Microwave Induced Transparency in Ruby

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We report experimental observations of field-induced transparency in a solid medium. Absorption reduction of 20% was observed in ruby using a magnetic field for the creation of closely spaced lower levels and a microwave field for the coupling of these states. [S0031-9007(97)03654-5]

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Recent theoretical [1–8] and experimental results [9–16] indicate that quantum interference can lead to lasing without inversion (LWI) and electromagnetically induced transparency (EMIT) for resonant enhancement of nonlinear effects with reduced absorption. Experimental studies of quantum interference have so far been focused on atomic gas media [8–15]. For the understanding of quantum coherence and interference in crystals and for various potential device applications, LWI and EMIT in solid media are interesting.

Commonly used schemes for achieving quantum interference are three-level systems with two levels coupled by an electromagnetic field. The difficulty of realizing quantum interference in solids using these schemes is the large optical linewidth, which is usually of the order of a few GHz compared with a few tens of MHz in atomic vapors. Since the essential requirement for quantum interference is the Rabi frequency of the coupling field to be larger than the transition linewidth, normally we need to use relatively high coupling field intensity in solids. In addition, due to the large linewidth, the quantum coherence in solids is not as good as that in atomic vapors, and it perhaps is more proper to say that only partial coherence can be created in solids. In this paper we report the first observation of field-induced transparency in a solid medium. We found that the general feature of the reduced abortion is similar to those in atomic vapors. The results are consistent with a modified theory of quantum coherence.

Ruby in a magnetic field is chosen as a medium for a three-level system for lasing without inversion. The main reason for using ruby is that its many optical and microwave spectroscopic parameters are precisely known [17–19]. In our experiments, we have used two ways to reduce the linewidth in ruby. First, we chose the coupling field at microwave frequency, since the linewidth of microwave transition is much smaller than that of optical transitions. Second, we used liquid helium to cool the crystal during the experiments. At this liquid helium temperature, the measured linewidth of microwave transitions is about 60 MHz [17]. Since the dipole moment of microwave transition is 5×10^{-20} esu [17], then the estimated power for realizing quantum interference is around 10 $\mathrm{MW/cm^2}$.

Our scheme is a three-level system with two lower levels coupled by a microwave field. This system has been theoretically shown to exhibit lasing without inversion [6–8]. The energy diagram of the system is shown in Fig. 1. The upper level is the ^2E level, and the lower two levels can be any two of the four Zeeman sublevels of the ground state ^4A. In our study we chose levels 1 and 4 as the lower levels. The separation of the Zeeman levels can be adjusted by changing the intensity of the applied magnetic field. A strong microwave field coherently couples levels 1 and 4. The transition dipole moments between these lower levels is known to be quite large [18,19]. The direction of polarization of the microwave field, the magnetic field, and the c axis of the ruby crystal are perpendicular to one another. A wavelength-tunable probe beam is used to monitor the absorptions from 4 to 5 ($E1$) and 1 to 5

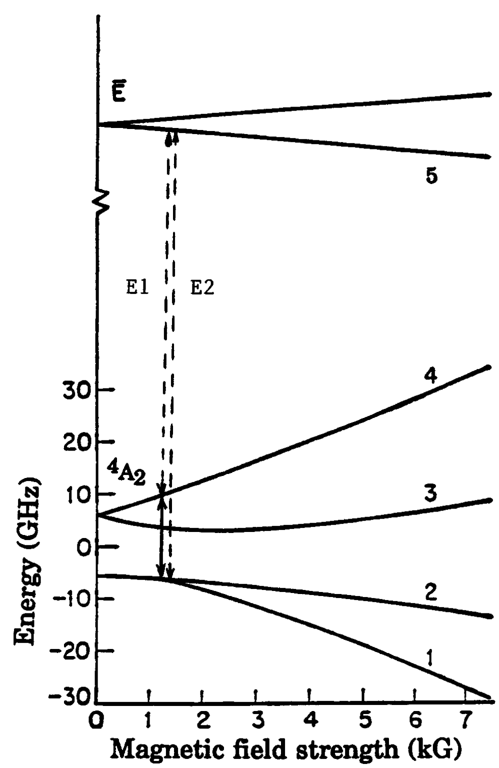

FIG. 1. Energy levels of ruby with a magnetic field for field-induced quantum coherence.

($E2$). The system is commonly denoted a "V" scheme if only $E2$ is used and a "ladder" scheme if only $E1$ is used. It should be noted that the Zeeman levels are mixed states and there are certain transition probabilities between any two levels. Therefore, strictly speaking in terms of total population, our system is an open system.

