Transitions between Dressed States

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Abstract – Transitions between dressed states of a driven two-level system and three-level system are illustrated by utilizing hyperfine and EPR transitions in a color centre in diamond. The transitions are detected by an optical Raman heterodyne technique.

1. INTRODUCTION

The response of atomic systems to strong, coherent electromagnetic fields displays a wealth of nonlinear effects common to all frequency ranges. However, in practice, it has been easier to conduct experiments in the radiofrequency (rf) region. In the present study, we employ a coherent optical Raman heterodyne technique [1] to observe the effect of strong near-resonant driving fields on rf transitions in the Nitrogen Vacancy (NV) color centre in diamond. This coherent experimental technique has the advantage that, as well as the usual increase in sensitivity associated with optical detection, it is frequency and phase specific. Hence, the response of an additional weak probe field can be detected even in the presence of one or more strong driving fields.

In a recent paper, we described the weak probe response of an almost purely homogeneous broadened hyperfine transition in the NV centre at 2.3 MHz to a single strong driving field [2]. In this paper, we present and discuss with respect to the above ideal system [2] our observations of two more complex situations. The first experiment detects the weak probe response of a three-level system to two near-resonant strong rf fields driving the 5.3 MHz transition. Secondly, the weak probe response of the nonideal inhomogeneously broadened hyperfine split EPR transition in the NV centre to a single strong driving field is investigated.

2.1. EXPERIMENT

The Raman heterodyne detection technique used was first introduced by Myllyniemi et al. [1] for studying the hyperfine transitions of rare earth ions in crystals. We have adopted the technique to great advantage to study hyperfine and EPR transitions in the NV color centre in diamond [2, 3]. The experimental setup, in its simplest form, is shown in Fig. 1. The rf produced by the tracking generator was applied to a coil wound around the sample and laser light transmitted through this sample was detected by a fast pin diode. When both the laser frequency and the rf are on resonance with a transition, there is a low-frequency beat signal on the light detector at the frequency of the rf field, which is detected by a spectrum analyzer. In the limit of weak laser power, the beat signal is proportional to the coherence between the resonant rf levels with the light merely acting as a carrier [1]. The component of the signal out-of-phase with the applied rf is proportional to the rf transition absorption and the in-phase signal proportional to the dispersion. The response in a given phase can be simply obtained by summing the photodiode signal with a reference from the tracking generator; however, it is better to use a double balanced mixer for phase sensitive detection [1]. Without the reference signal, the spectrum analyzer gives the intensity response.

The energy levels of the nitrogen-vacancy centre are shown in Fig. 2. The ground state is an electron spin triplet that is split by the trigonal crystal field into a doublet and singlet separated by 2.88 GHz. An external magnetic field along the axis of the centre splits the doublet and causes a level anticrossing (LAC) of one component of the doublet and the singlet at a field strength of 10.3 G. In the region of the anticrossing, the frequency of the EPR transition is in the MHz frequency range and can readily be detected by the Raman heterodyne technique. Hyperfine transitions are also found in the MHz frequency range. In particular, the nuclear spin of the nitrogen, I = 1, produces a hyperfine triplet. In a magnetic field close to anticrossing, the allowed \( M_s \) = \pm 1 transitions within the \( S_z = 0 \) state are Zeeman split and occur at 4.7 and 5.3 MHz. In this anticrossing region, the transverse hyperfine interaction causes the hyperfine transitions to gain intensity from the electron spin transitions. The enhancement can be as large as a factor of 100 [2].

As presented in an earlier work [2], the weak probe response (Fig. 3) of the strongly driven 5.3-MHz transition corresponds to that predicted from an analytical solution of the Bloch equations. After signal averaging, the absorption response can be seen to be the form of two dispersion lineshapes symmetrically displaced from the driving frequency. The dispersion response is not quenched to the same degree and gives two absorption shaped features, one positive and one negative in phase, equivalently displaced from the resonant frequency. The features are displaced from the resonant frequency by the Rabi frequency and are consistent with transitions between dressed state levels [4] as shown in Fig. 4. Since the measured transverses and longitudinal relaxation times \( T_2 \) and \( T_1 \) for this transition are almost equal [4], the system represents an almost ideal two-level system. It is apparent from Fig. 3 that the linewidth of the resolved dressed states for the homogeneously broadened transitions are one half of the unperturbed transition. This observation is in agreement with the Bloch equation model.

