PHYSICAL REVIEW A VOLUME 59, NUMBER 1 JANUARY 1999

Coherent microwave emission in cesium under coherent population trapping

Aldo Godone, Filippo Levi, and Jacques Vanier*
Istituto Elettrotecnico Nazionale, Torino, Italy

(Received 27 October 1997; revised manuscript received 26 May 1998)

Microwave emission has been observed at the ground-state hyperfine transition frequency of a cesium atomic vapor driven into a nonabsorbing state by means of coherent population trapping. The coherent emission observed is due to the oscillating magnetization generated by the coherence, which is induced between the ground-state hyperfine levels when they are coupled to an excited state by means of two laser radiations via a Λ scheme. The experiments described were done in a quartz cell containing buffer gases such as neon and nitrogen, reducing the linewidth through the Dicke effect. The cell was placed inside a microwave cavity tuned at 9.2 GHz, the ground-state hyperfine frequency of cesium, and a power output of the order of 100 fW was measured in the case where nitrogen was used as the buffer gas. [S1050-2947(99)51001-9]

PACS number(s): 42.50.Md, 32.10.Fn, 32.30.Bv, 42.50.Gy

Coherent population trapping (CPT), originally described by Alzetta *et al.* [1], is a quantum-mechanical effect that has drawn attention recently in view of applications in fields such as atom cooling [2], magnetometry [3], lasing without inversion [4], and frequency standards [5–7]. In the case of alkali-metal atoms, CPT may be readily observed through coupling of the two ground-state hyperfine levels to a common excited state, such as a *P* state, via two laser radiations in a Λ configuration. When the frequency difference between the two radiations is equal to the ground-state hyperfine frequency, the atoms can no longer absorb light. The atoms are trapped in the ground state and a so-called dark line is created in the fluorescence spectrum. Doppler broadening of this dark line may be avoided by means of the Dicke effect through the use of buffer gases [5]. For example, a linewidth as narrow as 50 Hz in cesium at 9.2 GHz has been reported with neon as a buffer gas [7,8]. Furthermore, as pointed out by Orriols [9], in view of the intrinsic properties of CPT, the dark line itself is not subject to a light-shift effect [10] of the type encountered in the case of intensity optical pumping with one laser. These two characteristics make CPT very interesting in the field of atomic frequency standards.

In the present work we are interested in the coherence induced in the ground state by the CPT phenomenon and its associated magnetization that is expected to radiate at the hyperfine frequency. We report the observation of this coherent emission in a microwave cavity with a *Q* of 3000 tuned at the hyperfine frequency of 9.2 GHz. This process does not require a population inversion as in the case of the standard maser approach where oscillation is achieved when the threshold gain for oscillation is reached through a significant population inversion and a high-cavity quality factor. As is shown by theoretical analysis [9,11], CPT traps essentially all atoms in the ground state. Furthermore, in the simple three-level system studied in these articles, both ground-state levels remain equally populated when the two laser radiations have equal intensities. One can thus say that the coherent microwave emission takes place without population inversion, although it is not essential to the phenomenon reported here. The effect could also be interpreted as a stimulated coherent Raman emission at the ground-state hyperfine frequency. By extension, the resulting device, using a microwave cavity that provides gain through stimulated emission, may be said to belong to the group of atomic oscillating devices such as the hydrogen and rubidium masers [12].

We consider the three-level scheme shown in Fig. 1 as representing the two hyperfine ground levels selected and the excited $P_{3/2}$ state of the cesium atom. This is a rather simplified model of the actual physical situation. However, due to the applied magnetic field, the various ground-state Zeeman hyperfine levels are all well resolved. Of the several three-level schemes that can be excited, only one is selected by choosing the appropriate difference angular frequency $(\omega_2-\omega_1)$. It is found that this simple model is sufficient to explain the essentials of the experimental observations reported below. Although the following discussion is applied to the cesium atom, it can also be extended to the general case of Λ transitions in alkali-metal atoms. In this figure γ_1 and γ_2 are the population and coherence relaxation rates, respectively, in the ground state and Γ^* is the decay rate of the excited *P* state, including spontaneous emission and the decay caused by the collisions with the buffer-gas atoms. In our experiments we have used both neon and nitrogen as buffer gases, at pressures of 37 and 19 Torr, respectively. We have evaluated $\Gamma^*/2\pi$ to be of the order of 600–700 MHz for these buffer gases [7]. Nitrogen has the added property of

