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Laser-polarization-dependent and magnetically controlled optical bistability in diamond nitrogen-vacancy centers

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ABSTRACT

We explore laser-polarization-dependent and magnetically controlled optical bistability (OB) in an optical ring cavity filled with diamond nitrogen-vacancy (NV) defect centers under optical excitation. The shape of the OB curve can be significantly modified in a new operating regime from the previously studied OB case, namely, by adjusting the intensity of the external magnetic field and the polarization of the control beam. The influences of the intensity of the control beam, the frequency detuning, and the cooperation parameter on the OB behavior are also discussed in detail. These results are useful in real experiments for realizing an all-optical bistate switching or coding element in a solid-state platform.

1. Introduction

Control of light by light is one of the most active research topics in quantum optics and nonlinear optics because of its potential application in optical transistors, all-optical communication, quantum information and optical computing. In the past few years, all-optical switching, and all-optical storage devices based on optical bistability (OB) in various quantum systems have been extensively investigated both theoretically and experimentally [1–10]. For example, Rosenberger et al. [4] discussed a theoretical model of OB in a two-level atom with a single mode field. Xiao group [5,6] demonstrated theoretically and experimentally the realization of OB in a three-level atomic system confined in an optical ring cavity. Harshawardhan and Agarwal [3] researched coherent control of OB using electromagnetic-field-induced transparency and quantum interferences, and demonstrated the possibility of control-field-induced multistability in two-level systems. Li et al. [8,9] studied the behavior of OB in semiconductor quantum well systems with tunneling-induced interference. Wu et al. [10] proposed a scheme for realizing OB and optical multistability (OM) in a double two-level atomic system and displayed the transition from OB to OM or vice versa by adjusting the relative phase between the control and probe fields. Recently, Sheng et al. [11] experimentally observed OM in an optical ring cavity containing three-level Λ-type Doppler-broadened rubidium atoms. Furthermore, some other researches have shown that the squeezed state field [12–14], the spontaneously generated coherence [15–18], the atomic cooperation parameter [19], the phase fluctuation [20,21], and the intensity of the microwave field [22] play a crucial role in controlling the bistable threshold intensity and the hysteresis loop.

On the other hand, the nitrogen-vacancy (NV) centers in diamond nanocrystal have emerged as particularly strong candidates for solid-state quantum physics experiments and quantum information processing because they possess a long electronic spin decoherence time at room temperature, single-shot spin detection, subnanosecond spin control, and efficient quantum state transfer between electron and nearby nuclear spins [23–48]. Owing to the potential key roles of diamond NV centers in solid-state quantum information and quantum computing, many properties and interesting phenomena about them are researched and discussed recently. Fuchs et al. [32] investigated spin coherence during optical excitation of a single NV center in diamond nanocrystal at room temperature using Ramsey experiments. Their measurements indicate the process fidelity is 0.87 ± 0.03 and the extrapolation to the moment of optical excitation is ≈ 0.95. Yang et al. [34] investigated the dynamics of a laser-driven and dissipative system consisting

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of the two NV centers embedded in two spatially separated single-mode nanocavities in a planar photonic crystal, and analyzed the relevant entanglement dynamics in the presence of decoherence. Wang and Dobrovitski [44] studied the applicability of the time-optimal bang–bang control designed for spin 1/2 to the rotation of the electron spin of an NV center in diamond. They find that the bang–bang control protocol decreases the rotation time by 20–25% in comparison with the traditional oscillating sinusoidal driving. Santori et al. [47] demonstrated, for the first time, a coherent population trapping (CPT) in a single NV center in diamond under optical excitation, the results show that all-optical control of single spins is possible in diamond. More recently, Du et al. [48] realized continuous-wave dynamical decoupling (CWDD) and quantum gate operation in a single NV center in diamond. The coherence time of the NV center is prolonged by about 20 times with CWDD and the performance of the quantum gate of a given duration is greatly improved compared to the same quantum manipulation without CWDD. However, to the best of our knowledge, no related theoretical or experimental work has been carried out to realize OB in diamond NV centers, which motivates the current work.

