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Randomized benchmarking of quantum gates implemented by electron spin resonance

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ABSTRACT

Spin systems controlled and probed by magnetic resonance have been valuable for testing the ideas of quantum control and quantum error correction. This paper introduces an X-band pulsed electron spin resonance spectrometer designed for high-fidelity coherent control of electron spins, including a loop-gap resonator for sub-millimeter sized samples with a control bandwidth ∼40 MHz. Universal control is achieved by a single-sideband upconversion technique with an I–Q modulator and a 1.2 GS/s arbitrary waveform generator. A single qubit randomized benchmarking protocol quantifies the average errors of Clifford gates implemented by simple Gaussian pulses, using a sample of gamma-irradiated quartz. Improvements in unitary gate fidelity are achieved through phase transient correction and hardware optimization. A preparation pulse sequence that selects spin packets in a narrowed distribution of static fields confirms that inhomogeneous dephasing ($1/T_2^*$) is the dominant source of gate error. The best average fidelity over the Clifford gates obtained here is 99.2%, which serves as a benchmark to compare with other technologies.

1. Introduction

Pulsed electron spin resonance (ESR) techniques have been developed and applied in many areas, including physics, chemistry and biochemistry [1–3]. Another important application is quantum information processing (QIP) [4–11]. Systems in which an electron is coupled to nuclei through the hyperfine interaction are advantageous over conventional nuclear magnetic resonance (NMR) QIP experiments. The electron spin polarization can be transferred to the nuclear spins [11–15], and fast gate operations can be realized using only microwaves, if the hyperfine interaction has a strong anisotropic component [7–9]. While gate operations are done through the electron via microwave control, relatively long coherence times of the nuclei can be exploited for storing information [16]. Thus the electron-nuclear hybrid spin system is promising for developing advanced QIP architectures [6,16,17]. Such systems permit testing the ideas of quantum control and quantum error correction [18–23] in a setting unavailable to classical simulations, opening a path to the development of large scale quantum devices based on spins.

The ability to generate accurate control pulses with arbitrary amplitudes and phases is required to realize a universal set of quantum gates with high fidelity. Moreover, in other spectroscopic techniques such as double electron–electron resonance (DEER) [24,25] and solution-state 2D electron–electron double resonance (2D-ELDOR) [1,26,27], arbitrary waveform generation is beneficial for creating desired excitation profiles [28–31]. Integrating an arbitrary waveform generator (AWG) into pulsed ESR spectrometers has been reported in several previous works [8,9,28–33]. In order to achieve precise coherent control, efforts have also been made to overcome pulse distortions due to limited bandwidth of the resonator and amplifier non-linearity [9,28–31,34]. However, quantitative characterization of unitary gate fidelities and detailed studies of the sources of infidelity in pulsed ESR systems have been rarely addressed [4,5,28].

Randomized benchmarking (RB) [35–39] is a well-developed, scalable approach for estimating the average error probabilities of quantum gates apart from the state preparation and measurement (SPAM) errors. When comparing to the CP/CPMG method

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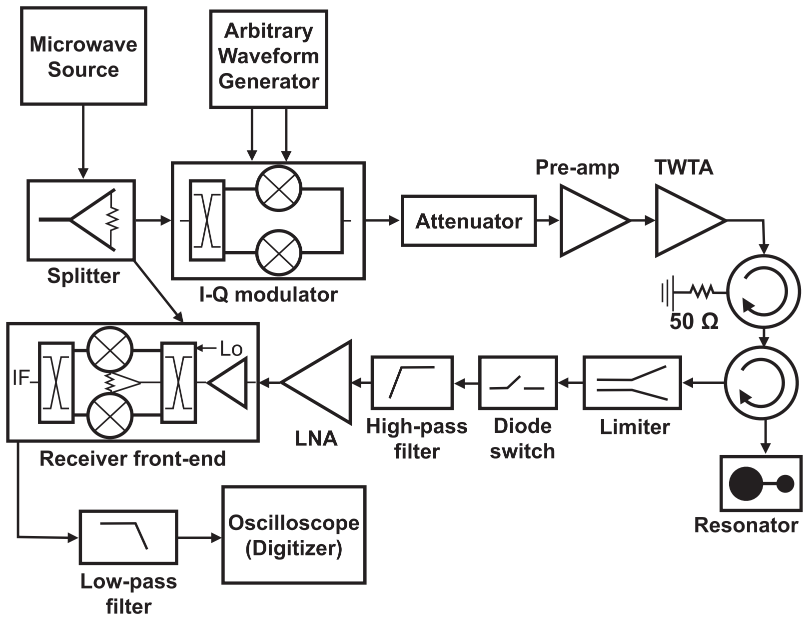