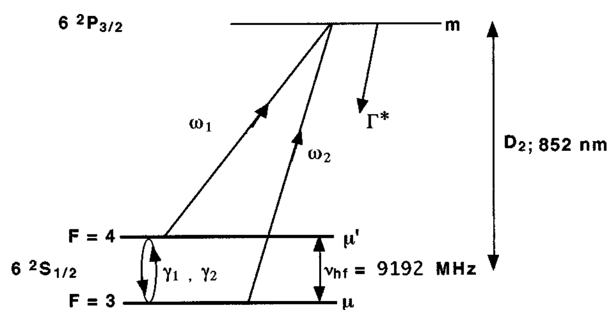

FIG. 1. Three-level system considered in the present work. Although the diagram addresses the case of cesium, it can also be applied to the case of the other alkali-metal atoms.

*Present address: Département de Physique, Université de Montréal, Montréal, Canada.

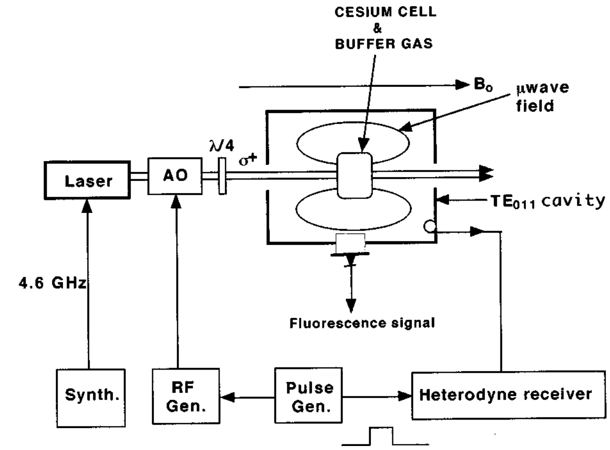

FIG. 2. Experimental setup used for the observation of either the dark line or the coherent emission. The acousto-optic modulator (AO) is used solely to modulate the laser-beam intensity and create the laser pulses for transient studies.

quenching the scattered optical radiation from the atomic ensemble [13]. This effect has the advantage of avoiding optical pumping of the atomic ensemble by the scattered radiation, which would tend to destroy the coherence in the ensemble. The relaxation rate γ_2 is controlled by diffusion to the walls of the cell, collisions with the buffer gas, and the spin-exchange collision rate, which is a function of the density of cesium atoms [12]. At the temperatures of operation in our experiments, the cesium density was sufficiently high for spin exchange to be the determinant contributor to γ_2. In our case the two coherent laser radiations at ω_1 and ω_2 are sidebands created by modulating the frequency of a laser tuned to the $S_{1/2}$ to $P_{3/2}$ transition (D_2 line at 852 nm).

A simple perturbation analysis provides the essential theoretical background for analyzing the experimental data reported in this Rapid Communication [11]. The main results are that when the two sidebands have equal intensities and are resonant with the two transitions, as shown in Fig. 1, the optical excitations interfere and all atoms are trapped in the ground state with both levels μ and μ' having equal populations. The process furthermore creates a strong coherence between the two levels μ and μ' that manifests itself as a macroscopic magnetization that oscillates at the frequency $\omega_2-\omega_1$ [12]. When the ensemble is placed in a cavity tuned to the frequency $\omega_2-\omega_1$, as illustrated in Fig. 2, coupling between the cavity mode and this magnetization takes place and the ensemble emits energy at the rate

$$P_{at}=\tfrac{1}{2}\hbar\omega_{\mu'\mu}Nk(4\delta_{\mu\mu'}\delta_{\mu'\mu}), \quad (1)$$

