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Simulation of Single-shot Qubit Readout of a 2-Qubit Superconducting System with Noise Analysis

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***Abstract*—It is desirable to reduce the readout time in a quantum computer so that more operations can be performed before decoherence occurs. In this paper, we propose and study a novel readout scheme of two qubits through simulations with a calibrated noise model. Two resonators with resonant frequencies only ~5MHz apart are designed and coupled to two superconducting qubits, respectively. A single shot readout is performed using one single frequency pulse to read the states of the two qubits. This has the potential to increase the number of qubits for a given bandwidth. The simulator used is written in Matlab which takes S_{21} calculated by Ansys HFSS as inputs. The know-how of performing repeatable and accurate simulations in HFSS is also discussed.**

***Keywords*—HFSS, Matlab, Noise, Qubit Readout, Quantum Computing, Resonator, Superconducting Qubit**

I. Introduction

Quantum computers are expected to revolutionize many engineering aspects from quantum simulation [1] to factorization [2] to finite element simulation [3]. Recently, quantum supremacy has also been demonstrated in a superconducting qubit quantum computer [4].

Besides qubit initialization and manipulation, qubit readout is one of the critical operations in a quantum computer [5]. It is important to reduce the readout time so that more operations can be performed in the system before the qubits become decoherent and information is lost. Superconducting qubits are usually read by sending an RF pulse through a feedline, which is coupled to a resonator and the resonator is coupled to a qubit (Fig. 1). The S_{21} of the scattering matrix is expected to have a dip at the resonant frequency of the resonator. However, the qubit acts as an artificial atom, and thus the resonator and the qubit form a cavity quantum electrodynamic system [5]. As a result, depending on the state of the qubit ($|0\rangle$ or $|1\rangle$), the dip in S_{21} will occur at a higher or lower frequency. The change of the frequency is also known as the cross-Kerr, χ [6]. By measuring the change of the resonant frequency, the state of the qubit is thus determined.

In order to simplify the circuit, multiple resonators/qubits are usually coupled to the same feedline and frequency multiplexing is used to read individual qubits. This means that the resonators need to have well-separated frequencies (preferably more than 50MHz [7][8]) and the total number of the qubit is limited by the bandwidth of the electronics.

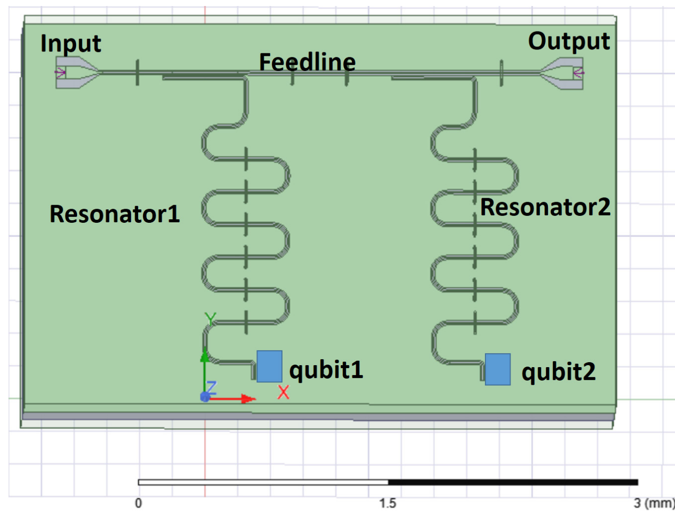

Fig. 1. The bird view of a 2-qubit readout system. "qubit1" and "qubit2" indicate the locations of the qubits. In this paper, qubits are not simulated explicitly. Its cross-Kerr effect on the resonator frequency is modeled by changing the length of the resonators. The short segments crossing the feedline and resonators are wirebonds.

In this paper, we propose to reduce the frequency separation of the two resonators in a 2-qubit system to about 5MHz and use one single frequency to read the state of both qubits. This has the potential to increase the number of qubits for a given

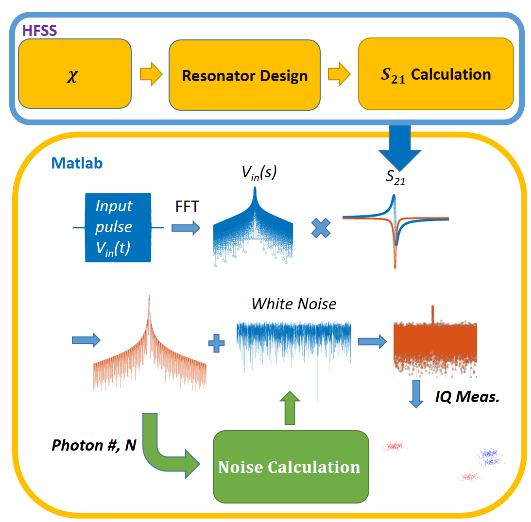

Figure 2: Illustration of the simulation flow.

