Pergamon

Prog. Crystal Growth and Charact. Vol. 33, pp. 413–417, 1996

0960-8974/96 $32.00

SPECTROSCOPIC PROPERTIES OF COLD RUBIDIUM ATOMS IN A MAGNETO-OPTIC TRAP

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Abstract

We investigate spectroscopic properties of cold ^{85}Rb atoms in a magneto-optic trap. Both the transmission and the reflection spectra of the trapped atoms are recorded. The dressed-atom picture and the density-matrix formalism are appropriately used to explain the absorption profile around the F=3-F'=2,3,4 and F=2-F'=1 transitions. Around the trapping laser frequency, phase-conjugation signals are observed (reflectivity is about 10^{-4}), which are attributed to the degenerate and nearly-degenerate four-wave mixing.

1. INTRODUCTION

In the past several years, techniques for laser cooling and trapping of neutral atoms have been developed at a phenomenal pace [1]. In particular, a magneto-optic trap (MOT) in a vapor cell [2] has provided many researchers with a simple and economic way of preparing a dense (about 10^{11}/cm^3) sample of ultracold (below 1mK) atoms, which has been used for a variety of experiments [1].

Thanks to the very small Doppler broadening and the high optical density, such an atomic sample in an MOT is expected to show a large, resonantly enhanced third-order nonlinearity at a relatively low laser intensity. Indeed it has been demonstrated that the probe laser beam through the cloud of trapped atoms is amplified due to the two- or three-photon Raman process stimulated by the trapping laser [3].

Motivated by these considerations, we perform the spectroscopy of trapped ^{85}Rb atoms to observe various kinds of nonlinear effects. We observe the transmission spectrum around the F=3-F'=2,3,4 transitions significantly modified by the trapping laser. A dressed-atom picture is used to explain the spectrum (Sec. **2.1**). We also observe the transmission spectra around the F=2-F'=1 transition to which the repumping laser is tuned with various detunings. The observed spectral features are compared with the calculations using the density-matrix formalism (Sec. **2.2**). Furthermore, we observe the probe reflection spectrum around F=3-F'=4 transition, namely *the phase-conjugation spectrum* around the trapping laser frequency. There are several peaks on the spectrum, which are associated to the degenerate and nearly-degenerate four-wave mixing (Sec. **2.3**).

2. EXPERIMENTAL RESULTS AND DISCUSSION

We construct a conventional MOT of Rb atoms in a vapor cell [2]. The trapping beams are 8mm in diameter, having an intensity of 10mW/cm^2 per each beam. The repumping beams are combined with all the trapping beams and have almost the same diameter and intensity as the trapping beams. The additional probe beam is focused through the trap (2mm in diameter) with a waist of 0.1mm and both the transmission and the reflection are detected by photodiodes. The probe beam makes an angle of 45° with the x- or y- trapping beams and its polarization is linear orthogonal to the x-y plane. Each of the trapping, repumping, and probe beams is derived from an individual external-cavity laser diode having the linewidth of about 1MHz.

2.1. The Transmission Spectrum around the F=3-F'=2,3,4 Transitions

The trapping laser is tuned 18MHz (a few natural linewidths) below the F=3-F'=4 transition. In such a condition, trapped atoms are strongly coupled with the trapping laser field, and a dressed-atom picture is convenient for considering the static properties of an atom such as absorption (transmission) spectrum [4]. Fig. 1(a) shows the probe transmission spectrum around the F=3-F'=2,3,4 transitions. Several additional peaks (**b**, **d**, and **f**) are clearly seen on the spectrum besides three large absorption lines (labeled **a**, **c**, and **e**) for F=3-F'=2,3,4 transitions. These spectral features can be qualitatively explained with a dressed-atom picture as illustrated in Fig. 1(b), where dipole allowed transitions are indicated by wavy arrows. The peak **a**,

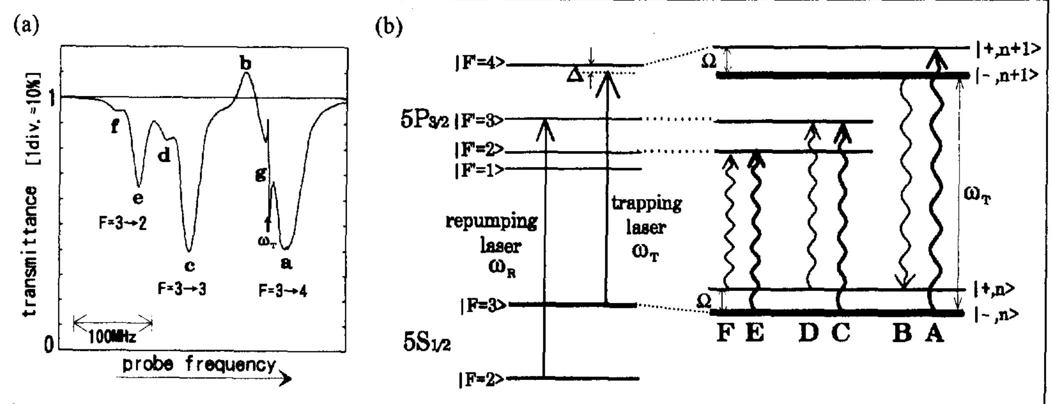

Fig. 1. (a)The transmission spectrum around F=3-F'=2,3,4 transitions. (b) Explanation of the spectral features with a dressed-atom picture. Ω is the generalized Rabi frequency defined as $\Omega^2=\Delta^2+\Omega_0^2$, where Δ is the detuning of the trapping laser ω_T from the F=3-F'=4 transition and Ω_0 is resonant Rabi frequency of trapping laser. The lines representing energy levels have widths indicating their relative population.