Based on these achievements, here we investigate the control of OB in diamond NV centers driven by an elliptically polarized coherent field and an external magnetic field inside a unidirectional ring cavity. Various parameters can be adjusted to change the bistable behavior, including a magnetic field. The physical mechanism of this type of OB is that the cavity field experiences third-order Kerr nonlinearities when it passes through an ensemble of NV centers in diamond, which can be coherently manipulated by an elliptically polarized control field. In the present system there is only one cavity field, since the control field (not on resonance in the cavity) is only used to prepare the coherent medium and generate a large Kerr nonlinearity. Our proposed scheme is mainly based on Refs. [47,49,50], but our work is drastically different from those works. First and foremost, we are mainly interested in showing the control of the OB behavior in an NV center system via the different parameters. Secondly, the intensity of external magnetic field can be used to control OB, which makes our scheme much more practical than the other schemes due to the magnetic field is more easily available and more effective control compared with an extra laser field. Thirdly, we only need one single elliptically polarized control field to couple two electric dipole transitions simultaneously and the polarization-dependent phase difference between the two circularly polarized components of the control field can control OB effectively. Naturally, the combination of an elliptically polarized laser field and an external magnetic field offers us further flexibility to manipulate OB.

The Letter is organized as follows. In Section 2, we present the theoretical model and establish the corresponding equations for the ring cavity input–output relation. In Section 3, we give a detailed analysis and explanation for the behaviors of OB. In Section 4, we provide a possible experimental realization of our proposed scheme. Finally, our main conclusions are summarized in Section 5.