The experimental setup is shown in Fig. 2. A ruby crystal (o.d. 2×10 mm), with 0.05% chromium concentration, is placed in the center of a microwave cavity which is cooled by liquid helium at 2.4 K temperature. The cavity has a dimension of $8 \times 8 \times 16$ mm^3 and small holes (1.5 mm diameter) on each of the two opposite walls for the probe beam to pass through. A microwave transmitter (Texas Instruments, QKH-1524) generated a pulsed field with 16.3 GHz frequency and 0.1 μs pulse width. The peak microwave intensity in the cavity was around 10 MW/cm^2, which was calculated from the measured input intensity and the Q factor of the cavity. The Rabi frequency created by the microwave can then be calculated from the field intensity and the measured dipole moment of the coupled transitions [18,19]. In our case, it is around 2 GHz. Spatial variation of the microwave field in the cavity can cause nonuniform Rabi frequency in the radial direction of the crystal. This nonuniformity is small since the crystal is small compared to the size of the cavity. A weak probe beam (0.1 μJ energy) from a pulsed dye laser (Quanta-Ray PDL 2) pumped by a Nd:YAG laser (Spectra-Physics DCR-2) was used for measuring optical absorption spectra. No attempt was made to select the single longitudinal mode of the dye laser. The probe beam has a measured linewidth of around 6 GHz, a spot size in the ruby around 0.21 mm, and a pulse duration of 7 ns. The frequency of the probe was tuned using a homemade mechanical tuning knob with a 0.5 GHz scanning step. The probe beam was detected using a silicon photodiode with a responsivity of 0.3 A/W. Since there was intensity fluctuation in pulsed laser, we used a boxcar (Stanford Research Systems, SR-250) to average the signal. The gate width of the boxcar was 9 ns, and the sample 30. The lasers, the microwave transmitter, and the boxcar were synchronized with a pulse repetition frequency of 10 Hz.

During the experiment, we first adjusted the magnetic field intensity at around $H = 1193$ G, in order to have an energy separation of 16.3 GHz between levels 1 and 4 (Fig. 1). The amount of energy separations was monitored from the peaks in the optical absorption spectrum. At $H = 1193$ G, only three of the four Zeeman sublevels were resolved (Fig. 3), since levels 1 and 2 overlap (Fig. 1). Next, we applied the microwave field to the system and measured the probe absorption spectrum again. This measured spectrum is also shown in Fig. 3. We can see that both absorption peaks 1 and 4 are reduced, and peak 4 has more reduction. Since the probes at peaks 1 and 4 correspond to V and ladder systems, respectively, this indicates that the quantum interference effect created by the microwave field can produce induced transparency for both the V and ladder schemes, and the ladder system is better in terms of induced transparency.

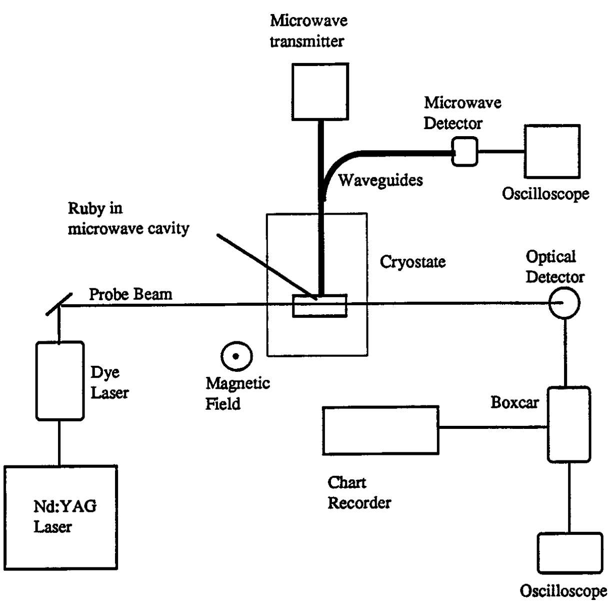

FIG. 2. Experimental setup for microwave-induced transparency in ruby.

