Hybrid continuous dynamical decoupling: a photon-phonon doubly dressed spin

Jean Teissier, Arne Barfuss and Patrick Maletinsky

Quantum Sensing Group, Department of Physics, University of Basel, Klingelbergstrasse 82, CH-4056 Basel, Switzerland

E-mail: patrick.maletinsky@unibas.ch

Received 27 October 2016, revised 16 January 2017
Accepted for publication 9 February 2017
Published 14 March 2017

Abstract

We study the parametric interaction between a single nitrogen-vacancy electronic spin and a diamond mechanical resonator in which the spin is embedded. Coupling between spin and oscillator is achieved by crystal strain, which is generated upon actuation of the oscillator and which parametrically modulates the spins’ energy splitting. Under coherent microwave driving of the spin, this parametric drive leads to a locking of the spin Rabi frequency to the oscillator mode in the megahertz range. Both the Rabi oscillation decay time and the inhomogeneous spin dephasing time increase by two orders of magnitude under this spin-locking condition. We present routes to prolong the dephasing times even further, potentially to the relaxation time limit. The remarkable coherence protection that our hybrid spin-oscillator system offers is reminiscent of recently proposed concatenated continuous dynamical decoupling schemes and results from our robust, drift-free strain-coupling mechanism and the narrow linewidth of the high-quality diamond mechanical oscillator employed. Our findings suggest feasible applications in quantum information processing and sensing.

Keywords: hybrid quantum systems, spin, mechanical oscillator, diamond, coherence

(Some figures may appear in colour only in the online journal)
driving field, would protect the spin even further. In principle, this procedure can be iterated ad infinitum and may then yield relaxation limited coherence times [17]. The application of many consecutive decoupling fields, however, exposes the spin to significant driving field powers and sets intrinsic constraints to the speed at which the final, decoherence protected spin states can be coherently manipulated [17]. New approaches to continuous dynamical decoupling are therefore required to yield fully robust spin systems which are of practical use to quantum information processing and sensing.

In this work, we experimentally demonstrate a novel and efficient approach to continuous dynamical decoupling, through the parametric interaction of a single electronic spin with a mechanical resonator. We employ a coherent microwave drive for first order decoupling and use the spin-oscillator interaction to decouple the spin from amplitude fluctuations in the microwave field. This concatenated, hybrid continuous dynamical decoupling (HCDD) builds on two key advances over past approaches [17]: (1) second order decoupling is achieved by a parametric drive along the quantisation axis of the undriven spin. The second order driving field is thus orthogonal to the first order drive, irrespective to the phase between these two fields, in contrast to the conventional dynamical decoupling by concatenated driving, where phase-locking between the driving field is required to ensure the necessary orthogonality. (2) The second order decoupling field is transduced to the spin through a mechanical oscillator, whose resonant behaviour effectively low-pass filters amplitude noise and yields a highly stable, second order driving field amplitude. A concatenation of only two driving fields thereby yields a coherence time nearly two orders of magnitude longer than that of an undriven spin, while also maintaining a final dressed state splitting close to one MHz. By using mechanical oscillators with even higher quality-factors, our scheme should allow us to prolong coherence times even further and ultimately reach the limit imposed by energy relaxation.

Our experiments were performed on individual, negatively charged nitrogen-vacancy (NV) defect centres embedded in singly clamped cantilever diamond mechanical oscillators (figure 1(b)). The cantilevers exhibited typical fundamental mode-frequencies $\omega_m$ in the MHz range ($\omega_m = 2\pi \times 5.81$ MHz for the cantilever studied here) and were fabricated along the [110] crystal axis of ultra-pure, single-crystal, synthetic diamond using top-down nanofabrication described elsewhere [18, 19]. NV centres were created at densities $<1$ $\mu$m$^{-2}$ by $^{14}$N ion implantation and subsequent high-temperature annealing [20]. We used a homebuilt confocal microscope to study spin-dynamics of a NV centre located at the base of the cantilever, where strain-fields for parametric driving are maximised [21, 22]. The cantilevers were mechanically actuated using a piezoelectric transducer, which was placed nearby the sample. All our experiments were performed under ambient conditions.

