Direct Excitation of Microwave-Spin Dressed States Using a Laser-Excited Resonance Raman Interaction

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We have used a laser-induced resonance Raman transition between the ground-state hyperfine sublevels in a sodium atomic beam to excite individual dressed states of the microwave-spin hyperfine transition. In addition, we have used the microwave interaction to excite the Raman trapped state. Extension of this technique to mm waves or to the far infrared may lead to applications such as mm-wave-beam steering and holographic image conversion.

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It is well known[1] that in a laser-excited resonant Raman interaction atoms are optically pumped into a pure dressed state, the so-called trapped state, which is transparent to the optical excitation fields. In atomic sodium, this trapped state consists of a linear combination of hyperfine sublevels, having a microwave frequency separation. We have demonstrated that in the presence of a resonant microwave field, the Raman trapped state translates into one or the other microwave spin-locked (dressed) state, under appropriate experimental conditions. Analogously, we have shown that a microwave field can also be used to excite the optical Raman trapped state.

Dressed states have been observed before in the microwave[2] and visible wavelength[3] regimes using excitation-field phase-shifting methods. In addition, the optical Raman trapped state was first observed indirectly, as a fluorescence reduction.[4] However, to the best of the authors' knowledge, this is the first time a double optical (Raman) interaction has been employed to excite the dressed state of a single-photon (microwave) interaction, and vice versa. This effect is of fundamental interest because it allows optical absorption to be modified by a change of only the phase of a microwave field. Such a phase-dependent optical-microwave absorption has numerous potential applications, as will be described later.

Figure 1(a) shows a three-level atomic system in the Λ configuration where ω_1 and ω_2 are the frequencies of the optical fields and ω_3 is the frequency of the microwave field. Here, it is assumed that states 1 and 3 are long lived, but state 2 is short lived with a decay rate of γ_2. For long interaction times (no microwave field) the atoms are optically pumped into a nonabsorbing trapped dressed state of the form[1,5]

$$\left[\frac{\Omega_2}{(\Omega_1^2+\Omega_2^2)^{1/2}}|1\rangle|n_1\rangle|n_2-1\rangle\exp(ik_1z_1)-\frac{\Omega_1}{(\Omega_1^2+\Omega_2^2)^{1/2}}|3\rangle|n_1-1\rangle|n_2\rangle\exp(ik_2z_2)\right]\Big/\sqrt{2}\,,$$

where $|1\rangle$ and $|3\rangle$ are the bare-atom states, and $|n_1\rangle|n_2\rangle$ is a field state with n_1 photons at frequency ω_1 and n_2 photons at frequency ω_2. Here, Ω_1 and Ω_3 are the Rabi frequencies of the $1\leftrightarrow2$ and $3\leftrightarrow2$ transitions, proportional to $\sqrt{n_1}$ and $\sqrt{n_2}$, respectively. In the experiment to be described, the semiclassical limit applies, and the sum over photon number states can be replaced by a single state having the average photon number. Finally, k_1z_1 and k_2z_2 are the spatially dependent phases of the optical fields.

For equal Rabi frequencies, the trapped state reduces to

$$\{|1\rangle|n_1\rangle|n_2\rangle\exp[i(k_1z_1-k_2z_2)]-|3\rangle|n_1-1\rangle|n_2+1\rangle\}/\sqrt{2}\,,$$

where the phase $\exp(ik_2z_2)$ has been factored out. In comparison, the high- and low-energy dressed states of

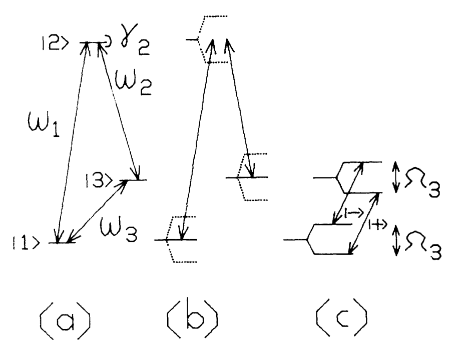

FIG. 1. (a) A three-level atomic system in the Λ configuration. (b) Dressed states for the resonance Raman interaction. The trapped state is denoted by the solid lines. (c) The microwave spin-locked (dressed) states.

the $1 \leftrightarrow 3$ microwave transitions are

$$|1\rangle|n_3\rangle \exp(-ik_3z_3) - |3\rangle|n_3-1\rangle\,,$$

$$|1\rangle|n_3\rangle \exp(-ik_3z_3) + |3\rangle|n_3-1\rangle\,,$$

respectively, where ω_3 is the microwave frequency, and the semiclassical limit is again assumed.

To help clarify the physics involved, consider a stepwise process wherein the optical Raman interaction and the microwave interaction are separated in time. First, the optical Raman interaction puts the atoms into the trapped state, as illustrated in Fig. 1(b). Next, the laser fields are turned off and a microwave field is turned on. In general, two microwave dressed states are possible, as shown by the energy-level diagram of Fig. 1(c). To determine into which microwave eigenstate the Raman trapped state evolves, it is necessary to know the relative phase of the microwave and the double optical (Raman) fields. This relative phase is given by

$$\phi \equiv (k_1z_1 - k_2z_2) - k_3z_3\,,$$

where it is assumed that all three states are in phase at $z_1 = z_2 = z_3 = 0$.

