COHERENT POPULATION TRAPPING EFFECT AND ITS APPLICATIONS FOR WEAK MAGNETIC AND ELECTROMAGNETIC FIELD DETECTION

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Abstract

An experimental demonstration of the possibility to use Coherent Population Trapping phenomenon occurring at Zeeman sublevels of hyperfine levels of Rb for measurement of weak magnetic and electromagnetic field is reported. For degeneracy of the ground level F_g higher that degeneracy of the excited level F_e, subnatural width dark resonances are observed irradiating Rb vapour by linearly polarized laser light. The width of the dark resonance changes significantly in the presence of several tens mG magnetic field. Under consideration is model giving quantitative dependence of resonance linewith on the value of the magnetic field. In case of $F_g \geq F_e$ and circularly polarized laser light, subnatural width bright resonances are observed in the fluorescence signal. Application of few tens mG magnetic field causes several times increase of the contrast of the bright resonances which can be used for precise magnetic field measurements. Better spatial resolution for measurement of weak magnetic field can be achieved, using methods based on CPT effect occurring at Zeeman sublevels. Simple and compact all-optical device can be built.

1. INTRODUCTION

An interesting quantum interference phenomenon takes place when an atomic system is illuminated by at least two coherent laser fields. This phenomenon is called Coherent Population Trapping (CPT) and its first observation was in 1976 by a group from Pisa [1]. In the last few years the CPT effect has attracted a lot of attention due to its increasing number of applications in the fields of laser cooling [2], lasing without inversion [3], magnetometry [4] and many others. The so called Λ scheme for CPT preparation in alkali atoms is based on coherent excitation of two ground hyperfine levels to a common excited state. Monitoring the fluorescence from the excited level by scanning the frequency of one of the fields around the two-photon Raman resonance value, a sub-natural width dip (dark line) is observed. The bottom of the dark line corresponds to the case when the frequency difference between the laser radiations matches the frequency separation of the ground states. Besides the fundamental interest, this phenomenon is attractive because of its peculiarity that a suppression of the absorption on resonant transition is present, which leads to a large increase in the nonlinear susceptibility [5]. The coherence induced between the ground hyperfine levels has been successfully used to influence a given velocity group in atomic fountain experiments [6].

Another very promising area of application of the CPT effect is in the field of building of a highly precise magnetometer using all-optical means [7]. Due to the fact that the dark resonance

lines are so narrow, a very precise determination of their position or of changes in those positions due to external influence is possible. A number of approaches have been developed utilizing optical and non-optical methods for magnetic and electromagnetic field measurements. In order to achieve high accuracy some of them process low spatial resolution (the coil magnetometer for example). Some of the possible solutions require building of a complicated semiconductor structures as in the case of Hall probe magnetometers. Very high accuracy has been achieved using superconducting quantum interference devices (SQUIDs). With such devices remarkably weak magnetic fluxes (of the order of a few tens of fT) have been measured, but with the major drawback of working at liquid He temperature.

Building of a magnetometer based on CPT effect promises to ensure high accuracy compatible with the SQUID based magnetometer, using all-optical methods and having a high spatial resolution.

2. SOME PRELIMINARY CONSIDERATIONS

A significant simplification of the experimental CPT preparation can be achieved by considering the Zeeman sublevels of a given hyperfine state as ground levels, coupled to the excited level using a single laser frequency. In this case, a linearly polarized laser beam might be assumed as a composition of two σ^+ and σ^- polarized laser fields. When these fields are tuned exactly in resonance with one of the hyperfine transitions in alkali atoms, starting from the ground state, a quantum interference on the Zeeman sublevels occurs. In order to monitor the CPT effect, the Zeeman degeneracy should be removed. Thus, by scanning the magnetic field around the zero value a narrow linewidth (below the natural linewidth) dark resonance is present in the fluorescence signal [8]. The contrast and the width of such resonances are very sensitive to the presence of stray magnetic and electromagnetic fields.