2. Description of physical model and cavity input–output relation

We consider NV color centers in diamond consist of a substitutional nitrogen atom (N) plus a vacancy (V) in an adjacent lattice site as shown in Fig. 1(a), which is negatively charged with two unpaired electrons located at the vacancy, usually treated as electron spin-1 [51–53]. The spin–spin interaction leads to the energy splitting $D_{gs} = 2.88$ GHz between the ground levels $|^3A, m_s = 0\rangle$ and $|^3A, m_s = \pm 1\rangle$ as depicted in Fig. 1(b). Meanwhile, the degeneracy of the ground sublevels $|^3A, m_s = \pm 1\rangle$ can be lifted by employing an external static magnetic field B along the quantized symmetry axis of diamond NV centers, which induces a Zeeman splitting $2\Delta_B$. We label $|^3A, m_s = 0\rangle$, $|^3A, m_s = -1\rangle$ and $|^3A, m_s = +1\rangle$ as $|0\rangle$, $|1\rangle$ and $|2\rangle$, respectively. The NV center has a relatively complicated structure of excited states [33], which includes six excited states defined by the method of group theory as $|A_1\rangle = \frac{1}{\sqrt{2}}(|E_-, m_s = +1\rangle - |E_+, m_s = -1\rangle)$, $|A_2\rangle = \frac{1}{\sqrt{2}}(|E_-, m_s = +1\rangle + |E_+, m_s = -1\rangle)$, $|E_x\rangle = |X, m_s = 0\rangle$, $|E_y\rangle = |Y, m_s = 0\rangle$, $|E_1\rangle = \frac{1}{\sqrt{2}}(|E_-, m_s = -1\rangle - |E_+, m_s = +1\rangle)$, and $|E_2\rangle = \frac{1}{\sqrt{2}}(|E_-, m_s = -1\rangle + |E_+, m_s = +1\rangle)$, with $|E_+\rangle$, $|E_-\rangle$ being orbital states with angular momentum projection ± 1 along the NV axis, and $|X\rangle$, $|Y\rangle$ being orbital states with zero projection of angular momentum. Spin-conserving transitions between the ground state and six different excited states can be driven optically. Under moderate transverse strain, level anticrossings in the lower excited-state orbital (Ex) mix electron spin projection, permitting optical transitions from both ground-state $m_s = 0$ and $m_s = \pm 1$ manifolds [47,49], the state $|3\rangle$ can be considered as a mixed state of two excited states $|E_x\rangle = |X, m_s = 0\rangle$ and $|A_2\rangle = \frac{1}{\sqrt{2}}(|E_-, m_s = +1\rangle + |E_+, m_s = -1\rangle)$, i.e., $|3\rangle = \alpha|A_2\rangle + \beta|E_x\rangle$ with $|\alpha|^2 + |\beta|^2 = 1$. The state $|3\rangle$ decays to the ground-state sublevels $|1\rangle$ and $|2\rangle$ with radiation of σ^+ and σ^- circular polarizations, respectively. While the state $|E_x\rangle$ can be coupled to the ground state $|0\rangle$ with linear polarization [33,34]. Now we couple the transition $|3\rangle \leftrightarrow |0\rangle$ with a linearly polarized probe field with a carrier frequency ω_p and one-half Rabi frequency $\Omega_p = \mu_{30}E_p/(2\hbar)$, where E_p is the amplitude of the probe field and μ_{30} is the electric dipole moment for the transition $|3\rangle \leftrightarrow |0\rangle$. The electric dipole transitions from the excited state $|3\rangle$ to the two ground states $|1\rangle$ and $|2\rangle$ are driven simultaneously by an elliptically polarized control field with a carrier frequency ω_c. The elliptically polarized control field can be regarded as a combination of the right- and left-circularly polarized components [50], which can be obtained by using a quarter-wave plate (QWP). An initial vertically polarized control beam with intensity I_0 and electric field amplitude $E_0 = \sqrt{\frac{2I_0}{\varepsilon_0 c}}$, where ε_0 is the permittivity of free space and c the speed of light, becomes elliptically polarized after passing through the QWP that has been rotated by an angle θ (the polarization-dependent parameter), so the polarized control beam can be decomposed into $E_c = E^+\sigma^+ + E^-\sigma^-$, where $E^+ = \frac{E_0}{\sqrt{2}}(\cos\theta + \sin\theta)e^{i\theta}$ and $E^- = \frac{E_0}{\sqrt{2}}(\cos\theta - \sin\theta)e^{-i\theta}$. Here, σ^+ and σ^- are the unit vectors of the right- and left-circularly polarized basis, respectively. When $\theta = 0$ and $\pi/2$, we have $E^+ = E^-$, that is, the control beam is linearly polarized. When $\theta = \pi/4$ ($3\pi/4$), we have $E^- = 0$ ($E^+ = 0$), that is, the control beam is right-handed circularly (left-handed circularly) polarized. The QWP can change the strengths and phase difference of the two electric field components. Then, the one-half Rabi frequencies become $\Omega_{c+} = \mu_{31}E^+/(2\hbar) = \Omega_c(\cos\theta + \sin\theta)e^{i\theta}$ and $\Omega_{c-} = \mu_{32}E^-/(2\hbar) = \Omega_c(\cos\theta - \sin\theta)e^{-i\theta}$, here we assume $\mu_{31} = \mu_{32} = \mu$ (μ denotes the electric dipole moment between the corresponding transitions) and $\Omega_c = \mu E_0/(2\sqrt{2}\hbar)$.

Under the rotating-wave approximation (RWA) and electric-dipole approximation (EDA), the interaction Hamiltonian for our system can be written as [54–56] (taking $\hbar = 1$)

$$\hat{H}_I = \Delta_p|3\rangle\langle 3| + (\Delta_p - \Delta_c + \Delta_B)|2\rangle\langle 2| + (\Delta_p - \Delta_c - \Delta_B)|1\rangle\langle 1| - \left[\Omega_p|3\rangle\langle 0| + \Omega_{c+}|3\rangle\langle 1| + \Omega_{c-}|3\rangle\langle 2| + \text{H.c.}\right], \quad (1)$$

where H.c. means Hermitian conjugation, the notations $\Delta_c = \omega_{31} - \Delta_B - \omega_c = \omega_{32} + \Delta_B - \omega_c$ and $\Delta_p = \omega_{30} - \omega_p$ are the detunings of the electronic transitions from the corresponding laser frequencies. Δ_B is the Zeeman shift of levels $|1\rangle$ and $|2\rangle$ in the presence of an external magnetic field (see Fig. 1(b)). Then, by the standard