where $\delta_{\mu\mu'}$ is the off-diagonal element of the density matrix and represents the ground-state hyperfine coherence existing in the ensemble ($\delta_{\mu'\mu}=\delta_{\mu\mu'}{}^*$). The term k is defined as

$$k=NQ_L\eta\mu_0\mu_B^2/\hbar V_c. \quad (2)$$

In these expressions, N is the total number of atoms contributing to the CPT, η is the filling factor, Q_L is the loaded cavity quality factor, V_C is the cavity volume, μ_0 is the permeability of free space, and μ_B stands for Bohr magneton; k is in units of s^{-1}. When the laser radiation is applied under the form of a pulse, the hyperfine coherence builds up at the rate $\gamma_2+\omega_R^2/\Gamma^*$ at the beginning of the pulse. The result is

$$\delta_{\mu\mu'}\delta_{\mu'\mu}=\frac{(\omega_R^2/2\Gamma^*)^2}{(\gamma_2+\omega_R^2/\Gamma^*)^2}(1-e^{-(\gamma_2+\omega_R^2/\Gamma^*)t})^2, \quad (3)$$

where ω_R is the Rabi frequency of the optical excitation associated with the sidebands. The power, as given by Eq. (1), builds up with the coherence. For a long pulse, where $\gamma_2 t\gg 1$, steady state is reached and the system emits continuously; $\delta_{\mu\mu'}\delta_{\mu'\mu}$ is given by the first part of Eq. (3). In such a case, calculations show that the emission linewidth is equal to $(\gamma_2+\omega_R^2/\Gamma^*)/\pi$. After the laser pulse, the system evolves freely in the cavity at the hyperfine frequency $\omega_{\mu'\mu}$. The power output may be calculated in a self-consistent approach by equating the power emitted by the atoms to the power dissipated in the cavity [14,15]. However, in the present case, the cavity Q is relatively low and the amplitude of the rf field in the cavity is weak. There is no radiation damping [14]. The power is given by

$$P_{diss}=\tfrac{1}{2}\hbar\omega_{\mu'\mu}Nke^{-2\gamma_2\tau}(4\delta_{\mu\mu'}\delta_{\mu'\mu}), \quad (4)$$

where τ is measured from the end of the light pulse and where $\delta_{\mu\mu'}\delta_{\mu'\mu}$ is given by the steady-state value reached at the end of the laser pulse as given by Eq. (3) when $\gamma_2 t\gg 1$. After the laser pulse the power decays at the rate $2\gamma_2$.

Although the cesium atom has many more energy levels than the three-level system studied, the above analysis provides an essential basis for the interpretation of the experimental observations reported below. In fact, the experiments were done in a magnetic field larger than 10^{-5} T (100 mG). In such a field all ground levels are well separated relative to their width and the hyperfine resonance lines are all well resolved. However, the laser, having a broad spectrum, excites all transitions from the ground state. In practice, in the experimental setup used, the CPT phenomenon is also observed for all $\Delta m_F=0$ transitions of the ground state. The contrast (2–3%) and relative amplitude of the observed dark lines agree, within experimental error, with calculations made with the help of Clebsch-Gordan coefficients [11]. From this observation, it is expected that the distribution of populations among the ground-state energy levels is not much perturbed from equilibrium by the excitation process and the assumption relative to the approximate equality of ground-level populations should thus be valid for each individual three-level system, giving rise to a dark line.

The two laser radiations are provided by the first sidebands of a frequency-modulated semiconductor laser diode [16,17]. The modulation signal at the angular frequency $\omega_m \sim(\omega_{\mu\mu'}/2)$ is added directly to the laser injection current. It is possible to obtain a frequency modulation index $\mu_f\sim 1$. This technique ensures a very high correlation between the two optical radiations used in the Λ scheme and avoids any divergence often encountered when two independent laser beams are used. The laser diode is coupled to an external cavity (Littrow configuration) for tuning purposes. The laser sidebands, depending on actual operating conditions, such as temperature, current, and microwave coupling, have been observed on occasion to be of slightly different amplitudes, at most 10%. This effect could cause a small intensity optical pumping effect in the cesium ensemble and could also cause

