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Hybridization: A tool to engineer and probe novel quantum metamaterials

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Abstract

The hybridization of distinct quantum systems allows one to engineer the properties of the composite system with superior properties. These systems can be used to explore novel nonlinear phenomena in new regimes.

1. Introduction

The last century saw the discovery of one of the most fundamental and far-reaching theories ever discovered [1]. The theory called 'quantum mechanics' has had a profound effect on our technologial society. Many of our current devices rely on phenomena associated with it. However, they have generally suppressed the more paradoxical features such as entanglement and nonlocality [2]. We are now at the stage when we can engineer quantum systems which are better than their natural counterparts. Quantum hybridization is an essential tool here where one can in principle exploit the best properties of these individual quantum systems to form a new composite system with superior attributes without the weaknesses of the components systems compromising it [3]. This in a real sense allows us to create new quantum metamaterials.

There are many potential choices for the individual quantum systems that could be used in a hybridization process. Superconducting qubits and circuits are a promising candidate systems for quantum computation with their easy fabrication, control and manipulation but have the potential disadvantage of short coherence times [4,5]. On the other hand, atomic systems are ideal memories as they generally have long coherence times but can be quite hard to control and manipulate [6,7]. Combining these two systems could level to a new system with easy control and manipulation coming for the superconducting part and long coherence times from the atomic side. Hybridization of superconducting circuits with an electron spin ensemble formed from NV centers in diamond has shown that these systems can be coupled together and in fact basic gate operations on the composite system have been performed [8-12]. Until recently however the properties of this hybridized system were inferior compared to the component system. Our recent experiments have shown that a system with superior properties can be created [13]. These systems can be used to explore new physical regimes.

2. Quantum Hybridization in superconducting systems

Our hybrid system, depicted in Figure 1, consists of a superconducting resonator with an ensemble of negatively charged nitrogen–vacancy (NV) centers in diamond magnetically coupled to it [13]. It can be described by a Hamiltonian of the form

$$\mathcal{H} = \hbar\omega a^\dagger a + \frac{\hbar}{2}\sum_j \omega_j \sigma_{z,j} + \hbar \sum_j g_j \left[a^\dagger \sigma_{-,j} + a\sigma_{+,j}\right] \quad (1)$$

with the resonator being associated with the creation/destruction operators while the j$^{\text{th}}$ NV spin is associated with the corresponding Pauli operator. The last term represents the magnetic coupling between the resonator and ensemble.

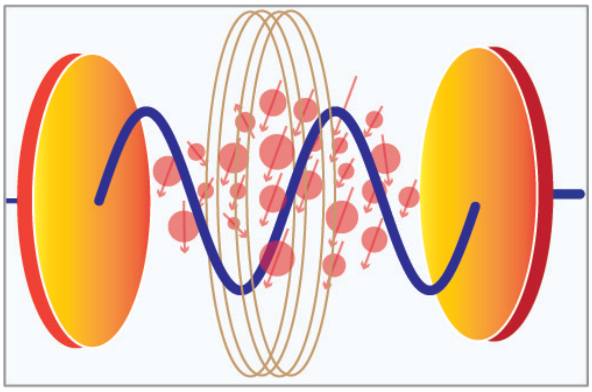

Fig. 1 Schematic representation of a superconducting cavity coupled with an ensemble of NV centers in a synthetic diamond crystal. It is surrounded by a Helmholtz coil that applies a magnetic field to the shift the energy level of the ensemble.

One of the key issues associated with the ensemble is the inhomogeneous broadening linewidth γ_{in} of several MHz compared to a sub MHz cavity linewidth κ. This unfortunately means the linewidth of the hybridized system

$$\Gamma \sim (\kappa + \gamma_{in})/2 \quad (2)$$

could be greater than the cavity linewidth [13]. Still such systems have shown strong coupling [8-10] and demonstrated various quantum gate operations and memories [11-12].