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bandwidth. We study the possibility of this scheme by using a Matlab simulator with calibrated noise from an actual quantum computer [9]. The scattering matrix is calculated using Ansys HFSS [10]. The know-how of performing accurate S_{21} calculations will also be detailed.

II. Simulation Setup

A. Methodology

Fig. 2 shows the simulation methodology. The qubit is not explicitly constructed in the simulation. The cross-Kerr is assumed to be about 1MHz. One may compute the cross-Kerr using Energy Participation Ratio (EPR) [6] or through experiment, if the design is known. Since the purpose of this paper is to study a novel readout scheme, the cross-Kerr can be an input and is assumed to be given. To model the qubit at different states ($|0\rangle$ or $|1\rangle$), the resonator length, thus the resonant frequency, is adjusted accordingly. The scattering matrix is extracted using HFSS and fed into the Matlab program in which a reading pulse is applied to the S_{21} matrix and quadrature measurement is performed to study the distinguishability of various states through the I-Q plots. Details of the simulation framework can be found in [9].

B. Tools used

To create the coplanar waveguide resonator structure in HFSS, Qiskit metal was utilized and modified [11]. This would allow the generated geometry to stay consistent while allowing modifications if necessary. Fig. 1 shows the structure created for a 2-qubit system. The ElectroMagnetic (EM) analysis tool that was utilized in conjunction with the generated geometry was Ansys HFSS. HFSS was used since it is a Finite-Element based EM simulation tool that can produce realistic results.

C. Robust Simulation

When analyzing coplanar waveguide geometries with HFSS to extract the scattering matrix, meshing is a problem that can be run into. It is important to have a dense enough mesh but it is difficult to judge how dense the mesh has to be. Such mesh can be found by first running an eigenmode simulation [13]. The eigenmode simulation will generate a mesh until convergence is reached for the specified settings. Here a 1% delta frequency was used. A minimum solution frequency of 5 GHz was used to give HFSS an estimate of where the resonant frequency of the structure should be. This can be approximated by calculating the frequency for the structure using the equations for the resonant frequency of a coplanar resonator. Once the eigenmode simulation has analyzed the structure, the simulation mesh can then be imported into a DrivenModal simulation. The mesh imported into the DrivenModal simulation should have the settings selected for "simulating the design source as needed" and "preserving the source design solution". This will allow for the DrivenModal simulation to refine the mesh as needed. In addition, seeding the mesh on the coplanar transmission line in DrivenModal should be done. This in return will ensure a denser mesh near the coupling section as well. Another important factor is the simulation type. The simulation type in DrivenModal can be chosen to be either Discrete or Fast Sweep. With the dense mesh imported from the converged eigenmode solution, it is found that Fast Sweep

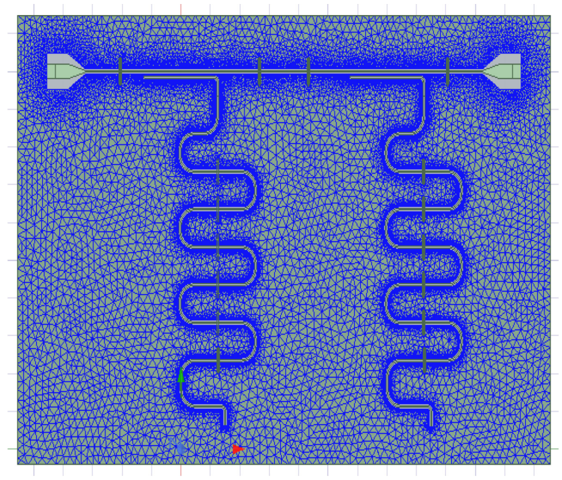

Fig. 3. Imported mesh in DrivenModal for two-resonator case.

gives accurate solutions. Fig. 3 shows the mesh used in the S_{21} study which is imported from a converged eigenmode result.

There are other issues as well such as the type of port that coplanar waveguides are fed with. When performing DrivenModal simulations in HFSS to extract the scattering matrix, it is necessary that the transmission line is fed with a component called LaunchpadWirebondDriven. This component in Qiskit allows the user to feed signals to coplanar structures and this is achieved by creating a ground pocket cut-out with a small pin which is used for DrivenModal simulations. When this is not used, spurious results can be obtained. Fig. 4 shows that the dip in the S_{21} does not change monotonically with the resonator length when LaunchpadWirebondDriven is not used. Another important feature to utilize is the use of wire bonds Fig. 1. Here wire bonds are used to "ensure the biasing of active areas on the chip and suppress multimode propagation along the RF signal paths" [12].