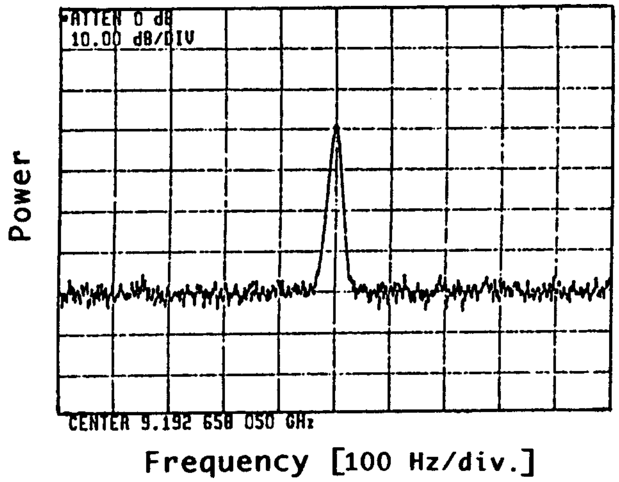

FIG. 3. Spectrum of the coherent emission: $t=41\,°C$; buffer gas, neon; horizontal axis, 100 Hz/div; vertical axis, 10 dB/div; resolution bandwidth, 10 Hz; peak value, 10^{-15} W.

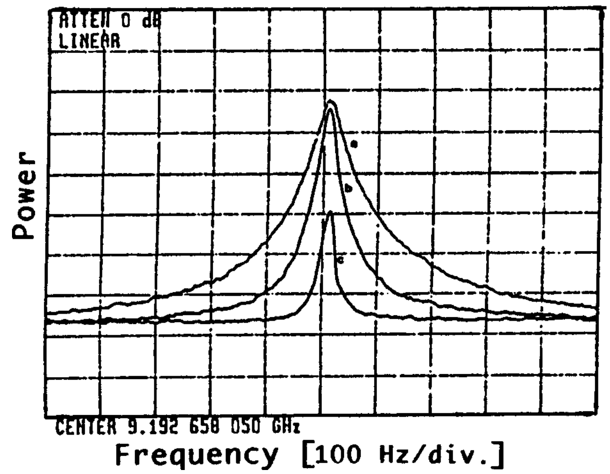

FIG. 4. Emission profile of the coherent radiation measured for different laser power densities: neon is the buffer gas; horizontal axis, 700 Hz/div; vertical axis, 2×10^{-16} W/div; resolution bandwidth, 10 kHz; curve a, 60 μW/cm^2; curve b, 25 μW/cm^2; curve c, 6 μ W/cm^2.

one ground level to be more populated than the other. However, this effect does not create any coherence or oscillating magnetization. Consequently it cannot produce emission of coherent microwave radiation of the type observed in the experiments reported here. Calculations show that, in our system, the cavity Q is much too low by at least three orders of magnitude to provide sufficient gain for maser action even if the populations were totally inverted [18]. Thus, this intensity optical pumping effect, if it exists, is totally negligible in the present experiments.

The quartz cell, containing the cesium vapor and the buffer gas, is placed inside a TE_{011} microwave cavity tuned to the hyperfine frequency of the cesium atom. The weak static magnetic field B_0, which defines the axis of quantization, is set parallel to the cavity axis. The active atomic region is a cylinder situated at the center of the microwave cavity and has a height of 1 cm (cell length) and a diameter controlled by the laser-beam diameter. The loaded cavity factor of the cavity with the quartz cell inserted is $Q_L=3000$. The setup also makes it possible to observe the fluorescence radiation and the dark line in the radial direction by means of a photodetector. The heterodyne receiver is a high-performance spectrum analyzer that can be used either to observe the spectrum of the emitted radiation in the frequency domain, or to perform an analysis in the time domain when it is operated in the video mode. Its sensitivity is 10^{-20} W/Hz. A Fabry-Perot cavity that is not shown in Fig. 2 is used to monitor the spectrum of the modulated laser radiation. The acousto-optic modulator (AOM), driven by a rf source at a frequency of 80 MHz and a pulse generator, is used when the transient behavior of the emission is studied.