Depending on the degeneracy of the excited and the ground hyperfine levels and possible population losses, the behaviour of the CPT resonances differs. According to the selection rules, there are three possible transitions keeping the following rules: $F_e=F_g-1$; $F_e=F_g$ and $F_e=F_g+1$. The corresponding interaction schemes are given in Figure1. In the case of degeneracy of the ground level F_g higher than that of the excited level F_e (see Figure 1a) and considering σ^+, σ^- excitation for CPT preparation, a number of Λ chains can be formed, starting and ending on the ground state. As a result two orthogonal noncoupled states are formed and the system becomes a perfect trap. Thus, in absence of losses a perfect electromagnetically induced transparency of the atomic system can be observed.

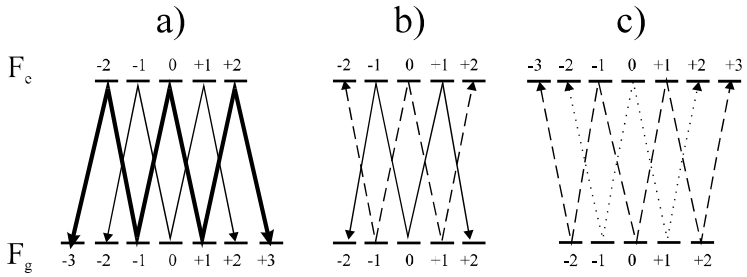

Figure 1. Examples of CPT schemes that can be established using hyperfine transitions of Rb with $F_g>F_e$ a), $F_g=F_e$ b) and $F_g<F_e$ c) when excitation with σ^+ and σ^- laser light is used.

When $F_e=F_g$ (Figure 1b), part of the ground states Zeeman sublevels contribute to the Λ chains (Figure 1b, solid lines). Part of the atoms involved in Λ chains are trapped and they do not interact with the field. The atoms which do not occupy those sublevels participate in V-shaped chains (dashed lines in Figure 1b) and can be excited by the resonant electromagnetic field. This leads to lower contrast of the observed CPT dark resonances for $F_g=F_e$ than for $F_g>F_e$, in the case of population losses.

When $F_e=F_g+1$ the atomic system might be thought as excited by V-shaped chains. Here experimentally an electromagnetically induced absorption (bright line) has been observed by scanning the frequency of one of the σ polarized fields with respect to the other [9] or by scanning the magnetic field around the zero point [10]. This peak in the fluorescence possesses also subnatural width and it is supposed that its appearance might be attributed for example to the transfer of low frequency coherence by spontaneous emission [11]. Still the exact physical reasons for this effect are under consideration.

In the present work we will present our experimental results on the influence of the magnetic and electromagnetic fields on the CPT resonances observed at the Zeeman sublevels of the hyperfine levels when illuminating a single hyperfine transition of Rb by a single frequency diode laser light (Hanle effect configuration). Our experimental investigations have been performed at the D_1 line of Rb contained in a cell. Different approaches for measurement of magnetic and electromagnetic fields will be presented and we will discuss the possibility to use them for realization of a simple and easy-to-operate magnetometers.

3. EXPERIMENTAL SETUP

The experimental set-up is shown in Figure 2. The fluorescence of the rubidium vapour (natural