2.2. DRESSING THE DRESSED STATE

In a three-level system, driving one transition will also affect the other two transitions associated with the three-level system. For example, as the 4.7-MHz transition in
the NV centre shares a common level with the 5.3-MHz transition, strongly driving the 5.3-MHz transition also causes a splitting of the 4.7-MHz transition. This splitting in the double resonance signal is usually termed the Autler–Townes effect [5]. The splitting is attributed to a transition between the dressed states associated with the driven 5.3-MHz levels and the unperturbed third level. This is illustrated in Figs. 5a–5c.

With the frequency and phase sensitivity of the Raman heterodyne technique, it is a simple matter to add any number of strong driving fields to the above experiment. Figures 5d and 5e display the change to the dressed states if a second strong 5.3-MHz driving field is introduced, and the frequency chosen to be on resonance with the transitions is shown in Fig. 5c. The second drive field is at a frequency of \( \omega_0 + \Omega \). It was kept weaker than the resonant driving field at frequency \( \omega_0 \) so that the dressed states of the stronger driving field were still valid. It can be seen that the second field causes a further splitting of the dressed state levels, i.e., it dresses the dressed states. Because there is a ladder of dressed states, there is a splitting of all of the dressed states. Experimentally, the splittings are observed in the transition to the unperturbed third level of the system as shown in Figs. 5d and 5e. It can be seen that pumping at \( \omega_0 + \Omega \) has almost the same effect as pumping at \( \omega_0 \). There are minor changes to the effective populations, and this results in changes to the relative intensities of the four spectral lines (Figs. 5d and 5e). We observe no significant change in the linewidths of the dressed state transitions when the second strong driving field is present.

2.3. STRONGLY DRIVING AN INHOMOGENEOUSLY BROADENED AND HYperfine SPLIT TRANSITION

Compared to the 5.3- and 4.7-MHz hyperfine transitions the EPR transition in the NV centre has a much larger homogeneous and inhomogeneous linewidth as well as having hyperfine structure. For an axial field of \( -1000 \) G, the frequency of the \( S_z = 0 \rightarrow S_z = -1 \) EPR transition has three hyperfine lines separated by 7.2 MHz centered about 93 MHz (Fig. 6a). The spectrum is power broadened.

If a strong driving field is applied at 93 MHz, the weak probe response exhibits much narrower features for the dressed state transitions (Fig. 6b). There are several contributions to the narrowing of the features. Firsty, looking at the hyperfine split components, the off-resonance driving field has a Rabi frequency of 40 MHz, while the Rabi frequencies for the 2 MHz off-resonance hyperfine components will be 10.2 MHz. The range of the Rabi frequencies is, therefore, very small. Thus, the hyperfine structure in the dressed state transitions is almost totally quenched by such a large driving field. The inhomogeneous broadening is likewise quenched, although it is possible that variations in the EPR transition strength would add to the width of the split components. Finally, from [2] and the previous section, the homogeneous component of the linewidth will be halved.

Thus, the major result of the strong driving field on a two-level system with resolved hyperfine structure and significant inhomogeneous broadening is two equally displaced dressed state transitions, each with a considerably reduced linewidth of 1 MHz (Fig. 6b). There are other minor changes such as the secondary peaks marked with a cross that require explanation, but these may arise from nominally forbidden transitions or macroscopic inhomogeneities with larger detunings. The main features, however, are accounted for by the model of a driven two-level system.

3. CONCLUSION

It has been illustrated that, in two- and three-level systems driven with strong CW resonant fields, e.g., amplitudes exceeding the linewidths due to homogeneous, inhomogeneous, and hyperfine structure, a considerable reduction in the linewidth occurs in the transitions detected by a weak probe field. It has been further found that the positions of the observed transitions are consistent with the dressed state description of the interaction of the driving field and the two- and three-level systems.

REFERENCES