Continuous operation. The microwave emission generated by the Cs atoms in the coherent superposition of the two hyperfine ground states is shown in Fig. 3 for a cell containing neon as a buffer gas and at a temperature of 41 °C. The laser power density is 100 μW/cm^2. A power output of 10^{-15} W and a signal-to-noise ratio of 10^4 in a resolution bandwidth of 10 Hz are measured. The frequency is twice the modulation frequency of the laser. No threshold in radiation emission as a function of laser intensity was found within the noise limits, in contrast to standard masers using the technique of population inversion. We have also studied the profile of the emitted coherent radiation in the continuous mode by scanning the modulation frequency of the laser. The results are shown in Fig. 4. The emission profile approximates a Lorentzian shape as expected from the calculations. We have verified that its width is proportional to the laser intensity (power broadening) and is equal to the linewidth of the dark line that is observed at the same time. The frequency, corresponding to the maximum emission power, coincides with the center of the dark line and is equal to the cesium hyperfine frequency shifted by the buffer gas and the magnetic field. The dependence of the emission frequency on laser frequency was also measured by locking the synthesizer to the peak of the emission profile. Preliminary experiments have shown that the light shift was essentially due to other causes than the CPT excitation itself, such as the residual carrier and other spectral sidebands. These experiments showed a quadratic dependence of the frequency shift on laser intensity, an effect that is described elsewhere [18].

The minimum width observed is a function of the temperature of the cell. At 41 °C in neon, it is 120 Hz, the main contribution originating from spin-exchange collisions [12]. In the case where nitrogen is used as a buffer gas, scattered radiation is quenched, as was mentioned above. It is then possible to operate at a higher temperature than in the case of neon, without the disadvantage of loss of coherence due to the incoherent fluorescence radiation. With nitrogen and with a laser beam larger than in the previous experiments, we could measure a power above 100 fW for a cell at 50 °C with a linewidth of the order of 300 Hz. This power is in agreement with Eq. (1) within approximately 50%, the difference essentially originating from a lack of knowledge of the density of atoms contributing to CPT. We have verified that within experimental error the emitted power is proportional to the square of the atomic density within the range 25 °C–50 °C, as predicted by Eq. (1).

Transient operation. The transient behavior of the emitted power upon laser pulsing is shown in Fig. 5. The laser is turned on for 6 ms and is delayed by 1.5 ms with respect to

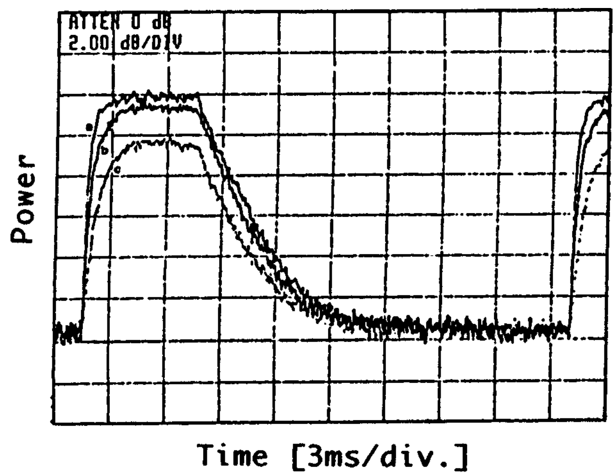

FIG. 5. Transient behavior of the emitted power observed for different laser power attenuations: neon is the buffer gas; horizontal axis, 3 ms/div; vertical axis, 2 dB/div; peak value, 10^{-15} W; resolution bandwidth, 10 kHz; curve a, 100 μW/cm^2; curve b, 40 μW/cm^2; curve c, 15 μW/cm^2. The sideband's frequency difference is equal to the hyperfine frequency.

the heterodyne receiver detection synchronism. The rise time and the fall time of the laser pulse are of the order of 1 μs and are totally negligible when compared to the rise time and decay time of concern in the present experiments. Several interesting phenomena predicted by the theory can be verified with the resulting patterns and measurements can be made to determine many physical parameters of the system. In particular are the following:

(a) The decay of the power after the laser pulse is a measure of the decay of the coherence in the ground state and allows a measurement of γ_2. We have found that this decay rate was within experimental error in agreement with the decay rate measured on the same setup by the standard population inversion and $\pi/2$ pulse technique.