When the laser difference frequency is exactly in (or out of) phase with the microwave frequency, i.e., $\phi = 0$ (or $\phi = \pi$), the Raman trapped state translates directly into the high- (or low-) energy microwave dressed state. For any other value of the relative phase ϕ, a linear combination of microwave dressed states results. In such a case, Rabi spin flips occur[6] (largest for $\phi = \pi/2$), partially destroying the original dressed state. To detect the degree of microwave interaction, the microwave field can be turned off and the Raman interaction can be turned back on. Population lost from the trapped state would then appear as an increase in optical absorption.

Experimentally, this three-step process can be realized using a separated-field excitation scheme in an atomic beam. The experimental setup we used is illustrated schematically in Fig. 2. Here, a sodium oven is operated at about 400 °C to generate a thermal atomic beam. The laser field at frequency ω_1 (590 nm) is the output of a cw dye laser having 1 MHz of frequency jitter. To minimize the effect of this jitter,[7] the field at frequency ω_2 is generated from that at ω_1 by using an acousto-optic modulator (A/O). The A/O is driven by a quartz-stabilized microwave oscillator at the $1 \leftrightarrow 3$ transition frequency (1772 MHz). The laser fields at ω_1 and ω_2 are made copropagating to a high degree of precision by coupling both through a common single-mode optical fiber (not shown). In this experiment, states 1 and 3 are the $F=1$ and $F=2$ hyperfine sublevels, respectively, of the $^2S_{1/2}$ ground state, and state 2 is the $F=2$ sublevel of the $^2P_{1/2}$ state. The laser beams in zones A and B are right circularly polarized, and a dc magnetic holding field of 0.3 G is applied parallel to the laser propagation direction, to lift the degeneracy of the Zeeman sublevels. The $m=0$, $\Delta m = 0$ Raman transition is used. For the microwave excitation, a TE_{201} rectangular resonant cavity is used in an orientation which excites the $m=0$, $\Delta m=0$ transition.

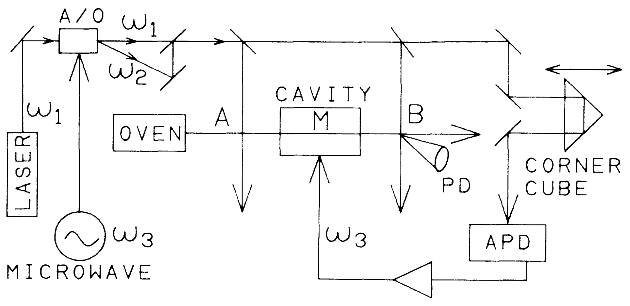

FIG. 2. Schematic diagram of the experimental setup.

First, Raman excitation in zone A pumps the atoms into the trapped state. Then, these atoms interact with a microwave field, zone M. The Raman probing interaction in zone B measures the degree of the microwave interaction by detecting any loss of the trapped-state population, via the fluorescence detecting photodiode (PD). The path lengths to zones A and B are set so that the optical difference frequencies in zones A and B are in phase.[7] The microwave field is generated by detecting and amplifying the beat between the two optical fields using a 2-GHz avalanche photodiode (APD). This ensures that the microwave and the double optical fields are phase locked. The relative phase ϕ between the microwave and the laser difference frequencies is controlled by changing the path length traversed by the laser beams before reaching the APD.

Figure 3(a) shows the Raman-Ramsey fringes observed in zone B when the laser difference frequency is scanned, for zero microwave power. Figure 3(b) shows

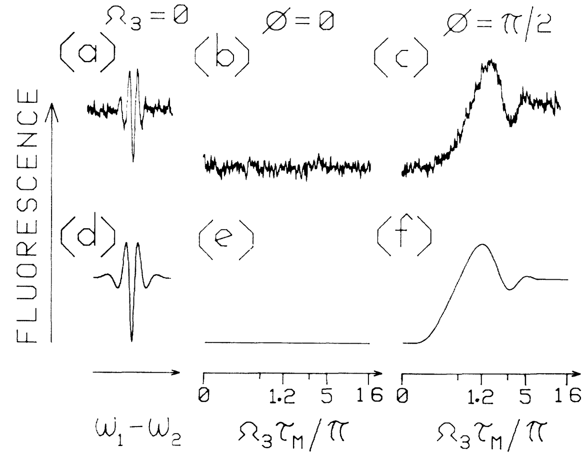

FIG. 3. (a) Ramsey fringe pattern in absence of microwave. (b) Zone-B fluorescence as a function of microwave power (in units of π pulses), for a relative phase of $\phi = 0$. (c) For $\phi = \pi/2$. (d)-(f) Theoretical plots for (a)-(c), respectively.