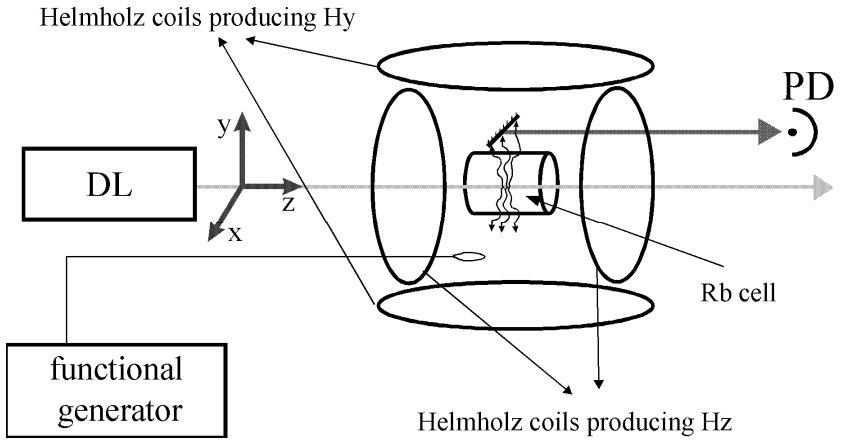

Figure 2. Experimental set-up for observation of the fluorescence signals in the vicinity of the D_1 line of Rb. Helmholz coils producing Hx are not shown in the figure.

mixture of isotopes) contained in a vacuum cell was registered. Inhomogeneous laboratory magnetic field in the Rb cell (3 cm long) was compensated using three pairs of coils (Helmholz coils) producing homogeneous magnetic fields in the x, y, and z directions. The compensating coils in the x-direction are not shown in Figure 2. The magnetic field Hz parallel to the direction of the laser beam was scanned around zero value in both directions in order to observe the CPT resonances in the fluorescence signal. The fluorescence perpendicular to the laser beam was measured.

The Rb vapour was illuminated by a laser diode (LD) emitting a single frequency with linewidth of the order of 20 MHz and output power of the order of 30 mW. By scanning the injection current it was possible to adjust the laser frequency at a given hyperfine transition. The temperature of the laser source was stabilized with precision of the order of 10^{-2}K.

It has been shown in our previous experimental investigations [10] that when a linearly polarized light illuminates Rb vapour, depending on the resonant transitions, an electromagnetically induced transparency (dark line) or absorption (bright line) can be observed when scanning the magnetic field in the direction parallel to the beam propagation. In Figure 3 the relative intensity distribution of the possible Rb transitions within the D_1 line is given. The transitions are denoted according to the discussion made above about dark lines being observed in case of $F_e \leq F_g$ and bright lines - when $F_e > F_g$.

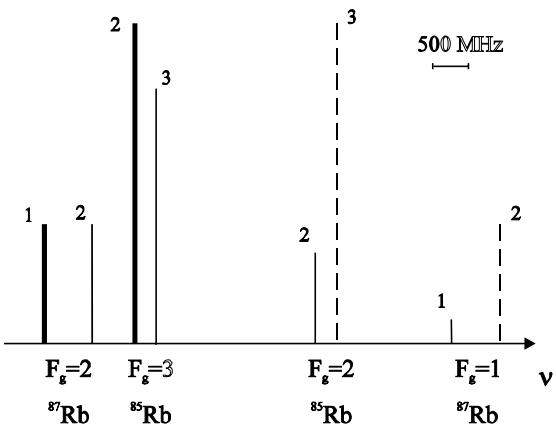

Figure 3. Relative intensity distribution of the Rb transitions in the vicinity of the D_1 line. Frequency separation between the hyperfine levels is noted in MHz. Bold lines denote transitions with $F_g>F_e$, solid line $F_g=F_e$, and dashed line $F_g<F_e$.

4. EXPERIMENTAL RESULTS AND DISCUSSION.

The behaviour of the CPT resonances depending on the laser light polarization was investigated. When a linearly polarized light illuminates the transitions starting from F_g=2 of ^{87}Rb, according to our previous discussion (see Figure 1 and Figure 3) a CPT dark resonance is expected. Curve 5 in Figure 4 represents a typical CPT dark resonance. However, it can be seen that when the polarization becomes elliptical, the shape of the resonance changes to a dispersive one (curves 3 and 4). A complete change in the resonance sign was registered when the light polarization approaches circular (curve 1 in Figure 4). Our experimental observation has shown that in case of F_g=F_e, the dark resonance transforms into a bright one when the beam polarization is changed from linear to circular.