The NV centre orbital ground state is a spin-triplet, with $S_z$ eigenstates $|-1\rangle$, $|0\rangle$, $|+1\rangle$, where $S_z$ is the angular momentum operator along the NV binding axis $z$. The magnetic sublevels $|\pm1\rangle$ are split from $|0\rangle$ by a zero-field splitting $D_0 = 2.87$ GHz and can be further split in energy by a magnetic field $B_z$ along $z$ [23]. Optical spin-readout and initialisation into $|0\rangle$ is readily achieved by green optical illumination and detection of red NV fluorescence, while the spin can be coherently driven by applying resonant microwave magnetic fields, $B_0$, transverse to $z$ [24, 25]. In this work, we consider the dynamics of the effective two-level system formed by $|0\rangle = |\downarrow\rangle$ and $|-1\rangle = |\uparrow\rangle$, while the state $|1\rangle$ is split off in energy by a static magnetic field $B_z = 10.7$ G and ignored in the following. In addition to near-resonant microwave driving with transverse magnetic fields, we employ parametric driving by time-varying (AC) strain fields along $z$ generated by the cantilever (figure 1(a)). The effective Hamiltonian for the two-level system spanned by $\{ |\downarrow\rangle, |\uparrow\rangle \}$ then reads

$$H/\hbar = (D_0 - \gamma_{NV} B_z + d_{||}(\Omega_{AC})\sigma_z + \gamma_{NV} B_{AC}^2 \sigma_z),$$

with $\sigma_i$ the Pauli matrices along direction $i \in \{ x, z \}$, $\gamma_{NV} = 2.8$ MHz G$^{-1}$ the NV gyromagnetic ratio and $B_{AC}^2 = (\Omega_{MW}/2\gamma_{NV})^2 \cos^2 (\omega_{MW} t)$ the microwave driving field with frequency $\omega_{MW}$ and amplitude (Rabi frequency) $\Omega_{MW}$. Parametric driving of the spin is achieved by on-axis, AC strain $\Pi_{AC}^z = \Pi_0^z \cos (\omega_{MW} t)$ with peak amplitude $\Pi_0^z$, induced by the cantilever oscillation. Such parallel strain
couples to the NV centre with strength $d_{ij} \approx 5.5$ GHz/strain [21, 22]. For this study, we worked with NV centres aligned along the [111] or [111] direction, which exhibit significant longitudinal strain and weaker transverse strain upon bending of our [110]-oriented cantilevers. The transverse AC strain component couples states $|-1\rangle$ and $|+1\rangle$, which leads to coherent Rabi oscillations, if the strain-field and the $|-1\rangle \rightarrow |+1\rangle$ transition energy are resonant [9]. To suppress this coupling, we used the bias field $B_z$ to set the transition energy $\gamma_{N1} B_z \approx 60$ MHz far off-resonance from the cantilever frequency. The effect of transverse strain can therefore be neglected for the present work. Note that while data for only one NV centre are presented here, we found consistent results for all investigated NV centres, which were oriented along [111] or [111], i.e. for 50% of all NVs present. This yield could be increased to close to 100% using recently developed growth methods for creation of fully aligned NV centres [26], together with an appropriate cantilever fabrication procedure.

To provide a baseline for our subsequent measurements, we first determined the relevant NV spin relaxation times in the absence of mechanical driving. The NV population decay time $T_1$ was determined using the experimental pulse sequence illustrated in figure 1(c). Following initialisation in $|\downarrow\rangle \rightarrow |\uparrow\rangle$, we determine the difference $\Delta P = P(\downarrow \downarrow) - P(\downarrow \uparrow)$, as function of the variable delay $\tau$, where $P(i|j)$ is the population in state $|i\rangle$, after initialisation in state $|j\rangle$ ($i,j \in \{\downarrow, \uparrow\}$). We obtain $\Delta P$ directly from the transient NV fluorescence photons $c_1$ and $c_0$ as defined in figure 1(c), as