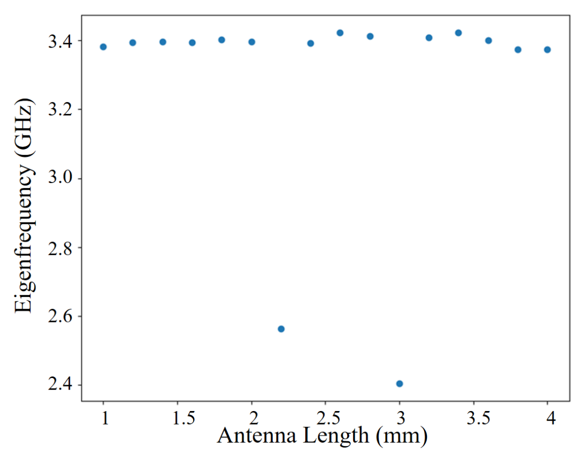

Fig. 4. Simulation result when LaunchpadWirebondDriven is not used.

III. S21 Simulation

The structure in Fig. 1 has a Si substrate thickness of 760um with a dielectric constant of 11.45, the value for silicon at cryogenic temperatures. The loss tangent of silicon is 1e-6. The resonator length and CPW dimensions are calculated so that the resonant frequency is about 5.5GHz and the characteristic impedance is about 50Ω.

Four structures are designed with different resonator length combinations for the first (L_1) and second (L_2) resonators. They are L_1/L_2 = 106μm/111μm, L_1/L_2 = 106μm/110μm, L_1/L_2 = 105μm/110μm and L_1/L_2 = 105μm/11μm, which represent qubit states of |00⟩, |01⟩, |10⟩, and |11⟩, respectively. Fig. 5 shows the S_{21} of the 4 structures as a function of frequency and Table I shows the dip frequencies. It can be seen that the simulation results are consistent with the length of the resonators and they have different real and imaginary values at frequencies at 5.5189GHz.

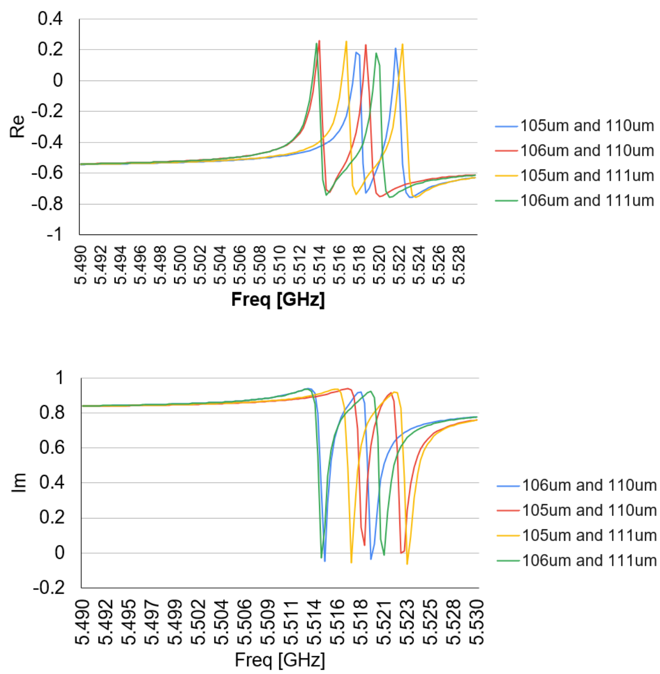

Fig. 5. The real (top) and imaginary part (bottom) of the S_{21} as a function of frequency of the 4 structures.

TABLE I: THE DIP FREQUENCIES OF THE 4 SIMULATION STRUCTURES.

Hanger Combination	***Hanger***	***Dips (GHz)***
106 and 111um	L1=106	5.5203
	L2=111	5.5142
105 and 111um	L1=105	5.5229
	L2=111	5.5172
105 and 110um	L1=105	5.5223
	L2=110	5.5182
106 and 110um	L1=106	5.5192
	L2=110	5.5145

IV. IQ PLOT

Based on the S_{21} results, a pulse width of 3.5μs at 5.5189GHz width is then applied to the resonator and the imaginary and real parts are extracted with noise applied to form an I-Q plot. The quantum computer is assumed to have the same temperature stages, attenuations, and amplification as in [9] (Fig. 6). However, a input power of -107dBm after attenuations is used.