Fig. 1. Schematic of the home-built X-band ESR spectrometer. A signal generated from the microwave source is mixed at the I–Q modulator with 0° and 90° phase-shifted components of a shaped pulse from the arbitrary waveform generator. The I–Q modulator outputs the shaped pulse at upconverted frequency, and the pulse phase is accurately controlled by a method explained in the text. A TWT amplifier combined with a pre-amplifier and an attenuator provides an output power up to 500 W. The amplified pulse is transmitted to the loop-gap resonator containing the sample. In the receiver, the ESR signal is mixed with the reference frequency and downconverted to an IF signal, which is digitized by a fast oscilloscope.

for quantifying single-qubit rotation amplitude and phase control errors applied in Refs. [4,5], RB has the advantage of being able to assess a broader class of operations than only π pulses. In the work of Ref. [28], a method was proposed to characterize the control accuracy by measuring the excitation profiles of different pulses experienced by the spins. However, the accuracy of the measured excitation profiles is limited by the ESR signal linewidth, and this method cannot provide a well-defined unitary fidelity that describes the gate performance. Moreover, there are other important sources of error beyond the imperfection of the pulse excitation profile. On the other hand, RB provides a quantitative characterization of gates in terms of the average fidelity of the unitary operation, which is a relevant quantity in the context of fault-tolerant QIP. Furthermore, it is unclear how to quantify multi-qubit operations in both the CP/CPMG method in Refs. [4,5] and the transfer function method in Ref. [28]. Therefore, RB is a more general characterization protocol that produces a quantity that can be directly compared to fault tolerance thresholds and to fidelities measured in other QIP implementations. RB has been applied in a wide range of QIP implementations, including trapped ions [36,40,41], liquid state NMR [42], superconducting qubits [43,44], atoms in optical lattices [45], ^{31}P donor in silicon [46–48], and nitrogen-vacancy (NV) centers in diamond [49,50]. However, as yet RB results in a conventional pulsed ESR system have not been reported.

In this work, we implement a single qubit RB protocol using pulsed ESR at X-band on a sample of gamma-irradiated fused quartz. The stable, spin-1/2 defect is an unpaired electron at an oxygen vacancy. In order to have the flexibility and precision of control necessary for QIP with arbitrarily shaped optimal control pulses, the spectrometer was custom built and includes an AWG and I–Q modulator for pulse generation, and a specially designed loop-gap resonator (LGR) for efficient, broadband control that accommodates small samples. One challenge with pulsed ESR that is not usually encountered in NMR is that the bandwidth of the microwave resonator that interacts with the sample is comparable to (or narrower) than the desired control bandwidth. Moreover, impedance matching of all elements in the pulse generation, amplification and transmission train is more challenging at microwave frequencies. Here, we identify and partially correct sources of gate error due to pulse distortions; these distortions arise both due to the finite resonator bandwidth and to hardware imperfections. Additionally, we narrow the distribution of local fields that lead to inhomogeneous dephasing (T_2^*) by applying a selection sequence, and this demonstrates the dominant role of the T_2^* process as a source of incoherent gate error. The initial RB result of >6% error probability per gate is significantly reduced to about 0.8% after identifying and mitigating several sources of error, with the lowest error rate being dominated by T_2^* dephasing. Our work provides a first benchmarking of experimental unitary gate fidelities in a conventional pulsed ESR system. This result can be compared, in an unbiased way, with the gate fidelities obtained in other QIP implementations. The use of RB in concert with simulations and the selection sequence sheds light on the contributions of different error sources – T_1, T_2 and T_2^* processes, $\boldsymbol{B}_1$ field inhomogeneity, as well as unitary errors. This is a powerful diagnostic tool that should be broadly useful in ESR applications that increasingly rely on sophisticated pulse sequences that demand high precision; such sequences will benefit from pulses with high unitary fidelities, i.e. pulses that work as desired, independent of the input state.

2. Instrumentation

2.1. X-band pulsed ESR spectrometer

A schematic of the custom X-band pulsed ESR spectrometer is depicted in Fig. 1. The microwave source (Rohde and Schwarz SMF100A) provides a continuous wave (CW) output at $\omega_0/2\pi \sim 10$ GHz, and features low phase noise and output power up to +25 dBm. In order to generate arbitrary shapes such as GRadient Ascent Pulse Engineering (GRAPE) pulses [51], we use a single-sideband (SSB) upconversion technique [52,53] with an I–Q modulator (Marki IQ-0714LXP) as the SSB mixer. A 1.2 GS/s arbitrary waveform generator (AWG, Tektronix AWG5014B with a memory expansion to 32 Mpts) provides both 0° and 90°