$$\Delta P(\tau) = (c_0(\tau) - c_1(\tau))/ (c_0(0) - c_1(0)).$$

Therefore, $\Delta P$ yields a measure for the spin population decay, from which we determine $T_1 = 51 \pm 8$ ms through an exponential fit (figure 1(c)). Similarly, we determined the decay-time $T_2$ of the spin’s Rabi oscillations by pulsed, coherent driving of the $|\uparrow\rangle \leftrightarrow |\downarrow\rangle$ transition with a resonant microwave magnetic field of variable duration $\tau$ (figure 1(d)). The observed Rabi oscillations show a pronounced beating pattern that results from the $\sim 2.18$ MHz hyperfine-splitting between the NV electronic spin and the nitrogen’s $^{14}$N nuclear spin ($\hbar\Omega_{MW} = 1$ [27]). Our data is well fit by $\sum_{i=\downarrow,\uparrow} A_i \cos(\Omega_{eff}^{i} \tau)e^{-\gamma_{fl}^{i}/T_2}$ (figure 1(d), orange), where $\Omega_{eff}^{i} = \sqrt{\Omega_{MW}^2 + \delta_i^2}$ are the effective Rabi frequencies and $\delta_i$ the detunings between the microwave drive and each of the three hyperfine transitions. From the fit, we find $\Omega_{MW} = 2\pi \times 5.81$ MHz and $T_2 = 5.3 \pm 0.2 \mu$s, which is three orders of magnitude shorter than the relaxation-limit set by $T_1$ [1].

The Gaussian decay-envelope of our Rabi oscillations suggests that slowly fluctuating noise sources are responsible for the excess dephasing we observed [28]. While both $\Omega_{MW}$ and $\delta_i$ may fluctuate, in our experiment, where $\Omega_{MW} \gtrsim 2\delta_i$, only the former contributes to first order to dephasing. Indeed, we were able to quantitatively reproduce the observed decay envelope (orange line in figure 1(d)) by numerically averaging over Rabi oscillations with random microwave amplitude noise of relative amplitude $6 \times 10^{-3}$—a typical value for the commercial microwave sources we employ.

In the presence of continuous, resonant microwave driving, the eigenstates of the driven spin system are the ‘dressed states’ $|\pm_N\rangle = (|\uparrow\rangle, |N\rangle \pm |\downarrow, N-1\rangle)/\sqrt{2}$ [17, 29], with energy difference $\delta |\Omega_{MW}$ and $N$ the number of microwave photons dressing the spin (i.e. the mean photon number in the coherent microwave field which drives the spin). These new basis states form a potential resource for quantum information processing [14] or sensing [17]. The Rabi decay time $T_R$, which can be interpreted as the dressed state relaxation time [30], is then a key figure of merit for such applications. To further prolong $T_R$, we decouple $|\pm_N\rangle$ from fluctuations in $\Omega_{MW}$ by applying an additional driving field,
which near-resonantly and coherently drives the $|+N\rangle \leftrightarrow |-N\rangle$ transition (figure 2(b)) and consequently lead to higher-order dressed states—the principle underlying dynamical decoupling by concatenated continuous driving [17].

We achieve second order dressing and the associated dynamical decoupling by driving the $|+N\rangle \leftrightarrow |-N\rangle$ transition using the time-varying, longitudinal strain field generated by the diamond cantilever in which the NV spin is embedded. Such driving is enabled by the coupling term $d_1|\Pi|^\dagger \sigma_z$ (see equation (1)), which drives the desired transition at a rate $\Omega_m = d_1|\Pi|^\dagger \langle +N | \sigma_z | -N \rangle \neq 0$. Resonance of that second drive tone with the dressed state energy splitting can be achieved by adjusting $\Omega MW$ to fulfill $\Omega MW \approx \omega_m$, while $\omega_m$ is fixed and given by the cantilever geometry.