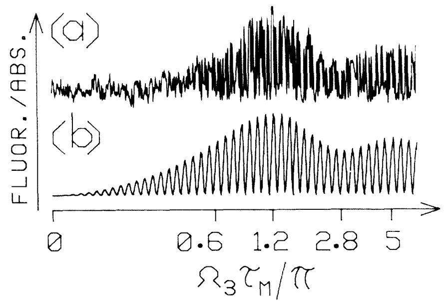

FIG. 4. (a) Zone-B fluorescence as a function of microwave power, while the relative phase ϕ is rapidly scanned. (b) Corresponding theoretical plot.

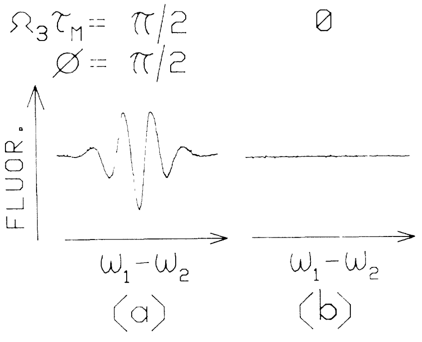

FIG. 5. (a) Microwave-Raman interference (Ramsey) fringes, generated for a relative phase of $\phi=\pi/2$ and a microwave $\pi/2$ pulse. (b) The fringe disappears for zero microwave power.

the fluorescence observed with the laser difference frequency held exactly on resonance (fluorescence minimum), but the microwave power scanned. Here, the microwave field is exactly in phase with the optical difference frequency, i.e., $\phi=0$. As can be seen, the microwave field has no effect, since in this case the optical Raman trapped state translates into a pure microwave spin-locked eigenstate. Figure 3(c) shows the case of $\phi=\pi/2$, as the microwave power is again scanned, with the laser difference frequency held on resonance. Here, the fluorescence depends strongly on microwave power, undergoing large oscillations caused by Rabi spin flips, indicating that a microwave eigenstate is no longer excited. The damping with increasing microwave power in Fig. 3(c) is caused by velocity-averaging effects. Comparison with the theoretical plots of Figs. 3(d)-3(f) shows good agreement.[8] To illustrate what happens for phases other than $\phi=0$ or $\pi/2$, Fig. 4(a) shows the absorption observed when the phase ϕ is rapidly varied while scanning the microwave power. Here, the absorption varies sinusoidally with ϕ, and the curves of Figs. 3(b) and 3(c) form the envelope function. Figure 4(b) shows the corresponding theoretical plot.

We also performed the complimentary experiment wherein a microwave field is used to excite the optical Raman trapped state. This involves replacing the first Raman zone in Fig. 2 by an optical pumping zone (not shown), which effectively puts all the atoms into state $|3\rangle$ before entering the microwave cavity. For a microwave power corresponding to a $\pi/2$ pulse, the resulting state is

$$-i|1\rangle|n_3\rangle\exp(-ik_3z)+|3\rangle|n_3-1\rangle\,.$$

This can be made to correspond to a Raman trapped state if the relative phase ϕ between the microwave and the laser difference frequency is $\pi/2$.

Experimental evidence of microwave excitation of an optical Raman trapped state appears in Fig. 5. Here, Fig. 5(a) shows the zone-B fluorescence[9] obtained by scanning the laser difference frequency with a microwave power corresponding to a $\pi/2$ pulse and a relative phase of $\phi=\pi/2$. As can be seen, Ramsey fringes are obtained which closely resemble those in Fig. 3(a), even though only one Raman excitation zone is present. Thus, an optical Raman trapped state has been excited by the microwave field. For completeness, Fig. 5(b) shows the zone-B fluorescence obtained with the microwave turned off. As expected, no Ramsey fringes are seen in this case.

Extension of these results to a single-zone excitation scheme (where both microwave and optical Raman fields are present simultaneously) is also of interest because of the possibility of exciting a three-photon trapped state.[10] This would occur for a relative Raman and microwave phase of $\phi=0$ or π. For other values of ϕ, all dressed states are partially optically absorbing, where the steady-state absorption depends on ϕ. For a properly chosen configuration, the position dependence of the relative phase ϕ would result in a grating being produced, which would diffract both optical and microwave fields. Numerous applications of this effect can be imagined if the microwave transition is replaced by a mm-wave or far-infrared transition. For example, real-time mm-wave-beam steering can be performed wherein the mm wave could be deflected by the optical beams. It should also be possible to perform real-time holographic far-infrared-to-visible image conversion.[11]

Finally, we briefly consider the effects of the finite photon-number spread. Because of this spread, dressed states exist in manifolds, each characterized by the photon number. In case of a microwave excitation, the manifolds are not coupled due to lack of spontaneous emission. Addition of the Raman field partially couples the manifolds, by an amount which depends on laser intensity. For example, a relative phase of $\phi=\pi$ would cause the weak-field-seeking microwave state to experience decay, and be optically pumped into the strong-field-seeking state. This process may have applications to collision studies, laser cooling, and possibly trapping of neutral atoms in a microwave cavity.[12] We are currently investigating some of these potential applications.

In summary, we have used a laser-induced resonance

Raman transition in a sodium beam to excite individual dressed states of the microwave-spin hyperfine transition, Conversely, we have also used the microwave interaction to excite the Raman trapped state. Extension of this technique to mm waves or to the far infrared may lead to applications such as beam steering and image conversion.

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