Some qualitative explanations of this behaviour can be deduced from the theoretical work [12], where it has been shown that the shape and the sign of the CPT resonances differ when the coupling of the two arms of the well known Λ scheme is different. In case of equal intensity of the two laser fields always dark resonance (dip) in the fluorescence is observed. However, if the intensity of one field is significantly larger than that of the other field, bright resonance (peak) in the fluorescence is obtained.

The same effect might be transferred to the case when a CPT resonance on a single hyperfine transition is considered, observed when a significant difference in the intensity of the σ^+ and σ^- polarized light is present. The physical reason for this change in the shape and the sign of the resonance is due to the fact that the Zeeman sublevels are unequally depleted by the σ^+ and σ^- polarized light and at the same time they are equally populated by the spontaneous decay. Close to the two photon Raman resonance condition a transfer of the population from the more to the less

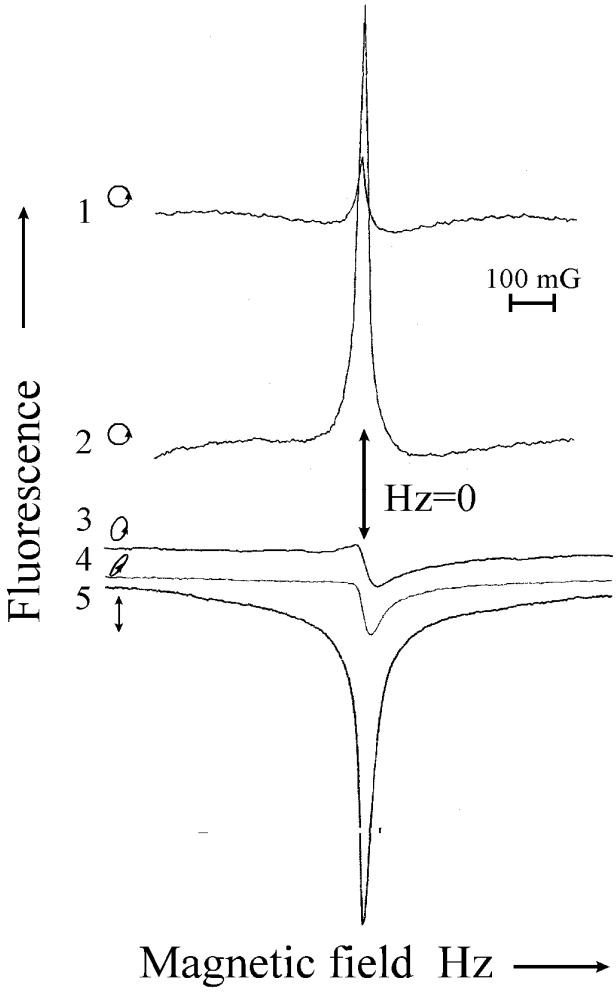

Figure 4 Fluorescence signals depending on the magnetic field (Hz) when the laser source frequency matches the maximum fluorescence arising from the F_g=2 of ^{87}Rb. Curves 1, 3, 4, and 5, are taken when the stray magnetic field is compensated. Curve 2 is taken when Hx=20 mG is applied. The laser light polarization is indicated in each curve.

populated sublevels occurs. This increase in the population of given sublevels leads to change in the shape of the resonance and at a certain level of difference between the coupling of σ^+ and σ^- fields - to inversion of the sign of the resonance.

When a constant magnetic field Hx is applied in the direction perpendicular to the beam propagation, an increase in the contrast of the bright resonance occurs. Resonant excitation by a circularly polarized light leads to predominant orientation of the atomic ensemble angular momentum. Presence of a small magnetic field perpendicular to the direction of the orientation leads to reorientation and consequently to population of previously depleted Zeeman sublevels. Thus an increase in the fluorescence signal can be observed. This redistribution of the population depends on the strength of the applied magnetic field and can be used for determination of its magnitude. It should be pointed out that in case of bright line a dramatic change in the contrast is observed (compare curves 1 and 2) when a very weak magnetic field is applied (Hx=20 mG).