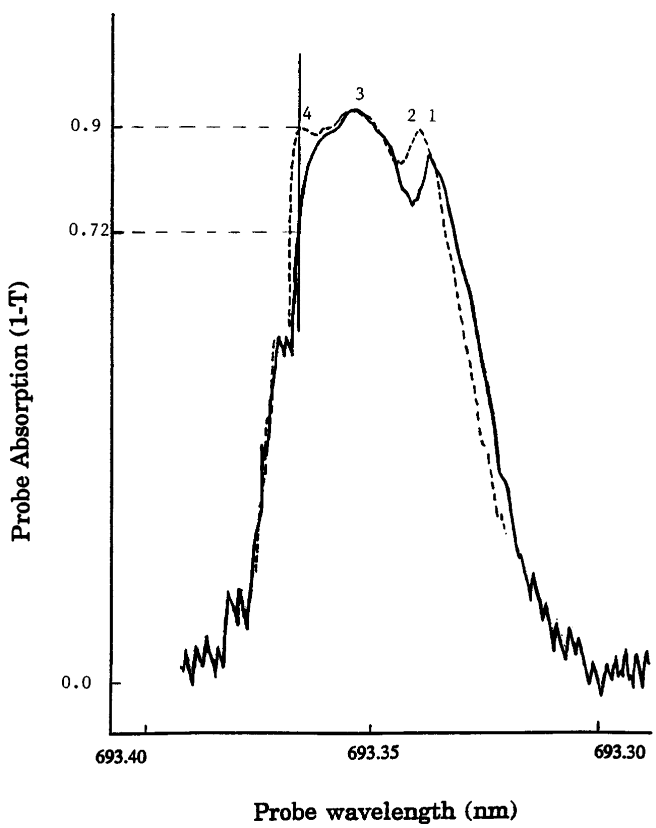

FIG. 3. Absorption spectrum of the probe with (solid line) and without (dashed line) the coupling microwave. Numbers 1–4 correspond to transitions from level 5 to levels 1–4 in Fig. 1.

To quantitatively measure the amount of the induced transparency, we fixed the probe beam at peak 4 (wavelength = 693.367 nm) and compared the transmitted optical intensity with and without the microwave field. Since it was impossible to measure the exact input and output intensities of the ruby crystal, we use the relative values for transmittance (T) with and without the coupling microwave field. These values were obtained by comparing the absorption peaks with those of total opaque (blocked beam, $T = 0$) and total transparency (at far off peak wavelength $T = 1$). The measured transmittance was 0.1 without microwave and 0.28 with microwave, which corresponds to a reduction of absorption from 0.9 to 0.72, or 20%.

We found that the amount of the induced transparency also depends on the microwave power and degree of coupling detuning, as expected. Within the range of the available microwave power in our experiments, we found that the decrease in absorption was proportional to the increase in microwave power. Change in magnetic field intensity is equivalent to the tuning of microwave frequency, since it causes the detuning of the coupling field. The amount of induced transparency was inversely proportional to the detuning of the magnetic field up to 400 G, corresponding to a detuning of 2 GHz. A change of magnetic field of more than 400 G caused the complete disappearance of the quantum interference effect. This result is consistent with our theoretical analysis.

Population change in our experiments was small and had little contribution to the reduced absorption. If there were any dominant population pumped from level 1 to level 4, we would expect to see the increasing absorption of $E1$ and decreasing absorption in $E2$. However, in our experiments, we have seen absorption reduction in both $E1$ and $E2$.

It should be noted that for each of the above cases, we normally expect to see two absorption peaks induced by the quantum interference. In our case, these peaks cannot be resolved due to the large probe linewidth (6 GHz), compared with the Rabi frequency. The results, however, are consistent with our theoretical analysis using the density matrix approach for a simplified three-level system when the effect of inhomogeneous broadening is included. The calculations are based on the modified density matrix equations [6–8] with inhomogeneous broadening as an additional decay term for field induced coherence. Since the measurements were performed using a probe with fairly large linewidth, the observed absorption spectra are results of convolution of the calculated spectra (assumed infinitesimally narrow probe linewidth) with the probe spectral profile. Therefore, we must compare the experimental measurements with convolved spectra. Using the values of wavelength, coupling power, detuning, and initial population distribution in our experiments, and the relative strength of the optical transitions, dipole moments, and inhomogeneous broadening published in

