Annals of Physics 369 (2016) 36–44

Contents lists available at ScienceDirect

Annals of Physics

journal homepage: www.elsevier.com/locate/aop

Bistability and steady-state spin squeezing in diamond nanostructures controlled by a nanomechanical resonator

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ARTICLE INFO

Article history:
Received 25 October 2015
Accepted 2 March 2016
Available online 10 March 2016

Keywords:
NV center
Spin squeezing
Bistability

ABSTRACT

As the quantum states of nitrogen vacancy (NV) center can be coherently manipulated and obtained at room temperature, it is important to generate steady-state spin squeezing in spin qubits associated with NV impurities in diamond. With this task we consider a new type of a hybrid magneto-nano-electromechanical resonator, the functionality of which is based on a magnetic-field induced deflection of an appropriate cantilever that oscillates between NV spins in diamond. We show that there is bistability and spin squeezing state due to the presence of the microwave field, despite the damping from mechanical damping. Moreover, we find that bistability and spin squeezing can be controlled by the microwave field and the parameter V_z. Our scheme may have the potential application on spin clocks, magnetometers, and other measurements based on spin–spin system in diamond nanostructures.

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http://dx.doi.org/10.1016/j.aop.2016.03.001

1. Introduction

A spin squeezing state [1] is a symmetric state of an ensemble of spin particles, whose fluctuation in one collective spin direction to the mean spin direction is smaller than the classical limit. The purpose of studying the spin squeezing [1] has arisen mainly from exploring the correlation and many-body entanglement [2–4] of particles, especially improving the measurement precision in practice [5–10]. Spin squeezing of many atoms is prepared using atom–light or atom–atom interactions [11–17]. Recently, a scheme for achieving coherent spin squeezing of nuclear spin states has been proposed in semiconductor quantum dots [18]. Very recently, spin-squeezed states are produced and characterized at a temperature of 26 °C in nuclear magnetic resonance quadrupolar system [19].

In recent years, in view of the tremendous progress of localized electron spins in solids which show long relaxation [20] and coherence times, especially their states can be easily controlled and manipulated via microwave or radio frequency pulses. Detection and manipulation of single electron spin states in solids have recently received much attention [21–25]. In the last decade, the negatively charged NV center in diamond has become a promising resource for future quantum technology [26–29]. NV centers, which are consisted by a nitrogen impurity atom with an adjacent vacancy, are naturally generated in bulk diamond or diamond nanocrystals and can be operated even at room temperature [30,31]. In numerous experiments, the coherent coupling and entanglement to nuclear spins of nitrogen [32,33] and carbon-13 [34,35] has been demonstrated. An important condition is to realize the controlling interactions between the NV centers, required for quantum gates or to produce entangled spin states in quantum-enhanced sensing [36]. In light of this challenge, a useful approach toward this goal is to couple NV centers to a resonant optical [37,38] or mechanical [39–41] mode.

In this paper, we consider the coherent coupling between an ensemble of NV centers and the quantized motion of the magnetized nanomechanical resonator tips, and externally driven by a microwave field. With the help of this microwave field, bistability and steady state spin squeezing can be obtained in our system. We already know that the master equation is rather difficult to calculate with for large N. However, in our system we give average value for the spin squeezing. Since the fluctuations scale as 1/N, mean-field theory becomes selfconsistent again when N is very large. In the limit of large N, the spin squeezing is calculated analytically by considering fluctuations around the mean-field steady states. Using this method, we prove the present system can produce steady-state spin squeezing. Especially, spin squeezing can be controlled by microwave field and the parameter V_Z.

2. Model

We consider the coherent coupling between an ensemble of NV centers embedded in a single crystal diamond nanobeam and the quantized motion of the magnetized nanomechanical resonator tips. At the free end of the cantilever, an ensemble of magnetic tips is mounted as illustrated in Fig. 1. On the other hand, the same number of NV centers are positioned at a distance. The ground state of the NV centers is known to have an electron spin triplet structure with a zerofield splitting of 2.88 GHz between the $m_s = 0$ and the degenerate $m_s = \pm 1$ states. Microwaves are applied to drive the two states of the spins. If the Rabi frequency field contains only one frequency resonant to the transition between the levels $|0\rangle$ and $|-1\rangle$, the system can be reduced to the $S = 1/2$ pseudospin model which describes transitions between the states $|-1\rangle$ and $|0\rangle$ only. Since the transition between the levels $|+1\rangle$ and $|0\rangle$ is off resonance and therefore forbidden [42]. Thus the Hamiltonian of the system in the frame rotating with the frequency of the rf field has the form [42–44]

$$H_{NV} = -\delta\left(\sum_n |-1\rangle_n\langle -1| - \sum_n |0\rangle_n\langle 0|\right) + \frac{\Omega}{2}\sum_n (|-1\rangle_n\langle 0| + |0\rangle_n\langle -1|), \tag{1}$$

where δ denotes the detuning between the microwave frequency and the intrinsic frequency of the spins. The Rabi frequency Ω can be described as $\Omega = \Omega_0 - \Delta\Omega$, with $\Delta\Omega = \mu_B(B_0 + B_{ms})$. Here B_0 is the amplitude of the external constant magnetic field applied on the system, B_{ms} is the magnetic field produced by the magnetic film on the cantilever at the position of the spins.