To demonstrate second order dressing and the subsequent coherence protection, we performed resonant Rabi oscillation measurements up to an evolution time $\tau_{\text{max}} = 16 \mu s$ at variable $\Omega MW$ and in the presence of a parametric, cantilever-induced strain-drive of fixed amplitude $\Omega_m$. We experimentally determined $\Omega_m \approx 2 \pi \times 4.1 MHz$ through characteristic spectral features appearing in the resulting NV Rabi oscillations (see below). Figure 2(a) shows the Fourier transformation of each experimental Rabi oscillation as a function of $\Omega MW$. For $\Omega MW$ far from the dressed-state transition energy (i.e. for $|\Omega MW - \omega_m| \gg \Omega_m$), the spin precession dynamics are dominated by a single peak at frequency $\Omega MW/2\pi$, as expected for conventional, coherent spin driving (white dashed line in figure 2(a)). The weak, additional spectral features visible in this regime stem from the two additional, hyperfine-split NV spin transitions, which are weakly, off-resonantly driven. For $\Omega MW \approx \omega_m = 2 \pi \times 5.81 MHz$, however, we observe a spectrum that shares striking similarities with the well-known Mollow-triplet in quantum electrodynamics [31, 32]: the measured coherent spin oscillations peak at a single frequency $\omega_m/2\pi$, irrespective of the exact value of $\Omega MW$, with only two weak side bands, which appear at $\omega_m \pm \Omega MW/2\pi$ and thereby allow us to quantitatively determine $\Omega_m$ [31]. Such spin-oscillator frequency-locking, induced by parametric strain-driving of a bulk NV centre in a mechanical oscillator, was previously observed for NV centres in diamond nanocrystals parametrically driven by the magnetic fields from a nearby antenna [31] or by the mechanical motion of a spin in a strong magnetic field gradient [32].

This phenomenon of frequency-locking is at the heart of our HCDD scheme and indeed efficiently decouples the NV spin from environmental fluctuations. The parametric drive couples the microwave dressed states $|\pm N\rangle$ and thereby yields new eigenstates $|\pm N,M\rangle$, now doubly dressed by $N$ photons and $M$ cantilever phonons [31]. For resonant strain-driving ($\Omega MW = \omega_m$, $\Omega MW = \omega_m \pm (M+1) \pm |+N, M\rangle |\Pi|^\dagger \sqrt{2}$, where $M$ denotes the mean number of phonons in the cantilever, and $|+N, M\rangle$ is split from $|-N, M\rangle$ by an energy $\hbar \Omega_m/2$. The resulting, doubly dressed energy spectrum is illustrated in figure 2(b) as a function of $\Omega_m$, along with the possible transitions allowed between adjacent dressed states. These transitions are indeed also observed in the experimentally measured spin-precession spectra (coloured dashed lines in figure 2(a)). The transition with the largest spectral weight, $|\pm N,M\rangle \leftrightarrow |\pm N,M-1\rangle$, occurs at $\omega_m/2\pi$ and corresponds to a transition that changes the phonon number $M$ at constant microwave photon number $N$. The data presented in figure 2(a) indicate how doubly dressing using mechanically induced parametric strain driving protects the Rabi oscillations from environmental noise and prolongs their decay time: All involved energy levels are insensitive to first-order to fluctuations of $\Omega MW$ around $\omega_m$, within the central peak at a precession frequency $\omega_m/2\pi$ insensitive to arbitrary orders. The same holds for vulnerability to microwave detunings (i.e. $\omega MW \neq \omega_0$): the only perturbation which affects the energies of the doubly dressed states to first order are fluctuations in $\Omega_m$, which are intrinsically low (see below).

This coherence protection through double dressing is already visible in the width of the dominant central frequency component (figure 2(a)), which is significantly narrower than all other spectral features but still limited by the measurement bandwidth $1/\tau_{\text{max}}$. To determine the intrinsic linewidth of this spectral feature, we conducted long-time Rabi oscillation measurements for resonant driving at $\Omega MW = \omega_m$. The result (figure 3) shows sustained, coherent Rabi oscillations at frequency $\omega_m/2\pi$ with a characteristic exponential decay over $T _{\text{Rabi}} = 2.9 \pm 0.3 ms$. This value is close to three orders of magnitude longer than the Gaussian decay time determined earlier without parametric mechanical driving, and the exponential decay we find indicates that the decay being induced by rapidly fluctuating noise sources, i.e. not by microwave power fluctuations anymore.

