intensity, but it is sufficiently less and in the Earth field it amounts less than 1% of Γ_{light}.

It makes sense to mention specially the problem of „temperature shift" of K-OPM readings which is very significant for any ordinary alkali-atoms OPM. The narrow-line K-OPM is in fact almost completely free of any temperature dependence. Direct investigation of a very small residual temperature shifts is hampered by slowness of such measurements and can be masked by long-term drifts and first of all by magnetic field instability. We observed small temperature effect, using special cell (d=85 mm) with the fifty-fifty mixture of the two isotopes ^{41}K and ^{39}K. Atoms of both isotopes "feel" the same magnetic field and any temporal variation of the latter can be completely excluded. The simplest approach consists in measuring the difference $\delta\Im$ of the principal resonance frequencies of the two isotopes which is 3000 times less sensitive to magnetic field than each frequency separately. But this difference can reveal some frequency shifts not necessary equal for both isotopes. Fig.6 shows $\delta\Im$ as a function of time when the heater of the cell was turned off. During 55 minutes the temperature dropped from 45° to 30° C, which was accompanied by a decrease of resolution and by deviation of $\delta\Im$ within 0.007 Hz (~1 pT). The experiment was

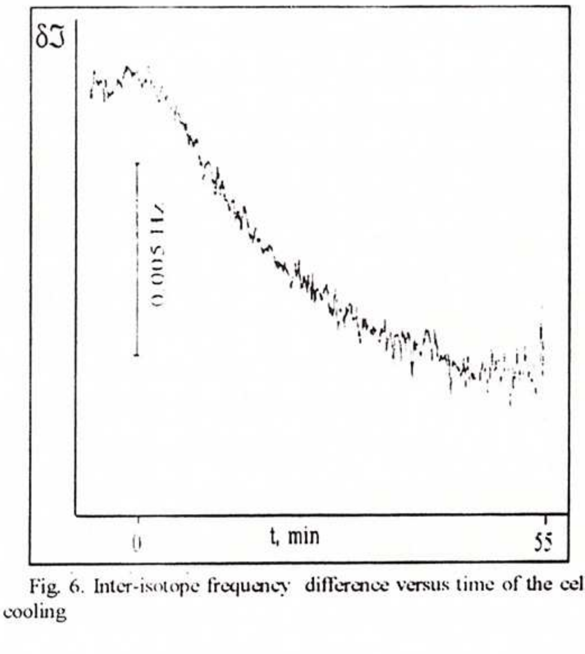

Fig. 6. Inter-isotope frequency difference versus time of the cell cooling

carried out in stabilized field, so that any magnetic origin of the shift was out of question. It should be attributed to light shifts: both isotopes were excited by light of ^{39}K lamp which is spectrally shifted by about half Doppler width relative to the centre of the absorption line of ^{41}K, producing much more pronounced AC Stark shift than in case of ^{39}K. Variation of the cell temperature was followed by variation of the average intensity and spectral profile of the pumping light which reflected in variation of $\delta\mho$. This experiment gives a right idea about limits of long-term stability of narrow-line K-OPM.

It was mentioned that for 1 Hz narrow line K-OPM the light-induced error is predominant. It can be linearly reduced by simple decreasing of the pumping light, but at the expense of much faster decrease of the short-term sensitivity. In fact, the base line stability within 1 pT could be realised under a resolution still as good as 1 pT/Hz$^{1/2}$ r.m.s. and providing that the pumping light intensity is stabilised within 10%.

As was pointed above, all systematic errors should be revealed as a long-term irreproducibility (or a slow drift) of the instrument readings and as tilt errors even for short-term observation. Being mainly stimulated by light shifts, tilt errors can not be reduced by perfect light intensity stabilisation (like long-term stability of a stationary installed instrument). But the tilt problem can be very much mitigated in gradiometer (differential) mode of measurement, using two highly identical instruments separated by a fixed base.

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7.BIOGRAFIES

E.B.Alexandrov was born in 1936 in Leningrad. Since graduating from Leningrad Politechnical institute in 1960 he has been working at State Optical Institute (St.-Petersburg, Russia). Doctor of Sciences (1966), professor, member of Russian Academy of Sciences. Scientific interests: atomic spectroscopy, optical pumping, magnetometry, laser physics.

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