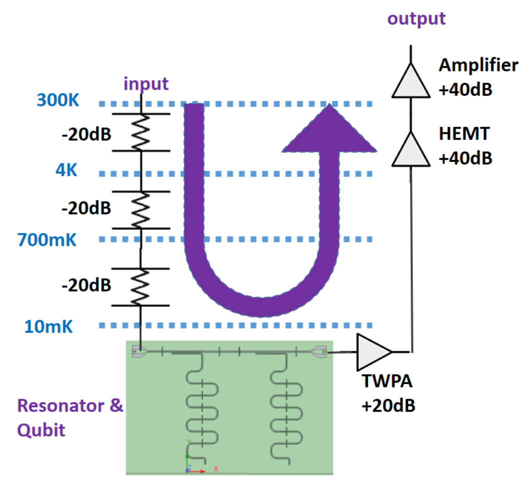

Fig. 6: The 2-qubit system simulated. The readout path is highlighted.

Fig. 7 shows the IQ plots of the readout. It can be seen that the 4 states can be distinguished successfully.

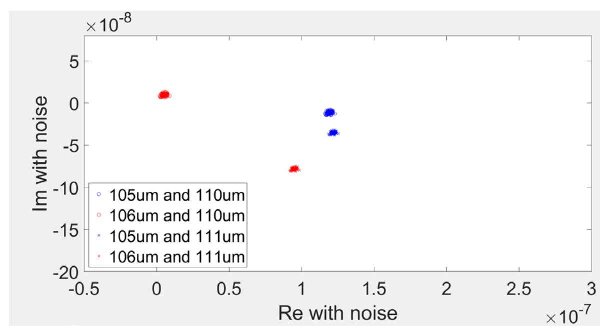

Fig. 7: The IQ plot with power of -107dBm and pulse width of 3.5μs.

We then study how the pulse energy will change the fidelity. Fig. 8 shows the IQ plots of the readout when the input is 9dB weaker (i.e. -116dBm). It is found that blobs are barely distinguishable.

We also study how the pulse width will change the fidelity. Fig. 9 shows the IQ plots of the readout when the pulse width is 1000ns. It is found that two of the blobs have merged and thus the 4 states cannot be fully distinguished.

Finally, we optimized the pulse width and energy together and Fig. 10 shows the IQ plots of the readout when the pulse

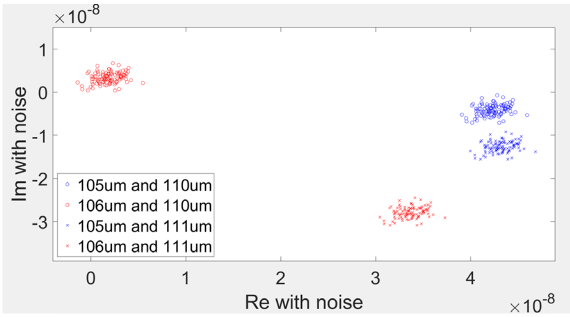

Fig. 8: The IQ plot with power of -116dBm and pulse width of 3.5µs.

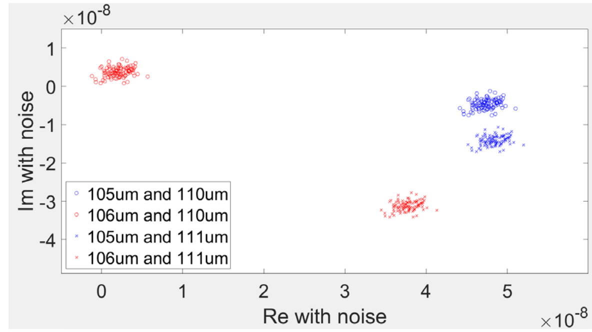

Fig. 9: The IQ plot with power of -110dBm and pulse width of 1.5µs.

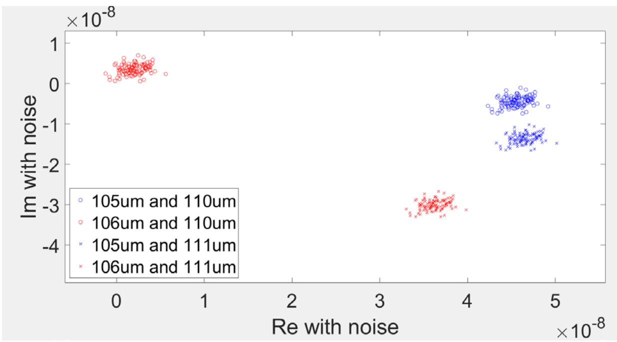

Fig. 10: The IQ plot with power of -107dBm and pulse width of 1µs.

width is 1500ns and power is -110dBm. It is found that the blobs are still distinguishable.

It should be noted that the noise margin in this study is larger than that in [9]. This is because the cross-Kerr used is about 1MHz in this study instead of 114kHz in [9].

V. Conclusions

In this paper, we proposed a novel single-shot reading scheme for a 2-qubit readout. We showed that it is important to have dense enough mesh setting and this can be obtained by first doing an eigenmode simulation. By using a simulation framework with noise, we show that this reading scheme is feasible and it works even with input power of -110dBm (after attenuation) and pulse width of 1.5µs.

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