(b) The power buildup time constant is correlated to the laser intensity in agreement with Eq. (3). It provides a means for measuring the factor ω_R^2/Γ^*, since γ_2 is obtained from the free-induction decay following the pulse. The time constant of the buildup was found to be in agreement within experimental errors with the linewidth of the dark line as measured on the same setup.

(c) We have verified that the frequency of emission during the pulse when steady state has been reached is equal to twice the angular frequency of modulation of the laser or $\omega_2 - \omega_1$. After the pulse, the frequency of the free-induction decay is the hyperfine frequency, $\omega_{\mu'\mu}$, shifted by the buffer gas and the magnetic field.

In this paper we have described the realization of a relatively simple system that produces coherent radiation at the hyperfine frequency of the ground state of cesium by means of coherent population trapping. We have shown that the experimental results obtained are in good agreement with a simple perturbation analysis of the phenomenon. The emission originates from the oscillating magnetization created by the hyperfine coherence introduced in the ensemble by the phenomenon of coherent population trapping. The effect does not require a population inversion as in the standard intensity optical pumping approach and may be said to take place without population inversion. The effect does not have a threshold either in laser intensity or density. The maximum of the emission is characterized by a large signal-to-noise ratio and, in principle, its frequency, aside from buffer-gas and magnetic-field shifts should be affected only by secondary effects (light shift) due to the presence of a residual carrier and other sidebands. The emission profile center can thus provide a good reference for the stabilization of a microwave oscillator, leading to a frequency standard with promising characteristics.

We wish to thank Professor N. Beverini for his expert help in filling the cells with buffer gases, and C. Novero, D. Andreone, and E. Arimondo for their comments and cooperation. This work has been partially supported by ASI (Italian Space Agency).

[1] G. Alzetta *et al.*, Nuovo Cimento B **36**, 5 (1976).
[2] A. Aspect *et al.*, J. Opt. Soc. Am. B **611**, 2112 (1989).
[3] M. O. Scully and M. Fleischhauer, Phys. Rev. Lett. **69**, 1360 (1992).
[4] For a review of this subject see, for example, the article by E. Arimondo, Prog. Opt. **35**, 257 (1996).
[5] N. Cyr, M. Têtu, and M. Breton, IEEE Trans Instrum. Meas. **42**, 640 (1993).
[6] A. S. Zibrov *et al.*, in *Proceedings of the 5th Symposium on Frequency Standards and Metrology*, edited by J. C. Bergquist (World Scientific, Singapore, 1995).
[7] F. Levi, A. Godone, C. Novero, and J. Vanier (unpublished).
[8] S. Brandt, A. Nagel, R. Wynands, and D. Meschede, Phys. Rev. A **56**, 1063 (1997).
[9] G. Orriols, Nuovo Cimento B **53**, 1 (1979).
[10] J. P. Barrat and C. Cohen-Tannoudji, J. Phys. Radium **22**, 329 (1961).
[11] J. Vanier, F. Levi, and A. Godone, Phys. Rev. A **58**, 2345 (1998).
[12] J. Vanier and C. Audoin, *The Quantum Physics of Atomic Frequency Standards* (Adam Hilger, Bristol, 1989).
[13] W. Happer, Rev. Mod. Phys. **44**, 169 (1972).
[14] J. Vanier, Phys. Rev. Lett. **18**, 333 (1967).
[15] S. Bloom, J. Appl. Phys. **27**, 785 (1956).
[16] C. J. Myatt, N. R. Newbury, and C. Wieman, Opt. Lett. **18**, 8 (1993).
[17] S. Kobayashi, Y. Yamamoto, M. Ito, and T. Kimura, IEEE J. Quantum Electron. **18**, 4 (1982).
[18] J. Vanier, A. Godone, and F. Levi, IEEE Trans. Instrum. Meas. (to be published).