The Rabi oscillation under parametric driving we observed allowed us to directly assess the coherence time $T ^*_{\text{d.d.}}$ of the doubly dressed spin states $|\pm N,M\rangle$. As indicated in figure 2(b), $|+N, M\rangle$ and $|-N, M\rangle$, are split in energy by $\hbar \Omega_m/2$ , whose fluctuations of variance $\Delta \Omega_m$ thus directly set the inhomogeneous dephasing time of the two-level system formed by $|\pm N,M\rangle$ as $T _{\text{d.d.}} = 1/\sqrt{2 \pi \Delta \Omega_m}$ [33]. To assess $\Delta \Omega_m$ and therefore $T _{\text{d.d.}}$, we determined the decay-time of the transient oscillations of the observed Rabi oscillations [17], i.e. the width of the Mollow-triplet sidebands, which are mutually split by $\Omega_m$ (figure 2(a)). Figure 4(a) shows how these transient oscillations decay for $\Omega_m = 2 \pi \times 200 kHz$, with a Gaussian decay-time $T _{\text{decay}} = 59 \mu s$. The coherence time is monotonically increasing with mechanical driving strength $\Omega_m$ (figure 4(b)), as expected for concatenated decoupling by continuous driving. This increase, however, does not persist beyond $\Omega_m = 2 \pi \times 800 kHz$ (for which $T _{\text{d.d.}} = 110 \pm 17 \mu s$), due to increased mechanical noise (presumably due to nonlinearities of our diamond oscillator) at these high driving amplitudes. This deterioration is already visible in figure 3, where $\Omega_m = 2 \pi \times 4.1 MHz$, and the initial, transient amplitude oscillations decay on a fast timescale $T _{\text{d.d.}} \approx 4 \mu s$. Extending $T _{\text{d.d.}}$ further by increasing $\Omega_m$ would be possible through mechanical oscillators which yield higher strain fields, while avoiding nonlinearities when driven at high amplitudes [10].
Our novel continuous decoupling scheme takes advantage of double-dressing with photons and phonons to enhance spin coherence of NV spins. In that sense, it bears strong similarity to the recently demonstrated decoupling by concatenated driving \[17\]. Here, however, we also take advantage of the properties of our diamond mechanical oscillator for amplitude noise filtering, which in principle eliminates the need for further, higher-order decoupling fields. Indeed, mechanical resonators in general act as a low pass filters for amplitude-noise, with a cut-off frequency set by the mechanical line-width \(\omega_{lp} = \sqrt{\frac{\kappa}{m_c}}\), with \(Q\) the mechanical quality-factor. For our experiment under ambient conditions, we find \(\sim Q \approx 530\), and therefore \(\sim f_{\text{cutoff}} \approx 11\) kHz, which still poses an important limitation to the coherence protection we can achieve. We note that under vacuum conditions, \(Q \approx 10^6\) was reported for diamond mechanical oscillators \[34\], which would then yield \(\sim f_{\text{cutoff}} \approx 5\) Hz \(< 1/T_1\) and decoupling from the environment and driving field noise up to the ultimate limit imposed by the spin lifetime, \(T_1\) \[17\].

To conclude, we have demonstrated a novel HCDD scheme for a single spin that combines resonant microwave excitation with parametric driving of the spin by using strain generated in a nanomechanical oscillator. With this approach, we decoupled the spin from environmental noise and extended both the coherence time (from the typical \(T_2^* \approx 2\) \(\mu\)s to \(T_{2,\text{d.d.}} \approx 100\) \(\mu\)s) and the Rabi decay time (from 5.3 \(\mu\)s to 2.9 ms). Next experimental steps may include the use of high quality-factor mechanical oscillators for coherence protection up to the \(T_1\)-limit and the demonstration of coherent manipulation of dressed spin states. Our work thereby offers attractive perspectives for employing HCDD of NV centre...
spins for applications in quantum information processing and quantum sensing.

Acknowledgments

We thank A Retzker, M Kasperczyk, M Munsch, B Shields and E Oudot for fruitful discussions and valuable input. We gratefully acknowledge financial support through the NCCR QSIT, a competence center funded by the Swiss NSF, through the Swiss Nanoscience Institute, by the EU FP7 project DIADEMS (grant #611143) and through SNF Project Grant 200021_143697/1.