Hence, observation of the amplitude of the bright resonances (for F_g=F_e) could be a very sensitive measure of weak magnetic fields perpendicular to the laser beam.

A well-known optical method for magnetic field measurement is based on optical pumping of alkali vapour by circularly polarized laser beam and application of rf field with variable frequency f. When the frequency f equals the Zeeman splitting of the ground-state hyperfine level caused by the measured magnetic field, rf transitions between the Zeeman sublevels occur, which are observed as increased absorption of the laser field (a peak in the absorption or in the fluorescence).

In our experiment we use rf excitation perpendicular to the laser beam propagation (for circularly polarized light) in order to make absolute scale for Hz. If Hz is scanned around zero value, the rf excitation induces two resonances in the fluorescence for Zeeman splitting equal to the rf transition frequency (Figure 5, curve 1). In this case rf resonance occurs for f=101 kHz. The

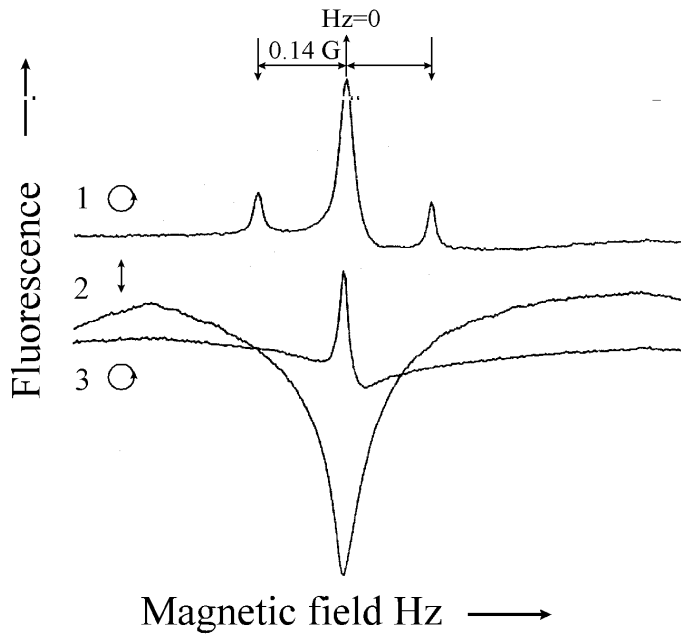

Figure 5. Fluorescence signals depending on the magnetic field when laser frequency reaches the transitions starting from F_g=2 of the ^{87}Rb. Curve 2 is taken when the laser source is linearly polarized, curve 3 when it is circularly polarized and curve 1 when rf perturbation with frequency f=101 kHz is applied.

value of the magnetic field Hz is determined by the simple expressions: f [MHz]=0.7×H [G] in case of ^{87}Rb and f [MHz]=0.47×H [G] in case of ^{85}Rb. For our case (Figure 5, curve 1), the maximum of the central peak is at Hz=0 and the two smaller peaks maxima appear at Hz=0.14 G. In Figure 5 (curve 2) the fluorescence signal arising when linearly polarized light illuminates the transitions starting from the F_g=2 of the ^{87}Rb is shown. In this case as is expected, a dark line is observed when scanning the Hz magnetic field around the zero value. The sign of the resonance changes when the