b,⋯, **f** in Fig. 1(a) are attributable to the transitions **A**, **B**,⋯, **F** in Fig. 1(b), respectively. It is easily understood that the transition **B** result in probe gain **b** at $\omega_T-\Omega$ because the upper level is more populated than the lower level [3,4]. This gain is alternatively called the three-photon Raman gain. The pair of absorption lines **c** and **d** (or **e** and **f**) separated by Ω is known as the Autler-Townes doublet [4]. The dispersionlike lineshape labeled **g** results from the stimulated Raman processes between ground-state Zeeman sublevels, allowing us to determine the position of ω_T [3].

2.2. The Transmission Spectra around the F=2-F'=1 Transition

In a usual MOT, the repumping laser is tuned to the F=2-F'=3 transition to prevent the atoms from accumulating in F=2 ground state which is out of the trapping cycle. However, we tune the repumping laser near the F=2-F'=1 transition to increase the population of F=2 ground state and to perform *pump-probe spectroscopy* on this transition using the repumping laser as the *pump* field. Even in this experimental condition, the repumping effect is enough to preserve the trap. Fig. 2(a) shows the probe transmission spectra around the F=2-F'=1 transition with the positions of the repumping laser frequencies ω_R indicated by arrows. Narrow features are seen just around ω_R on the spectra: the dispersionlike curve for $\Delta>0$ or $\Delta<0$, and the dip for $\Delta=0$ (Δ is the repumping laser detuning from the F=2-F'=1 transition). This dip is called the coherent-dip [5]. The dressed-atom picture cannot be applied to cases where pump-probe detunings are smaller than or comparable to the natural width of the atomic transition (about 5MHz for our experiment) [4]. Hence, for explaining the observed spectral features, we calculate the probe transmission spectra by using the density-matrix formalism of a two-level system with a pump field [6]. Fig. 2(b) shows the results of the calculation, which reproduces the observed spectral features

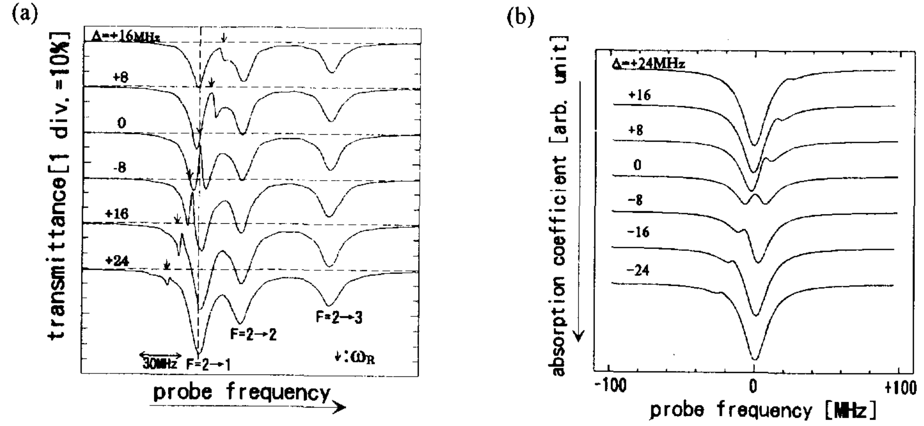

Fig. 2. (a) The transmission spectra around F=2-F'=1 transition for various repumping laser detunings. (b) Calculated spectra corresponding to the experimental results by using the density-matrix formalism of a two-level system.

in Fig. 2(a) qualitatively. However, the observed features are, on the whole, much sharper than those calculated. In particular, such a narrow dip observed for $\Delta=0$ is never reproduced from the calculation within the approximation of a simple two-level system with a linearly polarized traveling pump field. The calculations taking account of the effect of Zeeman sublevels, counter-propagating pump beams, and polarization will be reported in the future