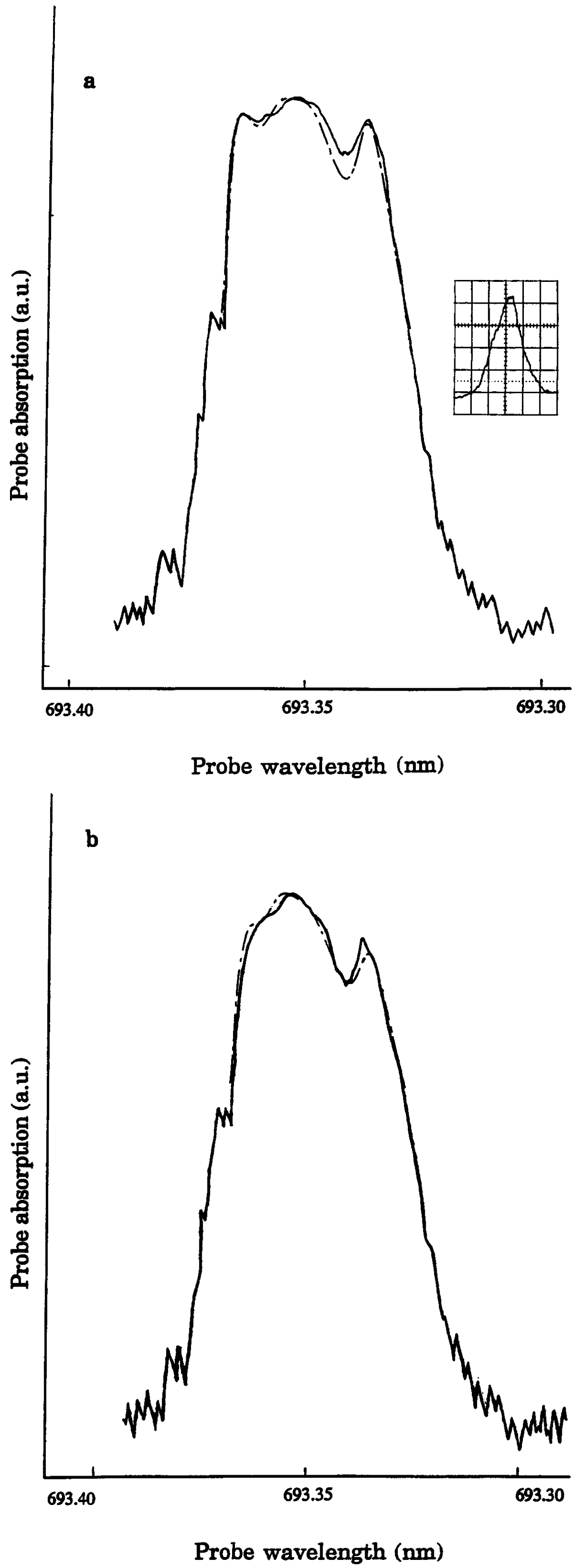

FIG. 4. Comparisons between theoretical and measured absorption spectra: (a) without the coupling microwave, and (b) with the coupling microwave. Solid line: experiment. Dash-dotted line: theory. Inset: probe spectral profile.

[17], we calculated the absorption spectra with and without the coupling field. In order to perform the convolution between these spectra with the probe profile, we measured the probe spectral profile using a Fabry-Perot interferometer. The measured linewidth is 6 GHz, and the spectral profile is shown in Fig. 4 (inset). The probe laser maintained this spectral profile well over many scans in our experiments, and the ruby absorption spectra are repeatable at different measurements. The convolved results are shown in Fig. 4 for cases with and without the coupling field. We found in our calculation that the convolution greatly depends on the linewidth and is insensitive to the probe profile.

We can see from Fig. 4 that there is a good agreement between theory and experiments. This verified that the observed induced transparency in our experiments was induced by the microwave field. The induced transparency in our experiments is not as strong as those observed in atomic vapors. This was caused by large transition linewidth in solid medium, and the large linewidth of the pulsed probe beam. We believe that there is little contribution from the optical Stark (or Autler-Townes) effect to the induced transparency. When the separation of the optical Stark peaks is less than the linewidth, as in our case, the addition of these peaks essentially forms a single peak, and no reduction in absorption can be observed [20]. With the field-induced transparency, however, the dip in the absorption still remains.

An obvious way to improve the induced transparency is to use high Rabi frequency. This will not only enhance the quantum coherent effect, but also widen the transparent wavelength range for easy probing. This, however, will require a higher microwave field intensity for coupling. This can be done by using a high-Q microwave cavity for increasing the intensity. In this case, a high-power tunable microwave transmitter is needed for matching the resonant wavelength of the cavity. Matching of the coupling microwave wavelength to the ruby transition can be achieved by tuning the magnetic field.

Amplification without inversion is also possible based on our calculations using the parameters in our experiments. The required incoherent pumping rate is the same for AWI in atomic vapors, and a Rabi frequency larger than 10 GHz.

In summary, we have reported the first observation of electromagnetically induced transparency in a solid medium. Electromagnetically induced transparency was observed in both the V and ladder schemes of a three-level system. We found that the ladder system has a larger induced transparency than the V scheme. The best reduced absorption was measured to be around 20%.

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