3. Tuning the properties of the ensemble.

A major challenge in solid-state-based hybrid systems is the suppression of spin dephasing induced by the host material as it affects the life time of the quantum memories for instance [12]. While echo refocusing techniques [14] can obviously be employed, they can be difficult to achieve in practice. Alternative approaches are possible where one creates collective dark states [15] that remove the necessity for refocusing recovery protocols and at the same time substantially improves the coherence times beyond the limit given by the cavity and spin ensemble individually. We show that it is possible to engineer through spectral hole burning [13] a hybrid quantum system where the coherence properties of the composite system are better than those associated with either of the individual component systems. This work is a proof-of-principle experiment illustrating the potential of hybrid systems and provides a test bed for a whole new class of circuit QED experiments. The inherent nonlinearity of our system also allows the exploration of such phenomena in entirely new regimes.

4. Probing the nonlinear regime

The superconducting – electron spin ensemble hybrid systems have generally been investigated in the linear regime where the ensemble itself only has a few excitations stored with it. In such a regime the ensemble behaves like a harmonic oscillator. However, this hybrid system is inherently nonlinear [13]. From equation (1) we can derive the equations of motion as

$$\dot{a} = -\kappa a + \sum_j g_j \sigma_j^- + \varepsilon$$

$$\dot{\sigma}_j^- = -(\gamma_\perp + i\mathrm{Z}_j)\sigma_j^- + g_j \sigma_j^z a \qquad (3)$$

$$\dot{\sigma}_j^z = -\gamma_\parallel(1+\sigma_j^z) - 2g_j(\sigma_j^- a^\dagger + \sigma_j^+ a)$$

where ε represents an external resonator drive field with Z_j being the frequency detuning of the j$^{\text{th}}$ spin with respect to the ensembles central frequency. Such detuning allows for the effects of inhomogeneous broadening to be naturally included. With typical parameters $\kappa > \gamma_\perp \gg \gamma_\parallel$ we can show the steady state behavior with C_j cooperativity per spin is given by

$$|a|^2 = \frac{\eta^2}{\kappa^2}\left(1 - \sum_j C_j \sigma_j^z\right)^{-2} \qquad (4)$$

$$\sigma_j^z = -\left(1 + \frac{4g_j^2 |a|^2 \gamma_\perp}{\gamma_\parallel(\gamma_\perp^2 + \Theta_j^2)}\right)^{-1}.$$

These are nonlinear in nature. Experimentally as we increase the driving fields amplitude we observe, as shown in Figure 2, a clear bistable behavior in the cavity amplitude $|a(t)|^2$

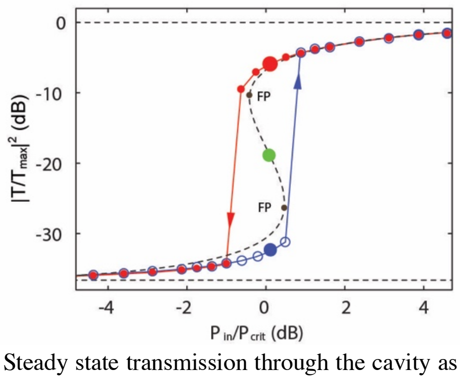

Fig. 2 Steady state transmission through the cavity as a function of increasing (blue) and decreasing (red) input power for a hybrid system with a cooperativity of $\sum C_j = C_{coll}$=78.

In the weak driving regime, the intra-cavity intensity does not saturate the spin ensemble so $\sigma_j^z \sim -1$ and so $|a|^2 \approx \eta^2/\kappa^2(1+C_{\text{coll}})^2$ while for strong driving the ensemble bleaches ($\sigma_j^z \sim 0$) resulting in $|a|^2 \approx \eta^2/\kappa^2$. There is several of orders of magnitude difference between these. Increasing the cooperativity of the system enhances this difference. We can also probe the temporal dynamics of this bistable phase transition and demonstrate a critical slowing down of the cavity population of over 10000 seconds.

Amplitude bistability is just one of the nonlinear effects this hybrid system can exhibit. Another important collective nonlinear effect is superradiance where an enhanced decay rate of the ensemble is amplified by the coherence of the electron. We demonstrate this superradiance behavior in this hybrid with an enhanced decay of a trillion of times faster than the decay for an individual NV centre.

5. Conclusions

In this work we demonstrate how a hybrid system formed by combining a superconducting circuit with an electron spin ensemble formed from NV centers in diamond has superior properties compared to those individual systems. We further demonstrate that these systems can be used to explore novel nonlinear phenomena in quantum metamaterials in a new physical regime. These proof-of-principle experiments may provide a foundation for future quantum technologies.

Acknowledgements

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