2.3. The Phase-Conjugation Spectrum

In a conventional MOT, there are three pairs of counterpropagating, near-resonant trapping laser beams. Hence one would readily expect to observe a phase-conjugation signal with the trapped atoms using the trapping beams as pump beams. Actually, such a phase-conjugation signal has already been observed for Cs [6]. We show our result of phase-conjugation spectrum around the trapping laser frequency ω_T in Fig. 3(a) (lower trace). The transmission spectrum is simultaneously recorded (upper trace) and is used to determine the position of ω_T and the amount of Ω of the trapping laser field (see Sec. **2.1**). There are five peaks on the phase-conjugation spectrum: the narrow (~3MHz) peak at ω_T and the four sidebands with relatively broad linewidths around $\omega_T \pm \Omega$. This symmetric, five-peaked spectrum had been predicted for a two-level system [7] and observed in a sodium vapor [8]. According to Ref. [7], the central sharp peak results from the degenerate four-wave mixing (FWM), while the sidebands result from the nearly-degenerate FWM which is enhanced by the ac-Stark effect. The schemes for degenerate and nearly-degenerate FWM are illustrated respectively in the upper and lower part of Fig. 3(b), where $\omega_2=\omega_T$ in the case of our experiment. Indeed, it is observed that the sidebands shift away from the central peak as the detuning of trapping laser increases. The observed width of the central peak is

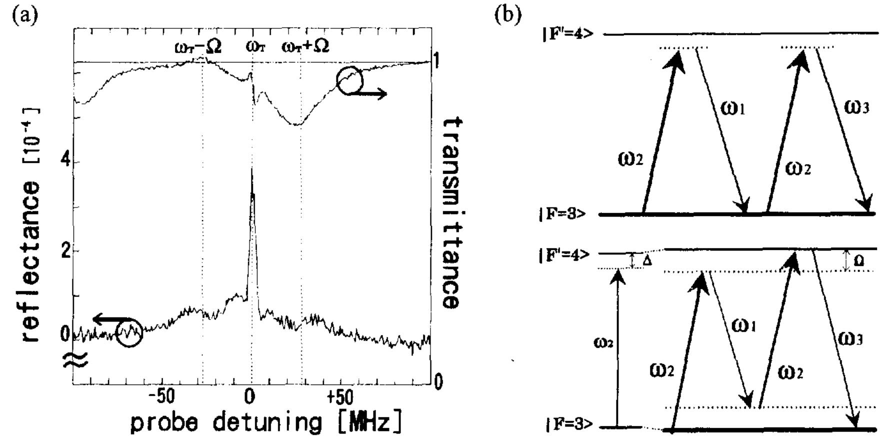

Fig. 3. (a) The phase-conjugation spectrum (upper trace) and the transmission spectrum (lower trace) around the trapping laser frequency. (b) The schemes for degenerate (upper part) and nearly-degenerate (lower part) four-wave mixing.

narrower than the natural width of F=3-F'=4 transition (~5MHz), which has also been observed by other groups [6,9]. This narrow peak seems to have its origin in the population difference between ground-state Zeeman sublevels [3,6]. Further analysis concerning whole spectral features will be reported in the future.

3. CONCLUSION

We investigated the nonlinear response of cold Rb atoms in an MOT by the spectroscopic methods. We observed various kinds of nonlinear effects on the transmission spectra such as the three-photon Raman gain, the Autler-Townes doublet, and the coherent-dip. These are the consequences of strong coupling of trapped atoms to the trapping and repumping laser field. The phase-conjugation signals associated with the degenerate and nearly-degenerate FWM were observed, from which it would be possible to obtain the dynamics of the atoms in a trap. Furthermore, the narrow spectral feature of the phase-conjugation could be applied to construct an extremely narrowband optical filter.

This work is financially supported by a Grant-in-Aid for Scientific Research from the Ministry of Education, Science and Culture of Japan and by the Sumitomo Foundation.

REFERENCES

[1] See, *e.g.*, "*Cooling and Trapping of Neutral Atoms* ", edited by H. Metcalt and P. Straten [Phys. Rep. **244**, 203-286 (1994)].
[2] C. Monroe, W. Swann, H. Robinson, and C. Wieman, Phys. Rev. Lett. **59**, 2631 (1990).
[3] J. W. R. Tobasa, G. Chen, Z. Hu, R. B. Lee, and H. J. Kimble, Phys. Rev. Lett. **25**, 3245 (1991); D. Grison, B. Lounis, C. Salomon, J. Y. Courtois and G. Grynberg, Europhys. Lett. **15** (2), 149 (1991).
[4] C. Cohen-Tannoudji, J. Dupont-Rot, and G. Grynberg: *Atom-Photon Interactions* (John Wiley & Sons, 1992), Chap. VI.
[5] B. R. Mollow, Phys. Rev. **A5**, 2217 (1972); P. Meystre, M. Sargent III: *Elements of Quantum Optics 2nd Edition* (Springer-Verlag, 1991), Chap. 8.
[6] L. Hilico, P. Verkerk, and G. Grynberg, C.R. Acad. Sci. Paris, **315**, **II**, 285 (1992).
[7] D. J. Harter, and R. W. Boyd, IEEE J. Quantum Electron. **QE-16**, 1126 (1980).
[8] D. G. Steel and R. C. Lind, Opt. Lett. **6**, 587 (1981).
[9] private communication with Dr. Mitsunaga at NTT Basic Research Laboratories.