References

[1] Slichter C P 1990 Principles of Magnetic Resonance vol 1 (Heidelberg: Springer)
[2] Myers B A, Ariyaratne A and Jayich A C B 2016 arXiv:1607.02553 [cond-mat.mes-hall]
[3] Amasha S, MacLean K, Radu I P, Zambühlt D M, Kastner M A, Hanson M P and Gossard A C 2008 Phys. Rev. Lett. 100 046803
[4] Fuchs G D, Dobrovitski V V, Toyli D M, Heremans F J and Awschalom D D 2009 Science 326 1520
[5] Viola L, Viola L, Knill E, Knill E, Lloyd S and Lloyd S 1999 Phys. Rev. Lett. 82 2417
[6] Viola L et al 1998 Phys. Rev. A 58 2733
[7] Fanchini F F, Hornos J E M and Napoliato R D J 2007 Phys. Rev. A 75 022329
[8] Golter D A, Baldwin T K and Wang H 2014 Phys. Rev. Lett. 113 237601
[9] Barfuss A, Teissier J, Neu E, Nunnenkamp A and Maletinsky P 2015 Nat. Phys. 11 820
[10] MacQuarrie E R, MacQuarrie E R, Gosavi T A, Gosavi T A, Bhave S A, Bhave S A, Fuchs G D and Fuchs G D 2015 Phys. Rev. B 92 224419
[11] Bar-Gill N, Pfam L M, Jarmola A, Budker D and Walsworth R L 2013 Nat. Commun. 4 1743
[12] De Lange G, Wang Z H, Riste D, Dobrovitski V V and Hanson R 2010 Science 330 60
[13] Van der Sar T et al 2012 Nature 484 82
[14] Timoney N et al 2011 Nature 476 185
[15] Xu X et al 2012 Phys. Rev. Lett. 109 070502
[16] Khodjasteh K and Lidar D A 2005 Phys. Rev. Lett. 95 180501
[17] Cai J-M, Naydenov B, Pfeiffer R, McGuinness L P, Jahnke K D, Jelezko F, Plenio M B and Retzker A 2012 New J. Phys. 14 113023
[18] Maletinsky P, Hong S, Grinolds M S, Hausmann B, Lukin M D, Walsworth R L, Loncar M and Yacoby A 2012 Nat. Nanotechnol. 7 320
[19] Ovartchaiyapong P, Pascal L M A, Myers B A, Lauria P and Bleszynski Jayich A C 2012 Appl. Phys. Lett. 101 163505
[20] Chu Y et al 2014 Nano Lett. 14 1982
[21] Teissier J, Barfuss A, Appel P, Neu E and Maletinsky P 2014 Phys. Rev. Lett. 113 020503
[22] Ovartchaiyapong P, Lee K W, Myers B A and Jayich A C B 2014 Nat. Commun. 5 4429
[23] Doherty M W, Manson N B, Delaney P, Jelezko F, Wrachtrup J and Hollenberg L C 2013 Phys. Rep. 528 1
[24] Jelezko F, Gaebel T, Popa I, Gruber A and Wrachtrup J 2004 Phys. Rev. Lett. 92 076401
[25] Gruber A, Dräbenstedt A, Tietz C, Fleury L, Wrachtrup J and von Borczyskowski C 1997 Science 276 2012
[26] Lesik M, Tetienne J-P, Tallaire A, Achard J, Mille V, Gicquel A, Roch J-F and Jacques V 2014 Appl. Phys. Lett. 104 113107
[27] He X-F, Manson N B and Fisk P T H 1993 Phys. Rev. B 47 8816
[28] Kubo Y et al 2011 Phys. Rev. Lett. 107 220501
[29] Cohen-Tannoudji C, Dupont-Roc J and Grynberg G 1992 Atom–Photon Interactions: Basic Processes and Applications (New York: Wiley-Interscience, Wiley)
[30] Rohr S, Dupont-Ferrier E, Pigeau B, Verlot P, Jacques V and Arcizet O 2014 Phys. Rev. Lett. 110 010502
[31] Rohr S 2014 Hybrid spin-nanomechanical systems in parametric interaction PhD Thesis Institut Neel, Grenoble
[32] Pigeau B, Rohr S, de Lépiney L M, Gloppe A, Jacques V and Arcizet O 2013 J. Phys. 82 113107
[33] Jamonneau P et al 2016 Phys. Rev. B 93 024305
[34] Tao Y, Boss J, Moores B and Degen C 2014 Nat. commun. 5 3638