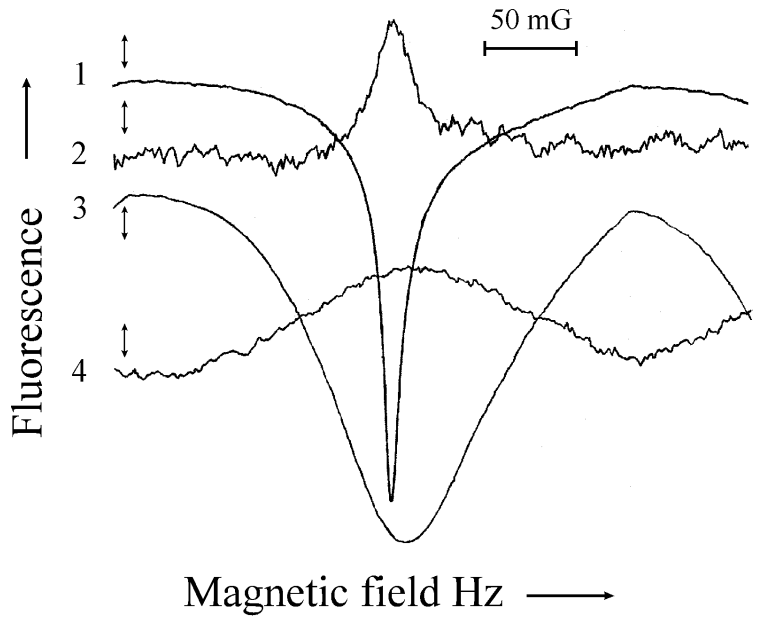

Figure 6. Fluorescence signals depending on the magnetic field when a linearly polarized laser frequency reaches the transitions starting from F_g=2 of the ^{85}Rb curves 2 and 4 and from F_g=2 of the ^{87}Rb curves 1 and 3. Curves 3 and 4 are taken when an additional magnetic field is applied.

polarization becomes circular (curve 3). The accurate magnetic (Hz) field scale is used to determine the linewidth of the dark and bright resonances.

The possibility to use the CPT resonance profiles for determination of the presence of a magnetic field perpendicular to the laser beam by considering the linewidth of the subnatural width resonances is shown in Figure 6. This influence was investigated for both cases - when a dark line is observed (curve 1 Figure 6) and for a bright line (curve 2). All the curves are taken by scanning the Hz. A permanent magnetic field Hx was introduced with a strength of 100 mG. As a consequence an increase in the linewidth of the CPT resonances was registered, where the FWHM in case of dark resonance was of the order of 100 mG (curve 3) and 130 mG (curve 4) in case of bright line. Theoretical investigations are in progress to build a model giving the dependence of the resonance linewidth on the value of the magnetic field. Using the CPT resonances broadening for determination of the value of the magnetic field has the advantage that no additional rf field needs to be used, which influences the measured one.

Broadening of the dark resonance is observed also when electromagnetic field in the kHz range is applied to the Rb cell perpendicular to the laser beam propagation. Experimental investigations are being carried out for investigation of the possibility to use CPT resonances for determination of the amplitude and the frequency of stray electromagnetic fields.

5. CONCLUSION

The possibility to use the effect of coherent population trapping occurring at the Zeeman sublevels of a given hyperfine transition of Rb for measurement of weak magnetic and electromagnetic fields has been demonstrated experimentally. The change in the contrast and linewidth of the subnatural width resonances could be used to determine the value of a present constant magnetic field. A broadening of these resonances occurs when an rf electromagnetic field is applied. Under theoretical estimation is the exact relation giving the absolute value of the magnetic field on the basis of change in the resonance contrast and linewidth.

Building of a magnetometer based on CPT resonance at the Zeeman sublevels possesses a number of practical advantages. A high spatial resolution could be achieved using an all-optical device. A very small, compact and easy-to-operate system could be built, which will facilitate the isolation of the system from the influence of external stray magnetic fields.

ACKNOWLEDGEMENTS

The authors wish to express their gratitude to Prof. E. Arimondo for his help in this investigation. This work was supported in part by the Bulgarian National Science Fund (grant V-F-3). S. C. thanks NATO and CNR for the financial support (NATO - CNR Senior Guest Fellowships Programme).

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